Ruiyu Yin

Metallurgical Process Engineering

Metallurgical Industry Press

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With 125 figures

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Foreword

Since the birth of modern steelmaking technique in the middle of nineteenth century, iron and steel are consistently the important basic materials for development of national economy and society in the world and the output of steel product is an important index of national strength. Thus, soon after foundation of new China, the development strategy of "taking steel as the key link" was established. In order to accelerate steel production, there was a movement of "making steel vastly", and in spite of dear cost, the result were negligible, but it was all over as a historical event. Since implementation of open policy in China in the middle of eighties of the twentieth century and due to rapid development of machinery and construction industries, the demands for steel products have been increased tremendously, in particular, because of right development strategy and continuous progress in technique, Chinese steel industry has stepped into stage of healthy development. In the nineties of the twentieth century, Chinese steel industry boomed. In 1996, the output of crude steel in China was over 100 Mt and China became the largest steel maker in the world and the output of crude steel was nearly doubled from 1990 to 2000. From 1996 to 2003, the output of crude steel was increased by over 100%. In 2003, the output of crude steel in China was over 220 Mt and at the same time, the energy consumption per ton steel was decreased greatly, such circumstance was recognized as a miracle by the world steel business circle. The author of this book has worked at steel works, research institution and national industrial department as an engineer, researcher and manager for long time, and experienced many important technical development projects, engineering practice, decision-making process for development, accumulated rich knowledge, and has been investigating and thinking *oretically*, and formed a theoretical frame at the level of metallurgical manufacturing process of steel enterprises, which has been used and popularized in the process of technical progress and technical modification of Chinese steel industry successfully as a main direction of development.

Based on the practice and thorough study for more than ten years, the author proposes an issue of engineering science in steel manufacture process creatively.

He proposes that in metallurgical manufacture process there would have problems to be solved by the sciences with different time-space scales, namely, fundamental sciences, technological science, engineering science, etc. and it is indicated that metallurgical industry is a typical process manufacturing industry. That means, manufacturing process is the "foothold to be based upon" for these industries. The manufacturing process is of extensive correlation and infiltration in process industry. The manufacturing process is correlated directly with the factors much as product quality/varieties, cost /price, input/output, efficiency/benefit, which affect on competitive of the steel plant in the market. On the other hand, it is correlated with the factors of sustainable development as availability of resources and energy, the emission of process, environment/ecology, and circular economy. The steel manufacturing process has been built up gradually on the basis of fundamental study on chemical reaction, deformation and phase transformation of unit procedure and knowledge of designing, and development of equipment for unit procedure. Now, from a viewpoint of scientific perception, the steel manufacturing process has been studied quite thoroughly as a branch of fundamental science on the scale of atom/molecule, but of technological science on the scale of procedure, device, it can be said, only a little has been studied, and on the scale (level) of process, the study in the field of engineering science has just started. Nevertheless, facing such complicated and serious dual challenge of enhancing competitive power in the market and sustainable development, world steel industry has to promote steel plant structure adjustment and optimization based on engineering science as one of the countermeasures.

So it can be said that the development and innovation in engineering science are the response to the calling of the times.

The author has investigated quite deeply the essence, attribute and connotation of steel manufacturing process recently and indicates that metallurgical manufacturing process consists of three elements, which are flow, process network and program, and the attribute of manufacturing process is of dissipative structure. He describes the theoretical frame and connotation of metallurgical process engineering in details, including analysis-integration of steel manufacturing process, control of multi-factorial mass flow in steel manufacturing process. At the same time, the author emphasizes the time in the manufacturing process, the operation dynamics in production of the steel plant and "interface technique" in production, and sums up that steel enterprise should optimize the structure, and innovate in operation mode.

For a modern enterprise, the sustainable development and possibility of developing circular economy should be considered. The author has proposed the direction of green manufacture for steel plants and the prospect of extending functions of steel manufacturing process to a circular economy. The description of physical models of steel manufacturing process by the author will be useful to guide concentrated integration of information technique with steel manufacturing process for total control and intellectualization of the latter.

Based on deep understanding of the domestic and foreign steel enterprises, in combination with the development of modern engineering science, the author writes this book, “metallurgical process engineering”, and doubtless, it is of great importance in guiding the development of Chinese steel industry along the healthier path. In the 21st century, steel is still the most important basic material and has a very important position in national economy. The publication of this book will be of great value as a reference for researchers, designing engineers, enterprisers and managers of steel industry.

Beijing Changxu Shi
May 2010

Preface

The twentieth century was the century in which metallurgy evolved from a handicraft to an engineering science. In the last thirty years of that century and, in particular, the twenty-first century, the world's steel industry, including the Chinese steel industry, are facing with new challenges and opportunities for development. New propositions have been put forward mainly by developments of the times, advances in science and technology, and changes in the global ecology-environment. Where further development of the steel industry is concerned, these propositions cannot be resolved simply by providing answers to such individual issues as quality and variety. A more important and forward-looking proposition calls for the comprehensive resolution of a number of major integrated tasks such as the enhancement of market competitiveness—including such aspects as production costs, materials consumption, energy consumption, production efficiency and investment benefits—and issues of sustainable development, such as the availability of materials and energy resources, and ecological harmony. These propositions for the steel industry in the new century cannot be solved by focusing studies simply on the fundamental sciences (such as thermodynamics, kinetics of chemical reactions, etc.) and the applied sciences (such as the transport phenomena and reaction engineering), but have to be resolved in their entirety by studying the functions, structure, efficiency, and other process engineering issues of metallurgical manufacturing.

Also, if research in the fields of metallurgical and metallic material sciences is limited to the fundamental or applied sciences or remains at the level of science and technology, it will probably be difficult to find a coordinated resolution for all the many complicated and practical problems in the production and construction of steel plants, and the efficient integration of information techniques into the entire process of steel manufacturing may even be negatively affected. In order to solve the above-mentioned integrated and complicated propositions, it is necessary to study and investigate the problems at the process engineering level of engineering science.

Science is the human activity of cognition. It is a "knowledge system that reflects the essence and regularities of movement of various phenomena in the real world in the form of categories, laws, and theorems." In the process of advancing science, it is necessary, on the one hand, to sum up the essence of matters and phenomena in the form of theories and to establish tenets and principles that must be observed. On the other hand, however, we must also be aware that human beings are prone to unavoidable limitations in their process of cognition. Thus, while attention should be paid to the theories and principles that have been summed up, one should at the same time avoid falling into the misapprehension that everything should proceed from existing theoretical cognitions to the exclusion of practical considerations. For example, taking existing theories and principles as the sole criteria of cognition would have the effect of ossifying and narrowing the sciences and their disciplines, and even turn already obtained results into fetters that restrict the further development of science. The reason for this is the complexity of the material world and the existence of limitless variations, levels or possibilities, even within limited dimensions of time and space. That is why scientific theories naturally generate a great many schools and branches with different characteristics, and why different systems of knowledge emerge even within one and the same disciplines of science and new disciplinary branches are formed with the passage of time.

In fact, metallurgy and the science of metallic materials—the main sciences that support the development of the metallurgical industry—themselves face the issues of disciplinary development, extension, and innovation. The methodologies of metallurgy and the science of metallic materials have for a long time been based on the reduction theory. True, the methodology of the reduction theory has played an important role in, and still affects, contemporary science and the development of the modern sciences. The conversion of metallurgy and the metallic materials theories from a handicraft to a science was brought about by the use of such methodology, for example the thermodynamics and kinetics of chemical reactions, crystallography, the theories of phase transformation and so forth. However, there are a great many important and complex problems in the metallurgical industry's production and construction that cannot be solved simply by means of the aforementioned fundamental theories. It must also be noted that these important and complex problems are proliferating in rapid succession in the wake of current developments. This has resulted in the emergence of the theories of such applied sciences as "transport phenomena and reaction engineering" and "controlled rolling and cooling." Toward the end of the twentieth century and in the twenty-first century in particular, the development of modern steel enterprises has raised the proposition of developing engineering science for resolving integrated issues on the basis of the fundamental and applied sciences, in the expectation of resolving complex integrated problems of greater dimensions and higher levels—problems that are of extreme importance for the development of enterprises and society. This calls for research in the macroscopic engineering science called Metallurgical Process Engineering.

Metallurgical process engineering pertains to the category of macroscopic engineering science. It studies, in the main, the physical nature, structure, and entire operation of the metallurgical manufacturing (production) process. Its aim is to clarify the driving forces of the flow (and storage) of materials (and energy) related to the metallurgical manufacturing process, and it deals with the process cycle that starts with the acquisition of materials and extends through product manufacturing, use, consumption, and recycling. The problems of function-structure-efficiency in the research and manufacturing processes involve a wide range of knowledge concerning spatial and planar dispositions, the ordering and control of time and time sequences, and the control and optimization of emissions and waste elimination (or recycling) during those processes.

Nobelist Dr. Gell-Man Murray has pointed out, for a complicated, highly nonlinear system, the whole behavior is not connected simply with the behavior of its parts. It is required that the whole behavior should be concerned from different sides widely and courageously, not with the details of some facets. From the methodological point of view, the above passage indicates the understanding that complicated and integrated problems in the domain of engineering science cannot be resolved simply by means of the methodology of reduction theory. This, of course, does not negate using the methodology of reduction theory for studying complicated and integrated problems of engineering science, and in some cases the strong points of the reduction theory are still employed to analyze complicated problems. However, it must be pointed out that these analyses are conducted within the framework of an entirty concept, and the findings of these analytical studies are then integrated into the overall framework. Hence, where the research method of engineering science is concerned, it is important that we learn how to combine entirty theory with reduction theory in a flexible and skillful way.

It may be said that at the present moment we have attained basically clear understandings of the knowledge of metallurgy and metallic materials at the level of the basic sciences. However, such understandings are still somewhere between "basic" and "approximate" at the level of the applied sciences, and are only just receiving attention and overall consideration at the engineering science level. Hence, one might say that social progress, industrial development, the spreading of science, and the training of qualified personnel depend to a large extent on the results of explorations and research in the fields of metallurgy and metallic materials at the level of engineering science.

In the new century, the world's steel industry and in particular the steel indusaies in China, India, Brazil and other developing countries are in a period of developmental opportunities—opportunities for coordinating and harmonizing steel plants with the environment, for coordinating the structures of products, materials, and energy resources, for upgrading the technological structure of steel plants as well as for further readjusting the distribution of the world's steel industries. At a time when opportunities and challenges exist in tandem, the steel industry and steel enterprises in particular should carry out comprehensive optimizations and innovations of their entire structures. This is especially important for new and upcoming investors.

I, the author of this book, have worked many years at steel enterprises and metallurgical departments and have acquired some understandings and cognitions about this rise as I look back at many events during the rapid growth of the Chinese steel industry in the 1990s. During visits to the world's main steel plants and exchanges with many well-known experts and scholars the world over, I have come to see, at the level of engineering science, that the manufacturing process (technological process) of the steel industry—as a typical process manufacturing industry—has a highly correlative and permeating nature.

It is, therefore, most important to explore and study the substance, the structure, and the regularities of the metallurgical manufacturing process. In order to investigate and study the functions, structure, and efficiency of the manufacturing process, one must first of all have a theoretical understanding of that process. The initial understanding today is that the manufacturing process consists of three main elements: "flow," "process network," and "order." The manufacturing process is a "multi-factor (multi-dimensional) flow" that moves in a dynamic and orderly fashion and according to certain program within a complex net structure (process net framework) composed of various procedures and inter-procedural connectors, to realize certain groups of objectives."

This book is written along the following train of thought:

- Process manufacturing industry and process engineering.
- What is metallurgical process engineering?
- Analysis and integration of the steel manufacturing process.
- Multi-factor mass flow control in the steel manufacturing process.
- The paramater time in the manufacturing process.
- The operation dynamics of steel production processes.
- The structures and models of steel plants.
- Steel plants and the environment.

This book is written as a reference for the leadership stratum and technicians at steel plants, teachers and post-graduate students at relevant institutions of higher learning, researchers at design and research institutes, and high-level managers at certain administrative departments. Due time constraints, some readers may be interested in only a few of the chapters, for which reason some chapters have been written as complete and relatively independent entities. It is thus unavoidable that the contents of some chapters are somewhat repetitive. Some repetition may be permissible and even necessary, since this book is not an ordinary text-book.

I encountered many difficulties in the writing this book. One of these was finding the proper reference books. Another was the time needed for collating and processing all the materials. In reality, however, the biggest difficulty lay in the crystallization of the concepts and the abstraction and construction of the models. Hence, the decade that it took me to prepare the book was in fact a process of "getting into the role" of theoretical cognition. Even now I do not claim to have acquired a complete understanding, and errors and mistakes are unavoidable. Where these occur, I sincerely hope my readers will correct me.

In the writing of this book, I received encouragement and support from academicians Changxu Shi, Xianghua Shao, Jun Ke, Kuangdi Xu, Dainzuo Wang, Shourong Zhang and Zhongwu Lu, and Prof. Ying Qu. Financial support for the book by the state fund for key scientific and technical publications was recommended and obtained by Academicians Changxu Shi and Shourong Zhang. As I recall, when I was elected academician in 1994, Changxu Shi suggested that I write a book describing my knowledge and lines of thinking with regard to ferrous metallurgy, and I have kept this suggestion constantly in mind. Thus, in the last ten years, I have give assiduous attention to forming theoretical conceptions at the level of engineering science as I studied, worked, and taught post-graduate students. I must admit, of course, that the study of integrated problems of metallurgy at the level of engineering science in still at an initial "getting-in-the-role" stage, and many topics, in particular those connected with information techniques and environmental sciences, require further study and exploration and are being carried to greater depths in the course of actual application.

As I wrote this book, chapter by chapter, I revised and corrected it several times. Prof. Ying Qu checked the drafts and gave me specific and considerate assistance. Prof. Qu was my teacher when I was a student fifty years ago. We have kept up contact for more than forty years, exchanging academic opinions from which I derived a great deal of benefit. Seventy years old at this time, he checked my draft line by line, and furnished many suggestions for modifications which helped to bring this book to fruition. In the past ten years, Prof. Naiyuan Tian has constantly supported me in my work, helped me with the teaching of post-graduates for doctoral degrees, and done much to enrich the theoretical and practical contents of the book. I must also mention a group of young Ph.D partners of mine——Bingxi Yi, Anjun Xu, Yingqun Wang, Xiaodong Wu, Jian Cui, Maolin Liu, Honghua Tang, Qichun Peng, Qing Liu, Jian Qiu, and Xinping Mao. Studies and discussions with them have done much to amplify and enrich the theoretical framework of this book. A few chapters in this book were checked and corrected by Academician Shourong Zhang. Some of the information was provided by Mr. Taichang Wang, Zhixiang Yu, Jie Fu, Jian Cui, and Zhongbing Wang. I must also mention Dr. Chunxia Zhang who contributed a great deal of effort in terms of collating, compiling, proofreading and revising after she joined the research on this subject in 1998. Mr. Xuxiao Zhang, who became my assistant in recent years, undertook the work of sorting, arranging, and printing the draft. I wish to express my deep gratitude to all the persons mentioned above for the help they have rendered.

Beijing
December 2009

Ruiyu Yin

Preface for the English Edition

The first printing of this book in Chinese edition was completed in May 2004. The book summarizes my understanding and cognitions about metallurgical engineering. Since 1990, I have come to see that the analyzing-optimization of the functions of many procedures at steel plant has been occurred, which has been resulted the coordinating-optimization between upstream and downstream procedure and the restructing-optimization of whole steel manufacturing process has been brought. It has been led to the changes of dynamic-operation mechanism and the mode of steel plant by above evolution and optimization. Analysis-integration method should be used for studying the contents.

Thanks to support from the Baoshan Iron & Steel Co., Ltd. (Baosteel), the first distribution took place in Shanghai on May 28, 2004, a memorable event that remains fresh in my mind. Thereafter, the Baosteel management, which had evinced close concern for the contents of the book, specially organized a study class voluntarily attended by about a hundred engineers and technicians. Starting in July 2004 and ending in May 2005, I gave a total of twelve lectures at the rate of approximately one per month. On May 12 and 13, a summing-up seminar was held at which eight experts at Baosteel delivered a number of vivid and variegated academic reports, supported by visual displays, in connection with the production, construction, and technological reforms at Baosteel. All these reports were of a high caliber and quite stimulating. On the following day I gave a summing-up discourse.

These lectures held by Baosteel helped me shed two misgivings that had been bothering me before the book's publication. One was an apprehension that the book's contents were too difficult to understand, that some of its readers might not be well-grounded enough to accept certain views and arguments since these had never been touched upon during their college educations, and because in-depth comprehension requires a broad range of knowledge on the part of the readers. The other was that readers would not be interested, as the book often places emphasis on physical fundamentals, on analyses and integration, rather than on the resolution of individual matters confined to specific issues. However, the

Baosteel series of lectures demonstrated that modern steel enterprises need theoretical knowledge regarding flow process engineering, or in other words, that such knowledge is necessary for the modernization and revamping of the steel industry.

The publishing of this book also drew the attention of a number of research institutions, such as Institute of Process Engineering, Chinese Academy of Sciences, Central Iron & Steel Research Institute (CISRI) and University of Science & Technology Beijing (USTB). Several institutions of higher learning invited me to give academic reports, and some universities even set up elective courses for postgraduates. The book also triggered interest among relevant experts at institutes of projection and consultation, and Capital Engineering & Research Incorporation Limited repeatedly invited me to deliver special-topic reports.

It is pointed out that from the viewpoint of physical essence of steel manufacturing process, multi-factor mass "flow" (mainly ferruginous mass flow) driven by carbonaceous mass flow, operates in a dynamic and orderly manner in accordance with given "programs" and within a complex "network structure". So, the function of steel plant should be developed as:

1. Operation function of ferruginous mass flow—the functions of steel product manufacturing.
2. Operation function of energy conversion—the functions of energy conversion and the functions of waste treatment and recycling related to energy.
3. Interaction function of ferruginous mass flow and energy flow—realizing the target of process technology and related functions of waste treatment and recycling.

Here, I would like to point out the characteristics of the book:

- It outlines a theoretical study of the energy sources and operation dynamic mechanisms of metallurgical process operations, the purpose being to reveal the essence and regularities of the whole metallurgical manufacturing process in order to optimize the flow of materials, energy, and information in the course of steel manufacturing.
- It presents studies of the "three elements"—flow, process network and order—of metallurgical process operations, the purpose being to minimize dissipation in the course of such operations so as to enhance the market competitiveness of steel plants and their ability to maintain sustainable development.
- It lays theoretical emphasis on dynamic and orderly operations in the metallurgical process, the purpose being to devise quasi-continuous/continuous operations in the metallurgical process so as to raise the technical and economic indexes of steel plant operation.
- It outlines a theoretical study of the integrated structure of the metallurgical manufacturing process, the purpose being to enable the setting up of a new generation of steel plants by optimizing the overall course and overall functions of

the metallurgical process through integrated innovations.

The author is indeed honored by the English edition of this book. By the time of issuing the English version of this book, the author would like to make grateful acknowledgement to Prof. Ying Qu and Prof. Wudi Huang from University of Science & Technology Beijing, and Dr. Chunxia Zhang from Central Iron & Steel Research Institute for their great support and earnestly proofreading the English manuscript of the book. The author would like to thank Prof. Weili Li, Dr. Longmei Wang, Dr. Anjun Xu, Dr. Bingxi Yi, Mr. Xinnong Pan, Ms. Yinghao Liu, Mr. Haifeng Wang, Mr. Fangqin Shangguan, Mr. Xiaojian Du and Dr. Xinping Mao et al for their joint effort on preparing English translation. The author also wishes to express his gratitude to Mr. Huimin Wang and Mr. Di Chen for their dedication in proofreading my English manuscript of the book into fine English. I must express my deep gratitude to above all because their contributions are involved in the English version of the book.

Beijing
May 2010

Ruiyu Yin

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Chapter 1
Steel—the "Material of Choice"

No substantial changes will take place in the position of steel as the important structural and functional material because of its abundant resources, comparatively low cost, excellent material characteristics, and ease of processing and recycling. Steel is still the "material of choice" and it is the recycling material. It is an important basic material in the processes of social civilization and economic development.

The Chinese steel industry has been rising since the 1990s. The development, integration and popularization of six key/common technologies—continuous casting, PCI technology, BF(Blast furnace) campaign elongation technology, continuous rolling, BOF (Basic oxygen furnace) slag splashing technology, and energy conservation—have promoted the optimization of the Chinese steel industry's production processes, energy-saving and emission reduction and improved its production efficiency, and put an important foundation for further rapid developement of the Chinese steel industry.

Steel and other metallic materials developed vigorously in the 20th century and have become an important material basis for the constant advances of the global economy and social civilization. Steel has been produced on an industrial scale since the invention of the Bessemer converter in 1856. Since then, the world crude steel output has undergone constant albeit frequently fluctuating development amid such major events such as economic booms and crises, world wars and oil crises, and with the development and application of oxygen converter steelmaking, continuous casting, large blast furnaces, continuous rolling and the use of information techniques. The advance in steel output in the world since 1870 is shown in Fig. 1.1. World steel output surpassed 1.2395 billion tons in 2006. People's cognition of the socio-economic value of steel has variously been consistent, divergent, or blurred and ambiguous in different periods of time and different countries/regions. In sum, it remains a matter that deserves concern and discussion.

R. Yin, *Metallurgical Process Engineering*

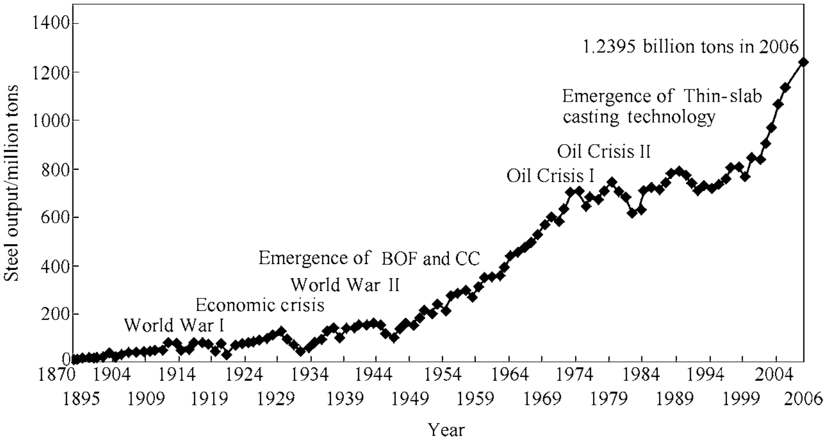

Fig. 1.1 Trend in world steel output since 1870

1.1 The Position of Steel among Diverse Materials

No major change has taken place in the position of steel as an important structural and functional material, yet this is still a matter that calls for discussion and analysis.

A fairly systematic survey is conducted in the article by Czichos Horst (1994) on the requirements and criteria for the evaluation of materials. Fig.1.2 provides an authoritative analysis of the evaluation criteria in industrial circles for the performance of materials, and shows that such qualities as strength, deformation,

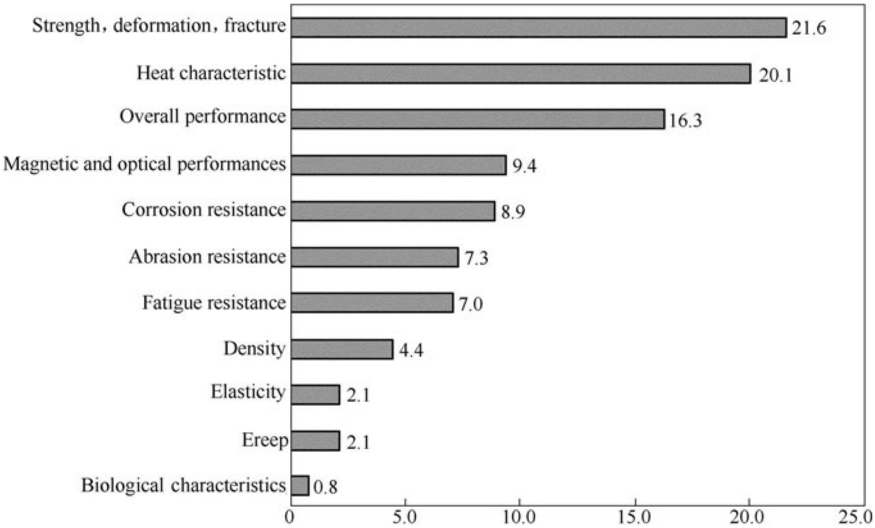

Fig. 1.2 Evaluation of the characteristics of materials vital to industry (Total points: 100)

fracture, thermo-properties, and integrate properties are still the main requirements for various kinds of materials. All engineering materials in terms of their strength, toughness and strength values at different temperatures were compared in the article by J. R. Davis (1995). It is evident that, at least in terms of current knowledge and existing technical conditions, steel possesses advantages in all the relevant aspects.

Evaluation indexes for materials and industrial techniques that will be used in the future have been put forward (Fig. 1.3, Horst, 1994). It is evident that the principal indexes for evaluation are such factors as low price, ease of recovery, environmental friendliness, and low consumption of energy and materials. Steel materials show comparative advantages in terms of all the factors evaluated.

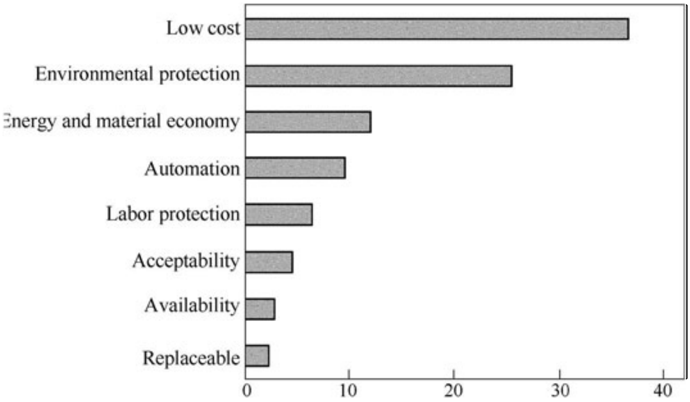

Fig. 1.3 Future requirements in terms of materials and industrial technology

Changes in the prices of various mass produced materials, such as steel, aluminum, plastics, and cement from 1974 to 1994 (Ruprecht, 1995), are shown in Fig. 1.4. The price of steel has fluctuated within a range of approximately 15%, whereas the prices of cement and plastics have risen significantly in the same period and the price of aluminum has fluctuated sharply and risen more than the price of steel.

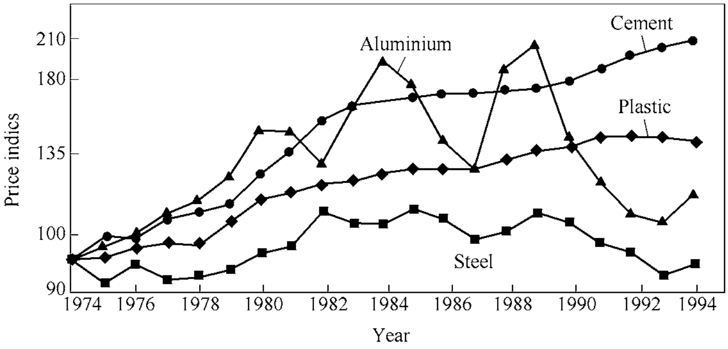

Fig. 1.4 Prices of various materials since 1974 (Price indices for 1974 = 100)

Changes in the relative prices of steel and its downstream processed products are shown in Fig. 1.5 (Schulz, 1993). In the 20 years after the oil crisis, the prices of household appliances, automobiles, and machinery made of steel have increased at a rate significantly higher than the price of steel materials.

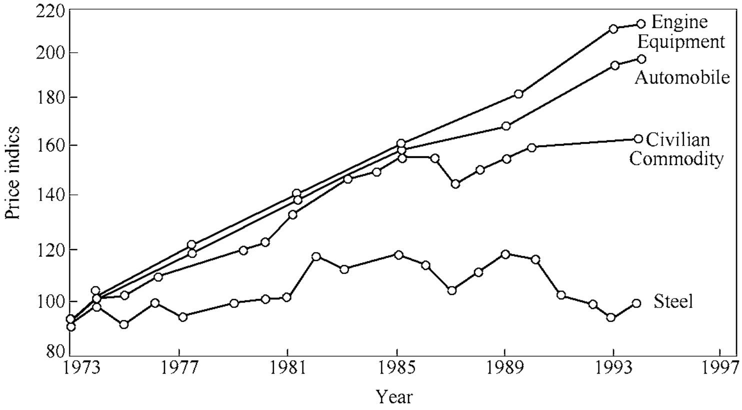

Fig. 1.5 Changes in the prices of steel and its downstream processed products (Price indices for 1974 = 100)

The effects of materials recycling on energy savings and the environment are also important evaluation criteria (Fig. 1.6, Schulz, 1993). It shows the recycling rate of such principal materials as steel, glass, paper, aluminum, and plastics. The recycling rate of steel is significantly higher than that of other materials. Global output of steel scrap has fluctuated in the range of approximately 350 million tons per year in the last 30 years and reached 469 million tons in 2006. Compared to extracting iron from iron ore, the use of scrap steel as a recycled resource is of significant importance for saving natural mineral resources and energy, with energy saving approximately 36% (Yin and Cai, 1999). World crude steel

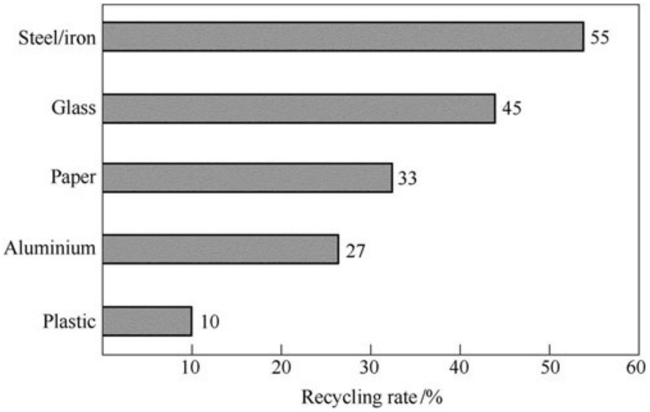

Fig. 1.6 Recycling rate (%) of various materials

output was 1.2395 billion tons in 2006. Of the corresponding consumption of ferrous element resources, steel scrap accounted for about 33.5% (469 million tons), pig iron about 63% (881 million tons), and DRI/HBI about 3.5% (49.46 million tons) (IISI, 2007) in 2006.

In sum, steel is still irreplaceable for the world’s primary basic industries and infrastructure and even daily consumption due to its excellent overall properties. The competitiveness of steel in terms of price is also quite obvious. The cost per unit strength of steel compared with those of various structural materials is only 1/4 to 1/5 that of aluminium, ceramics, and carbon materials.

Also, iron ore deposits for the manufacture of steel are available in large quantities and easy to exploit, and steel products are easy to process and recycle. Thus steel will remain as the principal basic material worldwide in the foreseeable future, and will continue to play an active role in the world’s social civilization and economic development, especially in China where the national economy is growing at a rapid pace.

In the 21st century, the international steel industry has been paying close attention to the position and role of steel materials and has expressed many views of an evaluating nature. It appears that the opinions of all countries are unanimous in these aspects. A typical opinion is that of the AISI (Kavanagh , Carson , Dasgupta, et al, 1998), which maintains that steel will continue to be the “material of choice”.

In China, where the economy is in a period of rapid growth, steel consumption is swiftly increasing in the wake of the country’s rapidly developing national economy and social civilization, the apparent consumption of steel reaching 411.6 million tons in 2007. Relevant studies hold that petroleum, steel, aluminum, and copper are strategic materials for this country and should be given a high degree of attention.

1.2 Steel — An Important Basic Material in the Process of Industrialization

Industrialization is an indispensable stage in China’s efforts to become a modern country. China is currently in the course of industrialization, or, more accurately, in the middle period of industrialization. Practice has prove that in this middle period of industrialization, increases in gross domestic production (GDP) hinge mainly on the growth of the secondary industries (i.e. the manufacturing and construction industries). China’s GDP, which was 1854.8 billion yuan (RMB) in 1990, amounted to 24661.9 billion yuan (RMB) in 2007. In this period, significant changes have taken place in China’s industrial structure. The proportion of the national economy’s secondary industries has increased considerably (from 41.6% in 1990 to 49.2% in 2007), while that of the primary industries (agriculture, forestry, animal husbandry, and fishery) decreased significantly (from 27.1% in 1990 to 11.7% in 2007). The tertiary industries also grew significantly in terms of total output but increased only slightly in terms of their proportion in the industrial structure (from 31.3% in 1990 to 39.1% in 2007). The evolution of China's industrial structure from 1970 to 2006 is shown in Fig. 1.7 (Yin, 2008).

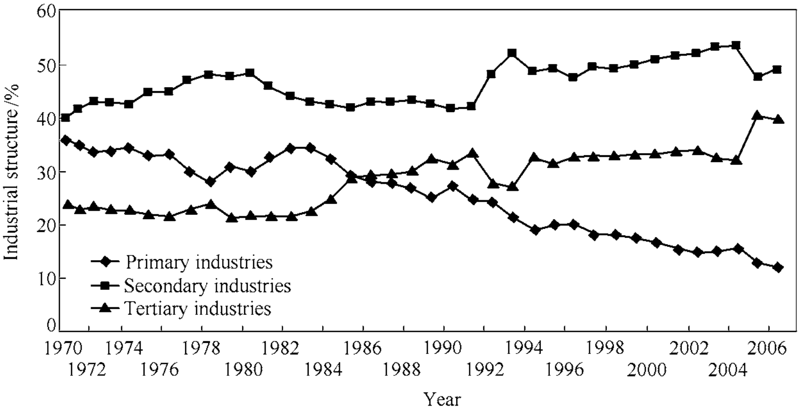

Fig. 1.7 Evolution of China's industrial structure from 1970 to 2006 (Yin, 2008)

Statistics compiled in past years show a close relation between China's consumption of steel products and its GDP and especially with developments in its secondary industries and fixed assets investments.

China's steel consumption has increased with increases in its GDP. For example, when calculated according to comparable prices, the average yearly increase in China's GDP was 9.75% in the period from 1986 to 2002, while that of steel consumption was 9.3%. Of course, there have been some differences in steel consumption and GDP growth trends in different phases of China's economic development, and abnormal situations have also occurred in certain years.

There was a significant correlation of steel products consumption with the construction and secondary industries in the 1980 to 2002 period. The average annual increase in output of the construction industry was 17.8% and that of the secondary industries as a whole was 21.67%, while that of steel products consumption in the same period was 17.6%.

The relationship of steel products consumption with the amount of fixed assets investment was even more evident. From 1981 to 2002, steel products consumption increased synchronously with increases in fixed assets investment. In general, of course, steel products consumption increases at a slightly lower rate than fixed assets investments, depending in the main on the structure of fixed assets investments in different years. Steel products consumption may increase at a higher rate than fixed assets investments when the latter are focused on infrastructure and real estate projects. In China, fixed assets investments increased at a yearly rate of

25.5% between 1981 and 2002 while related steel consumption rose at a yearly rate of 20.6% in the same period.

The structure of China’s steel products consumption still bears certain characteristics of a developing country as it is concentrated primarily on users in the construction, machinery, light manufacturing, automobile, shipbuilding and shipping container industries (Table 1.1) .

Table 1.1 Percentages of steel consumption by China’s relevant manufacturing industries from 2001 to 2006 (Unit: %)

Year	Construction (building)	Machinery	Light manufacturing	Ship building	Shipping containers	Automotive
2001	59.02	15.63	12.65	1.29	1.06	4.12
2002	55.00	15.03	10.36	1.15	0.92	3.76
2003	52.35	15.53	9.11	1.08	1.38	3.97
2004	55.19	16.28	9.12	1.32	1.31	4.69
2005	52.37	15.88	8.18	1.33	1.36	4.78
2006	53.12	15.54	7.55	1.56	1.25	4.82

From the perspectives of either the global economy and social development or of China’s modernization process, steel will, in the foreseeable future, remain as a highly important basic material in the world, not only as an important construction material but also as the world’s most-used functional material (such as stainless and electrical steel). Consumption of stainless steel has risen rapidly in the world since the 1980s, with the world’s output of stainless steel almost tripling (Fig. 1.8) in the past thirty years and reaching approximately 28.4 million tons in 2006. World stainless steel output grew at an annual rate of 5.8% over the fifty or more years from 1950 to 2001, close to that crude steel.

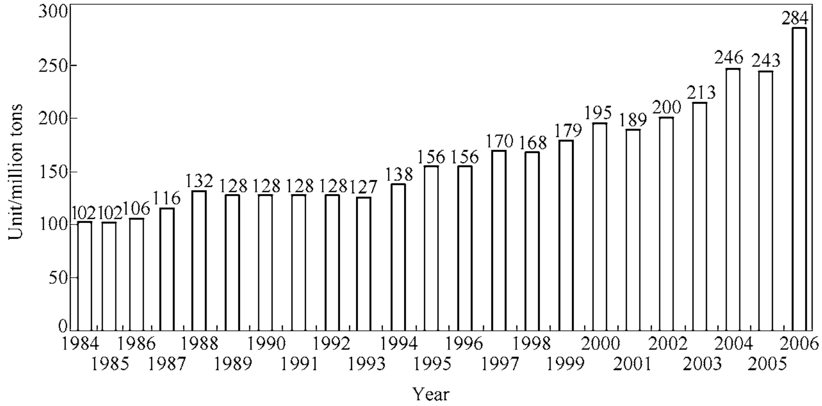

Fig. 1.8 Development of world stainless steel output from 1984 to 2006 (China Steel Yearbook)

In sum, from a global point of view, the steel industry is not a "setting-sun industry," and expanding the steel industry constitutes a most important fundamental and economic growth point for China, India and other developing nations. Steel consumption will continue to increase in the world (and especially China) in order to bolster the rising national economies and social civilizations. To put it in a nutshell, steel is still the "material of choice," and we will still be faced with the serious issue of developing the steel industry in a scientific and sound manner.

1.3 The Rise of the Chinese Steel Industry

A review of the development of the Chinese steel industry shows that the industry has traversed a winding path marked by advances, fluctuations, and a rapid rise. Its course of development has been arduous but rich and rewarding (Fig. 1.9).

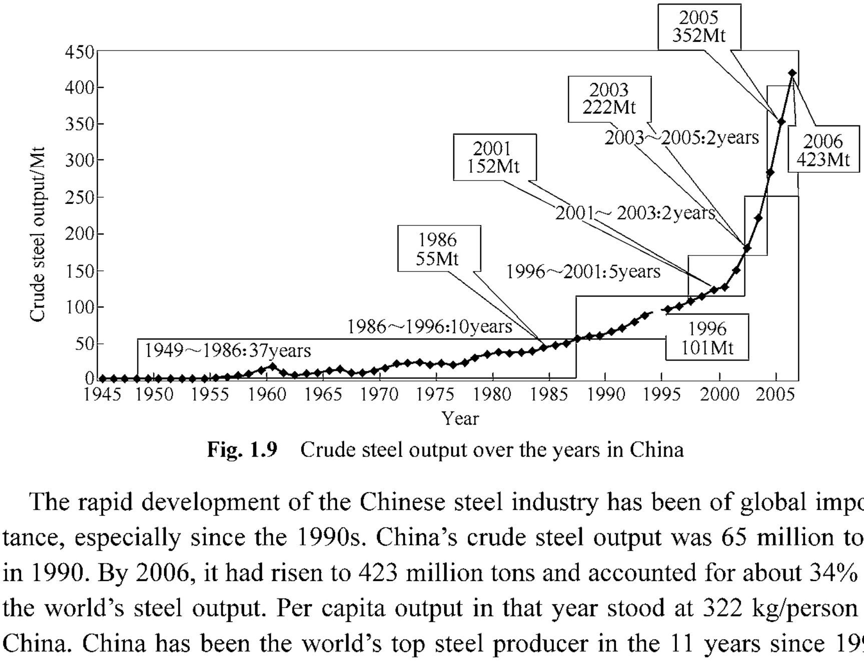

Fig. 1.9 Crude steel output over the years in China

The rapid development of the Chinese steel industry has been of global importance, especially since the 1990s. China's crude steel output was 65 million tons in 1990. By 2006, it had risen to 423 million tons and accounted for about 34% of the world's steel output. Per capita output in that year stood at 322 kg/person in China. China has been the world's top steel producer in the 11 years since 1996 (Fig.1.10). Its steel output increased by 540% from 1990 to 2006.

Due to a series of technological advances and effective investments in China's steel plants since the 1990s, the structure of China's steel plants has been adjusted and optimized and the distribution of Chinese steel enterprises has been further expanded and regulated.

In the process of revamping and development, a large number of steel plants have undergone economic optimization in terms of scale. In 1990, only 14 steel plants had an annual output of over 1 million tons. In 2002, the number had increased to 53, and by 2006, to 67 (Fig. 1.11).

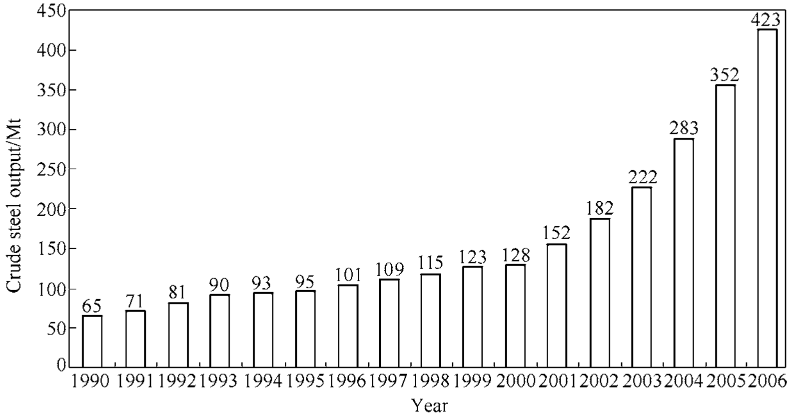

Fig. 1.10 Increases in China's steel output since 1990

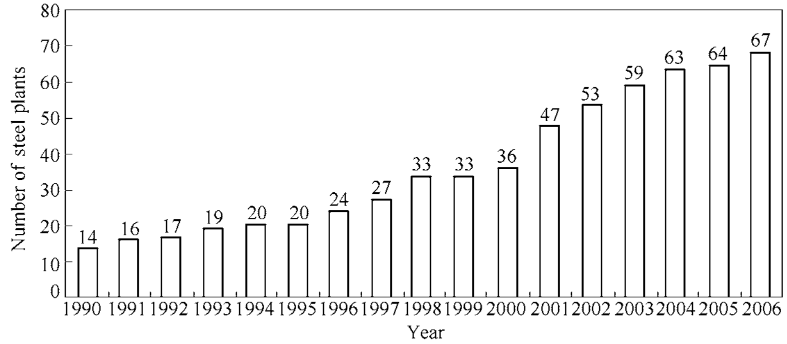

Fig. 1.11 Increases in the number of Chinese steel plants with annual outputs of over 1 million tons since the 1990s

Meanwhile, the distribution of China's steel plants has been correspondingly expanded and optimized. The regional distribution of steel production in China is shown in Table 1.2 and Fig. 1.12. On the whole, the majority of China's steel plants are concentrated along the eastern seaboard and the middle and lower reaches of the Yangtze River.

Table 1.2 Changes in regional steel production from 1950 to 2006 in mainland China

Region \ Year	1950	1970	1980	1990	2000	2002	2004	2006
North China	12.7	20.0	21.5	22.7	25.8	28.9	33.1	33.4
Northeast China	82.8	37.3	26.4	20.9	14.2	12.7	11.8	11.1
East China	2.0	23.7	24.8	27.6	31.9	31.4	30.3	28.7
Central-south China	0.9	13.6	15.1	16.6	15.8	16.3	15.3	17.4
Southwest China	1.6	4.5	10.3	9.4	8.9	7.8	6.6	6.0
Northwest China	0.0	0.9	1.9	2.8	3.4	2.9	2.9	3.4

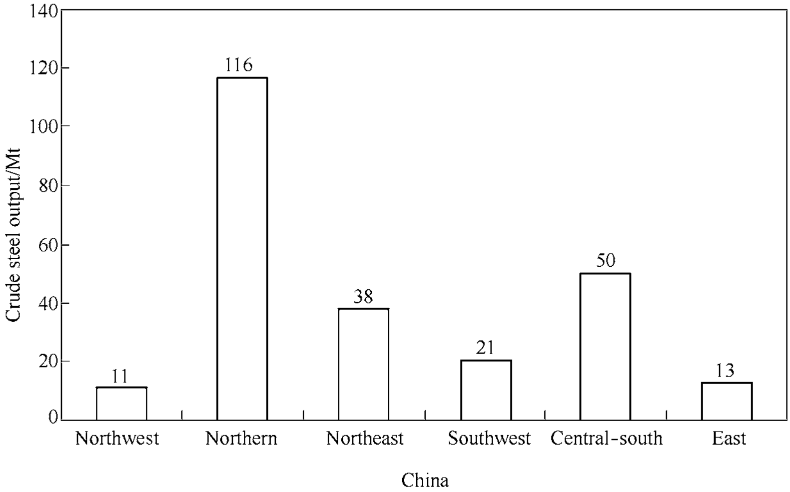

Fig. 1.12 Regional distribution of crude steel output of mainland China in 2005

The technical and economic indexes of the Chinese steel industry have risen dramatically. China's overall yield of finished steel products averaged 95.65% in 2006, 12% higher than in 1990. Comparable energy consumption per ton steel in the same period dropped from 1.611 tce (tons of coal equivalents) to 0.741 tce❶. In 2006, the average utilization coefficient of blast furnaces at key large and medium steel enterprises reached 2.675 t/(m^3 · d), the average coke ratio fell to 390 kg/t, the average PCI rate rose to 135 kg/t, and the average campaign of converters stood at 6052 heats and even exceeded 10,000 heats on many converters. Also in 2006, the continuous casting ratio in the Chinese steel industry reached 98.57%, a significant increase over the 25.07% attained in 1990, and a large number of fully continuous casting steel plants had emerged. Outdated technologies and equipment were also discarded in large numbers. Due to these remarkable structural improvements, many steel plants have become economically effective in scale, reduced their production costs, and increased their profits.

The product structure has changed as well, and the output of flat products, in particular, has risen rapidly.

The main reasons for the rapid rise of the Chinese steel industry since 1990 (Yin, 2004) are as follows:

- Increased market traction on the demand for steel products in the course of national economic development;
- Correct judgments and choices and the orderly implementation of technological progress strategies (i.e. the development, popularization and integration of 6 key/common technologies and the optimization of production processes);

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❶ ce: coal equivalent; 1kgce=29308 kJ.

- The promotional effect of extensive utilization of world mineral resources and scrap iron;
- The domestication of substantial amounts of advanced technology and equipment and reductions in unit production capacity investment; and
- Coordinated techno-economic efficacy brought about by the orderly integration of effective investments and technological progress strategies.

1.3.1 *The traction of market demand*

The background to the rapid development of the Chinese steel industry since the 1990s is the continuous and rapid development of the national economy. China’s GDP, which was 1854.79 billion yuan(RMB) in 1990, rose to 20940.7 billion yuan(RMB) in 2006. Meanwhile, changes have taken place in China’s industrial structure. The proportion of secondary industries in the national economy has increased sharply and that of the primary industries has registered a significant decrease. That such factors as the growth of China’s GDP and constant increases of total investment since the 1990s have strongly promoted the demand for steel products is shown in Fig. 1.13. China’s GDP in the years 1990 to 2006 and the contributions of the primary, secondary and tertiary industries to the total GDP are shown in Table 1.3.

Table 1.3 China’s GDP in recent years and contributions to the GDP by the primary, secondary and tertiary industries

Year	Total GDP /billion yuan(RMB)	Contribution by primary industries /billion yuan(RMB)	Percent /%	Contribution of secondary industries /billion yuan(RMB)	Percent /%	Contribution of tertiary industries /billion yuan (RMB)	Percent /%
1990	1854.79	501.70	27.1	771.74	41.6	581.35	31.3
1999	8205.40	1421.20	17.3	4080.60	49.7	2703.60	33.0
2000	8940.40	1455.30	16.4	4472.30	50.6	2914.50	33.0
2001	9593.30	1461.00	15.2	4906.90	51.2	3225.40	33.6
2002	10239.80	1488.30	14.5	5298.20	51.8	3453.30	33.7
2003	11669.40	1724.70	14.8	6177.80	52.9	3766.90	32.3
2004	13651.50	2074.40	15.2	7238.70	53.0	4338.40	31.8
2005	18232.10	2271.80	12.4	8620.80	47.3	7339.50	40.3
2006	20940.70	2470.00	11.8	10200.40	48.7	8270.30	39.5
2007	24661.90	2891.00	11.7	12138.10	49.2	9632.80	39.1

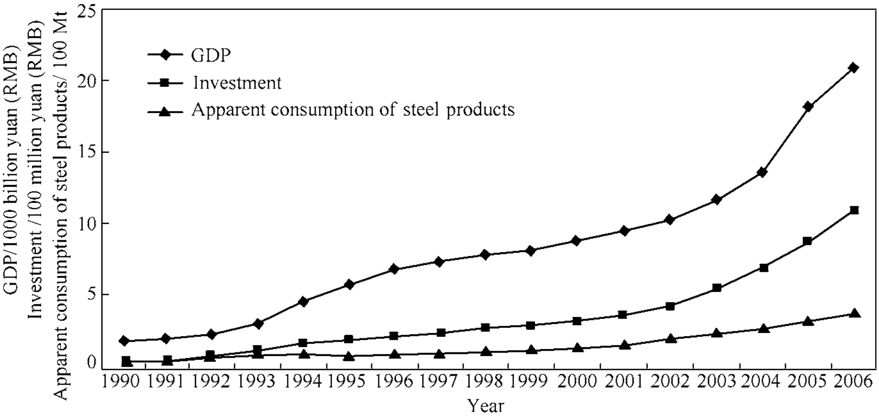

Fig. 1.13 Impact of investment increase on China's apparent consumption of steel products

China's apparent consumption of steel products rose from 53.12 million tons in 1990 to 386 million tons in 2006.

1.3.2 *Correct judgments and choices and the orderly implementation of technological progress strategies*

To clarify the line of thinking for the steel industry's technical advances, it was imperative to start by analyzing the "technical bottlenecks" that structurally affected the entire production process in order to define these bottlenecks and their order of importance. Since the 1990s, the Chinese steel industry has made breakthroughs in 6 key/common technologies (this will be discussed in 1.4). These were, in chronological order: the continuous casting technology, the PCI technology, the technology for the elongation of BF campaigns, the technology of continuous rolling of long products, the comprehensive energy saving technology with production process adjustments, and the slag splashing technology for BOFs.

When discussing the technological progress strategy for the Chinese steel industry in the 1990s, mention must also be made of the significant progress in the UHP EAF techniques and production processes at modern EAF steelmaking plants. Beginning in the mid-1990s, China has set up 36 UHP EAFs and phased out about 1,400 small electric furnaces. China's UHP EAFs are currently used to make both flat and long products and have registered substantial technological progress.

While China is rapidly increasing its manufacturing of steel products, the relative shortage of steel scrap and the high price of electricity have had a restricting effect on the rapid development of electric steel. However, total EAF steel output is still increasing although the ratio of electric steel is decreasing (Table 1.4).

Table 1.4 Total output and ratio of EAF steel in China since 1990

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998
Total steel output/Mt	65.4	71.0	80.9	89.5	92.6	95.4	101.2	108.9	114.6
Electric steel output/Mt	14.0	15.0	17.6	20.3	19.7	18.1	18.9	19.1	18.1
Proportion of electric steel/%	21.5	21.1	21.9	23.2	21.2	19.0	18.7	17.6	15.8
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007
Total steel output/Mt	124.0	128.5	151.6	182.3	222.3	282.8	352.4	422.7	494.9
Electric steel output/Mt	19.5	20.2	24.0	30.5	39.1	42.9	41.8	44.2	58.4
Proportion of electric steel/%	15.7	15.7	15.9	16.7	17.6	15.2	11.9	10.5	11.8

1.3.3 *The promotional effect of using international mineral resources and scrap*

Since China began to implement its policy of opening up to the outside world, the Chinese steel industry has been making active use of mineral and steel scrap resources from other countries. Table 1.5 lists China’s output and imports of iron, manganese and chromium ores in the years 1990 to 2006, and Table 1.6 lists China’s import volume of steel scrap from 1991 to 2006.

Table 1.5 China’s outputs and imports of iron, manganese and chromium ores from 1990 to 2006

Year	Output (Raw ores)			Import volume (Rich ores)		
	Iron ores /Mt	Manganese ores /Mt	Chromium ores /Mt	Iron ores /Mt	Manganese ores /Mt	Chromium ores /Mt
1990	179.3	4.1	0.10	14.2	—	0.5
1991	190.6	4.2	0.02	19.0	—	1.1
1992	209.8	5.3	0.10	25.2	—	7.4
1993	226.4	5.9	0.05	33.0	—	0.0
1994	250.7	5.8	0.06	37.3	1.0	0.7
1995	261.9	6.9	0.20	41.2	1.3	1.4
1996	252.3	7.7	0.13	43.9	1.6	0.8
1997	268.6	6.0	0.20	55.1	1.3	0.9
1998	246.9	5.3	0.02	51.8	1.2	0.7
1999	237.2	3.2	—	55.3	1.1	0.8
2000	222.6	2.6	—	70.0	1.2	1.1
2001	217.0	2.3	—	92.3	1.7	1.1
2002	231.4	2.5	—	111.5	2.1	1.1

Continued Table 1.5

Year	Output (Raw ores)			Import volume (Rich ores)		
	Iron ores /Mt	Manganese ores /Mt	Chromium ores /Mt	Iron ores /Mt	Manganese ores /Mt	Chromium ores /Mt
2003	261.5	2.9	0.02	148.2	2.9	1.8
2004	310.1	8.5	—	208.1	4.6	2.2
2005	426.2	10.0	—	275.3	4.6	3.0
2006	588.2	12.0	—	326.3	6.2	4.3

Table 1.6 China's scrap imports from 1991 to 2006 (Unit: Mt)

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Import	0.1	1.5	3.2	2.1	1.4	1.3	1.2	2.0	3.3	5.1	9.8	7.8	9.2	10.2	10.1	5.4	3.4

1.3.4 *Domestication of advanced technology and equipment*

From the perspective of China's total investment in, and its effect on, the Chinese steel industry in the 1990s, the domestication of advanced technologies and equipment from abroad has done much to promote reductions in investment for unit production capacity. In the 1990s, total investment in China on steel plants was 400.6 billion RMB, overall steel production capacity increased by 82 million tons per year, and investment on unit steel production capacity amounted to approximately 4,800 RMB, or about 55% of the average world level (Yin, 2004). There are, of course, different ratios of flat and long products in China and abroad, but an important factor that cannot be ignored is that domestication has decreased unit investment and improved investment returns.

1.3.5 *The coordinating effect of effective investments and a technological progress strategy*

In the 1990s, investment in the 6 key/common technologies mentioned earlier amounted to 140 billion RMB, or 35% of the total investment in the steel industry in that period (Yin, 2004). Timely and well-ordered investments gave impetus to measures for technological progress that promoted the rapid maturing, popularization, and application of key/common technologies and produced excellent technological and economic results. A large number of steel plants optimized their production and product structures and improved the quality of their products. China's practice in adjusting its steel industrial structure has proved that the orderly combination of timely and effective investments with a strategy for technological progress is able to produce a coordinating technological/economic effect. This is another key factor for developing comprehensive competitive strengths in the steel market.

1.4 Technological Progress of the Chinese Steel Industry

There have been six important key/common technologies for the development of the Chinese steel industry since the 1990s.

1.4.1 *Continuous casting technology*

Starting in 1988, China has adopted the policy of “centering on continuous casting” and used this to guide the technical reform of, and investment in, the steel industry. Since the 1990s, the development of continuous casting has received much more attention and has been constantly promoted and improved by means of technological optimizations, equipment improvements, and domestication.

Continuous casting technology in the Chinese steel industry has gone through 3 stages:

- The stage of “taking continuous casting as the center, steelmaking as the foundation, and equipment as a guarantee,” during which the design parameters of continuous casters was optimized, problems in production organization were resolved, the design capacity of the casters was attained, and full play was given to the production functions of the casters.
- The stage of “optimization of the three-in-one integration of steelmaking, secondary refining, and continuous casting”, during which steel plant production operations by means of complete continuous casting was realized and ingot-casting was discarded, which in turn triggered the elimination of open hearth.
- The stage of “making further leaps forward in terms of coordination and optimization by means of developing high-efficiency, high-speed continuous casting technology, and near-net shaped continuous casting technology”, during which optimal matches were effected between steelmaking furnaces and continuous casters and between casters and rolling mills, and the manufacturing process and product structures of China’s steel plants were optimized.

As a result of more than 10 years’ efforts, the continuous casting ratio of the Chinese steel industry rose from 25.07% in 1990 to 98.57% in 2006.

Advances in the continuous casting technology have given impetus to the development of secondary refining technology (Fig. 1.14). This was required not only for quality and variety, but also for the logistic management and “buffer” function of multi-furnace continuous casting.

Today, the argon bubbling and wire-feeding technology are advancing basically in synch with continuous casting.

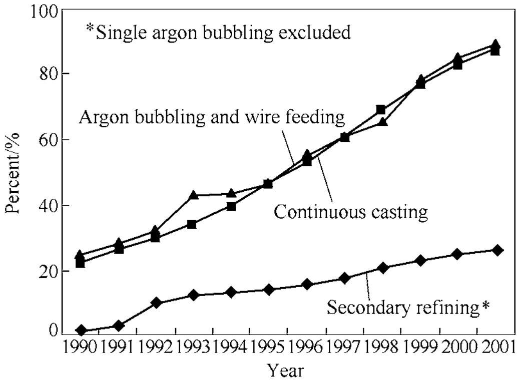

Fig. 1.14 Increases in the ratios of continuous casting, argon bubbling & wire feeding, and secondary refining in the Chinese steel industry

Domestic high-efficiency and high-speed continuous casting technology and equipment have been developing rapidly in China since 1996. The independent development of such technology has brought about a general increase of 50% to 80% both in casting speed and annual single-strand output, advanced the development of hot charge technology, and promoted productivity and energy savings at rolling mills.

China's thin slab casting/rolling technology has been developing swiftly since 1998. By the end of year 2006, 12 production lines were already in operation, i.e. at Zhujiang Steel, Handan Steel, Baotou Steel, Anshan Steel, Tangshan Steel, Ma'anshan Steel and Lianyuan Steel respectively (Yin, 2008). China's output from thin slab casting and rolling lines will, in the near future, constitute a large proportion of the world's output from such lines.

The rapid development of the continuous casting technology has generated the following technological and economic benefits:

- The overall yield of steel products has risen by about 12% (of course, the contribution by continuous rolling technology is included).
- The productivity of converters has been significantly raised with increased utilization coefficient. Particularly, the utilization coefficient of small and medium converters increased from 22.60 t/(t·d) in 1990 to 34.20 t/(t·d) in 2006.
- Blooming mills and breaking down mills were quickly eliminated. At the same time, a large number of open-train bar and wire mills lost their competitiveness and were replaced by continuous rolling mills.
- The process has been adjusted with hot charging with energy saving.
- Since 1996, when China's continuous casting ratio exceeded 50% and a large number of complete continuous casting steel plants appeared, the open hearth—ingot-casting technology has been quickly eliminated and by the end of 2002, open hearths were abandoned completely (Table 1.7).

Table 1.7 Effects of increasing continuous casting ratios on the use of China's open hearths

Year	Total output of crude steel	Continuous casting ratio/%	OH steel		BOF steel		EAF steel	
			Output /Mt	Proportion in crude steel output/%	Output /Mt	Proportion in crude steel output/%	Output /Mt	Proportion in crude steel output/%
1990	6535.0	25.1	13.2	20.1	39.1	59.8	14.0	21.4
1991	7100.0	27.7	13.1	18.4	42.8	60.3	15.0	21.1
1992	8093.0	31.8	14.0	17.3	49.2	60.7	17.6	21.8
1993	8954.0	36.1	14.4	16.1	54.2	60.6	20.8	23.2
1994	9261.0	41.8	13.8	15.0	58.9	63.4	19.7	21.2
1995	9536.0	49.4	13.1	13.7	63.6	66.7	18.1	19.0
1996	10124.0	55.9	12.6	12.6	69.8	68.6	18.9	18.7
1997	10891.0	63.8	9.7	8.9	79.8	73.3	19.1	17.6
1998	11459.0	71.1	5.4	4.7	90.8	79.2	18.1	15.8
1999	12395.0	78.6	1.8	1.5	102.5	82.7	19.5	15.7
2000	12850.0	84.8	1.1	0.8	105.8	82.4	21.6	16.8
2001	15163.0	89.7	0.8	0.3	126.0	83.1	24.0	15.8
2002	18225.0	93.0	0.0	0.0	153.6	85.0	28.0	15.0

1.4.2 *PCI technology*

Since the 1990s, China has taken further steps to independently develop PCI by devising numerous new technologies and investing in corresponding technological renovations, with the result that PCI technology has made rapid advances and found extensive application. The average PCI for hot metal at major steel plants rose significantly from 50 kg/t in 1990 to 125 kg/t in 2002. It was 135 kg/t in 2006. At the same time, the average coke ratio for blast furnaces (BF) in China dropped from 557 kg/t in 1990 to 396 kg/t in 2006.

1.4.3 *Technology for the elongation of BF campaigns*

Multiple technological measures were implemented at the beginning of the 1990s to resolve the bottleneck caused by short BF campaigns, and in consequence the BF campaign at most Chinese steel plants now exceeds 8 years (it is 8 to 10 years at 24 blast furnaces, and the record campaign is 15 years). Significant results have been achieved in China by the systematic development and integrated application of the BF campaign elongation technology, which has promoted the efficiency of the steel manufacturing process and the stability of operations and directly lowered repair expenses. Of course, China's BF campaigns need to be further prolonged, and the objective is 15 years without medium repairs or as long as 20 years at some of the more advanced steel plants.

1.4.4 *Technology for continuous rolling of long products*

Bars and wire rods for building construction, which have long been the main varieties of steel products used in China, have comprised 46% to 48% of the overall consumption of steel products after the 1990s. Since the majority of China's steel plants make these products, the continuous rolling of long products is a common technology used all over the country. Since 1992, China has gradually developed its own complete manufacturing technology for bar and high-speed wire-rod continuous rolling mills on the basis of imported technology. The annual capacity of Chinese-developed bar mills has now reached 600~1000 thousand tons and that of high-speed wire rod rolling mills, 400~600 thousand tons. The efficiency of imported bar and wire rolling lines has also been developed to the full, with the annual outputs of bar rolling mills attaining 1,200 thousand tons and high-speed wire rod rolling mills, 600 to 750 thousand tons.

1.4.5 *Comprehensive energy savings by means of production process adjustments*

Advances in energy saving technology in the Chinese steel industry began, in the 1990s, mainly with adjustments in and optimizations of production process procedures, as for example:

- Replacement of ingot casting and blooming mills with continuous casting;
- Replacement of open hearths with converters;
- Replacement of small EAFs with UHP EAFs;
- Elimination of cupolas;
- Implementation of hot charging of slabs and billets instead of cold charging;
- Proactive use of energy saving technologies such as CDQ, TRT and power generation, etc; and
- Promotion of energy saving and heat recovery technologies such as converter gas recovery.

Comparable energy consumption per ton of steel at China's steel plants dropped during the years 1990 to 2005 (Fig. 1.15), down to 0.714 tce per ton of steel in 2005. China's steel output almost doubled between 1990 and 2000 while the energy consumption of the steel industry increased by only about 31%.

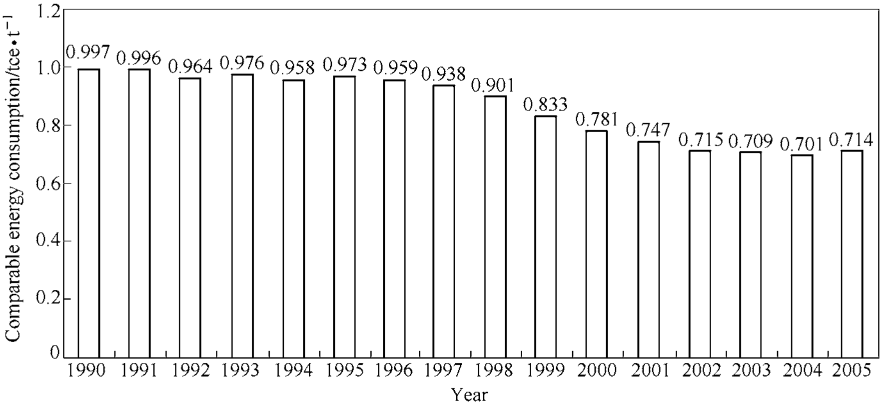

Fig. 1.15 Changes in specific energy consumption at China’s key steel plants from 1990 to 2005

1.4.6 *Slag splashing technology for BOFs*

Attention was first brought to bear, in the middle and late 1990s, on the effectiveness of the slag splashing technology first developed in the United States, and breakthroughs were soon effectuated by combining technology imported by individual steel plants with independently self-developed technology. Slag splashing has now been popularized in China and has substantially prolonged converter campaigns in this country. The campaign of many converters now exceeds 10,000 heats and, in some cases, 20,000 heats (Table 1.8). In 2002, the average campaign life of China’s BOFs was 4,000 plus heats, and the consumption of refractory materials on a large number of converters dropped to about 1 kg per ton of steel.

Table 1.8 The effect of slag splashing technology on BOF campaigns in China

Year	1994~1995	1996	1997	1998	1999	2000	2001	2002
Number of steel plants using slag splashing	3	10	21	31	36	65	>70	>70
Number of BOFs using slag splashing	4	21	67	91	124	~200	~220	>220
BOF steel produced with slag splashing /Mt·a^{-1}	0.3	7.0	20.0	34.5	63.0	~90.0	~128.0	~140.0

Continued Table 1.8

Year	1994~1995	1996	1997	1998	1999	2000	2001	2002
Proportion of BOF steel produced with slag splashing /%	0.5	10.4	25.1	38.1	61.2	~83.2	~95.1	~95.2
Average campaign of BOFs (heats)	1081	1200	1350	1827	2512	3580	3762	4268
Longest campaign (heats)	5 014 (Baosteel)	8 580 (TISCO)	10 500 (Baosteel) 10 126 (Sanming Steel)	14 001 (Baosteel)	15 028 (WISCO)	19 324 (WISCO)	22 726 (WISCO)	29 924 (WISCO) 37 271 (Laiwu Steel)

1.4.7 *Summary*

The successive breakthroughs in and sequential integrations of the above-mentioned 6 key/common technologies has brought about structural changes in the production processes at the majority of China's steel plants, and may be seen as a process of technological integration that has had substantial effects on scale rationalization, energy saving, cost reduction, product quality improvement, emissions reduction, and labor productivity enhancement. A great improvement in technological and economic indexes has been effected (Table 1.9).

Table 1.9 Changes in techno-economic indexes of the Chinese steel industry since 1990s (Yin, 2008)

Year	1990	1992	1994	1996	1998	2000①	2001①	2002①	2003①	2004①	2005①	2006①
Output of steel/ Mt · a^{-1}	65.4	80.9	92.6	101.2	114.6	128.5	151.6	182.3	222.3	272.8	352.4	422.7
CC ratio of steel industry/%	25.1	31.8	41.8	55.9	77.6	87.0	89.4	93.0	96.2	98.4	97.5	98.6
Comprehensive energy consumption per tonne steel of steel industry② /t ce · t^{-1}	1.611	1.574	1.519	1.392	1.009	0.920	0.876①	0.815①	0.770①	0.761①	0.741	0.645
PCI to BF of steel industry/kg · t^{-1}	50.0	50.3	61.3	72.0	94.9	117.0	122.0①	125.6①	117.7①	116.0①	124.0	135.0
BF coke ratio of steel industry/ kg · t^{-1}	557.0	551.0	566.0	495.0	496.0	437.0	422.0①	417.0①	430.0①	427.0①	412.0	396.0
BF utilization efficiency of steel industry/t · (m^3·d)$^{-1}$	1.73	1.81	1.81	1.75	2.02	2.15	2.34①	2.46①	2.47①	2.52①	2.62	2.68

Continued Table 1.9

Year	1990	1992	1994	1996	1998	2000①	2001①	2002①	2003①	2004①	2005①	2006①
BOF utilization efficiency of key steel enterprises /t · $(t\cdot d)^{-1}$	22.6	30.2	28.2	25.6	27.4	31.8	28.1	34.6	36.1	35.6	37.0	34.2
BOF campaign of steel industry(heat)	438	487	592	1127	1858	3500	3526①	4386①	4631①	5218①	5647	6052
Yield of steel products in key steel enterprises /%	83.2	—	—	—	89.8	92.5	94.0	94.2	94.9	95.6	95.6	95.7

① Data from 2000 and onwards are statistics from the key steel enterprises only, with the exception of steel output and CC ratio, which include the entire industry. Source: “***China Iron and Steel Statistics***”.

② Specific energy consumption per ton of steel includes many procedures, such as mineral processing, sintering, coking, and auxiliary procedures.

1.5 Comparative Superiority, Restrictions and Prospects of the Chinese Steel Industry

By comparison with the steel industry worldwide, the Chinese steel industry enjoys substantial relative advantages in terms of the market, later investment, and trained personnel.

1.5.1 *Advantages*

China has an obvious market advantage. Since China is still in the process of industrializing itself, or in other words, is just beginning its second stage of industrialization, steel products are still needed to support the growth of the national economy.

Thanks to the relative prosperity of its domestic market, China enjoys the advantage of later investment as compared to the steel industry worldwide. Because of later investment, the Chinese steel industry is better able to adopt advanced technologies and equipment, to build up a rational enterprise structure, to fix a correct position in the market for each steel plant, and even to establish a correct social/economic role for steel plants in the new century. It is apparent from recent trends in the world’s steel industry that the latest technologies are usually developed in Europe and Japan, but most of these technologies tend to be applied and popularized in countries with later investments. Such being the case, countries with later investments have greater opportunities to adopt new technologies and equipment and are more likely to achieve overarching technological leaps forward. The Chinese steel industry should, in the 21st century, make good use of its later investment opportunity, conduct a new round of technical reforms, and strive for a leading technological position in the world.

Compared to the world steel industry, China also has an advantage in terms of trained personnel. Today, China's institutions of higher education enroll notably more new talent—more than any other country in metallurgical and material science and the related mechanical engineering, electronics, financial and management specializations, providing us with a fairly ample labor backup force. Moreover, the experiences gained in initial founding, in weathering fluctuations, and in handling rapid growth during the fifty years or so years of the Chinese steel industry's development have given us a contingent of managers and experts who are adaptable to the rigors of changing situations and a contingent of well-trained employees and staff members. These contingents, which constitute a most important and valuable foundation for future growth and development, are constantly growing in size and vigor.

1.5.2 *Restrictions*

There are, of course, restricting factors and risks for the further development of the Chinese steel industry, as for example shortages of iron, manganese, and chromium ores, the problems of railroad and maritime transportation, the problems of environmental protection, the market competitiveness of certain varieties of products and certain types of enterprises, and even the risk of blind and ill-advised investments by some enterprises. These problems must be studied and resolved in the course of development.

The main policy and overall objective of the Chinese steel industry in the new century should be: to dynamically adapt to market trends and continue to restructure itself as the principal means of enhancing its market competitiveness and ensuring sustainable development. The measures for implementing this policy and objective are as follows:

In face of fierce domestic and international competition in the steel market, the Chinese steel industry should, on the premise of voluntary and self-determined participation, gradually promote the process of forming groups or strategic alliances of steel plants, as this would be conducive to rational deployment, sound development and sensible investment and discourage blind investment and competition. It would also help to exercise rational controls over product sales prices, raw materials purchase prices, and so forth.

1.5.3 *Prospects of the Chinese steel industry*

China's steel plants should, in the immediate future, orient themselves toward the domestic market. As far as China's steel plants are concerned, international competition in steel materials is manifested first of all as establishing a strong competitive position on the domestic market. In terms of China's overall interest, exporting machinery, electrical appliances, ships, and light industrial products processed from steel products is better than exporting the steel products. The former course would be beneficial for creating employment and expanding manufacturing chains in our country on the one hand and, on the other, would do much to obviate international disputes over steel exports. It would, moreover, be advisable for China to appropriately maintain the status of a steel importer for the time being, as this would avert setting up an oversized steel industry and prevent oversupply and under-capacity operation at a later date.

As regards product development, emphasis should be placed on deep processed and high value-added products, such as flat steel products and thin strips in particular, including hot-rolled and cold-rolled strips, galvanized strips, color sheets, cold-rolled silicon steel sheets, and stainless steel sheets. In the first 10 to 15 years of the 21st century, China should make sustained and systematic investments for manufacturing the above types of products, seek comparative advantages as the market matures, and build up new competitive abilities.

From the national perspective, we should proceed from the specific conditions of the different types of steel plants and give overall and coordinated consideration to the development of flat products.

One type of steel plant is the super-integrated enterprise with good foundations and a capacity of over 7 million tons per year, and usually based on two hot strip mills. These plants should focus on the development of high grade and deeply processed products, raise the proportion of cold-rolled sheets (to 60% or more), and vigorously develop automobile sheets, electrical appliance sheets, and cold-rolled silicon steel sheets.

Another type is the enterprise with a production capacity of over 4 million tons. Such enterprises manufacture mostly long products and a few flat products. They should be encouraged and assisted to switch to making flat products in the main.

The third type consists of existing and newly-constructed plants that make stainless steel products. Those with the requisite conditions should be helped to attain an annual output of 1 million tons or more.

One of the weak links in the Chinese steel industry is the construction and technical reform of plants making special steels. These deserve close concern and vigorous support in the next 10 to 15 years.

The Chinese steel industry must also further reduce energy consumption (by a national average of 20%, for example) and fresh water consumption (to a national average, for example, of 6 tons per ton of steel in 2010 and further to 5 tons by the year 2020).

During the development of the steel industry, a high degree of importance must be placed on raising the utilization rate of steel (i.e. increasing the yield of steel products and improving the performance of steel). It is anticipated that the utilization rate of steel will go up by 10% to 20% in the coming 10 to 20 years.

An important topic of the times, as we enter the 21st century, is gaining a clear understanding of the socio-economic role of steel plants and especially the functions of the steel manufacturing process.

From the viewpoint of the future socio-economic role of steel enterprises, the manufacturing process of steel plants should fulfill three principal functions:

- The function of steel product manufacturing;
- The function of energy conversion;
- The function of waste treatment and recycling.

On the premise of the above understanding, we shall gradually implement technically progressive measures for clean production and green manufacturing, and harmonize steel plant development with the ecological environment, i.e. ensure sustainable development while achieving a good competitive position on the market.

References

Davis J R (1995) Guide to Material Section. In: Engineer Materials Hand book, Desk Edition. ASM Section. 149-150

Schulz E (1993) Die Zukunft des Stahls im Spannungsfeld zwischen Ökononie und Ökologie. Stahl und Eisen 113(2): 25-33

Czichos H (1994) Werkstofftechnik als Basis industrieller Produkte. Stahl und Eisen 114 (12): 63-70

IISI(2007) World Steel in Figures

Kavanagh L, Carson C, Dasgupta B, et al. ed.(1998). Steel Industry Technology Roadmap. American Iron and Steel Institute (AISI), Jingtao Han, Fuming Wang, et al, translated, Science Press, Beijing, p.1 (in Chinese)

Vondran R (1995) Haben private Europäische unternehmen eine chance auf den Stahlmärkten der Zukunft. Stahl und Eisen 115(4): 51

Yin R Y, Cai J J (1999) Steel production process vs emission atmosphere, Iron and Steel 34(5):61-65 (in Chinese)

Yin R Y (2004) Rise and Technological Progress of the Chinese Steel Industry. Metallurgical Industry Press, Beijing, (in Chinese)

Yin R Y (2008)Achievement on the thin slab casting process in China. Iron and Steel 43(3):1-9 (in Chinese)

Chapter 2
Process Manufacturing Industry and Process Engineering

Manufacturing processes principally characterise the process manufacturing industries. The evolution of manufacturing processes has had a wide-ranging effect on problems that have emerged during the existence and development of process manufacturing industries. The series of changes and events that are taking place in manufacturing processes usually consist of a comprehensive integration of the mass flow, the energy flow, and the information flow. The science of metallurgical process engineering concerns the movement, transfer and chemical/physical transformations of mass flow, energy transfer and conversion, the relationships among materials and energy, and all other relevant information occurring at different levels, within different structures, and in different scales of the metallurgical manufacturing process. Its main intent is to study the structural evolution of the manufacturing process (the technological process of production) as well as the analysis/integration optimization of its structures and functions, or its restructuring optimization based on the integration optimization.

The existence and sustainable development of human society are closely linked to manufacturing industry. It is obviously that human beings cannot exist without clothing, food, shelter and transportation, all of which are both the motive force for the development of manufacturing industry and the large and wide market of manufacturing industry. Therefore, manufacturing industry is indispensable for human beings. As living organisms and social groups, human beings always put forward new propositions for development of manufacturing industry to enhance their life quality and develop forever.

In modern society, manufacturing industry is the material basis and the main industry for the development of the national economy; it is the essence to make the country powerful and the people rich; it is also the important sign of the comprehensive national strength and the level of science and technology. However, it is both the engine of rapid growth of Chinese national economy and the basic

R. Yin, *Metallurgical Process Engineering*

carrier and the breeding body of science and technology. At the same time, it is the important reflector of the comprehensive competitiveness of the nation and the main undertaker of world industry transfer and adjustment; it determines the role in international division of labor and the position of China in economic globalization pattern.

2.1 Manufacturing Industry and Its Technological Process

The connotation of manufacture develops dynamically with the times.

Manufacturing industry refers to a group of industry sections collectively (Zhu, 2003), including the industries processing or re-processing of the raw materials, which are the products of mining industry and agriculture, and the industries assembling the details and parts. It can be considered as an industry (Fig. 2.1), which transforms usable resources and energy into industrial products and consumer goods by corresponding manufacturing process.

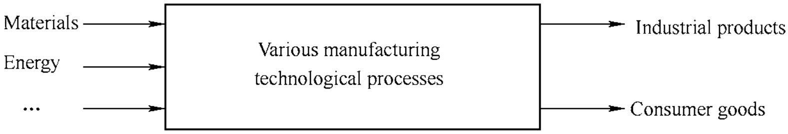

Fig. 2.1 Concept of manufacturing industry and manufacturing process

The so-called manufacturing industry should be understood as “the broad manufacture”, it has expanded significantly in its field, scope and process. In terms of its field, it includes not only a variety of industries, but also with a number of agriculture-related branches. While in terms of its scope, it is no longer confined to the original meaning of machinery manufacturing, but includes chemical industry, metallurgical industry, building material industry, light industry, textile industry, food processing industry, electronic industry, medical industry, military industry and many other industries of national economy.

At the same time, from an engineering point of view, the manufacturing process is the “broad manufacture”, a system crossing and integrating of multiple disciplines, rather than the simple process performed by a number of specialized techniques and technological equipment. Manufacturing process includes not only the input of materials and energy, the manufacturing processing itself and the output of finished products, but also the connotations of process engineering and green manufacturing, which refer to the product design, design of manufacturing process, control of discharging process, recycling, treatment for elimination of hazards, and life cycle assessment (LCA) concerning using, discarding and recycling of products.

2.2 Process Manufacturing Industry and Equipment Manufacturing Industry

The categories of manufacturing industry are various and there are plenty of classification methods, such as heavy industry and light industry, traditional manufacturing industry and advanced manufacturing industry, etc. Classified by production modes, changes undergone by the materials during the production and product features, the manufacturing industry can be divided into process manufacturing industry and equipment manufacturing industry.

Process manufacturing industry usually refers to an industry, which changes physical and chemical properties of raw materials to produce products of specific physical and chemical properties or products for specific usage through a series of processing-modification treatments. Sometimes it can be also called process industry to highlight continuous processing-modification, deformation characteristics of the mass flow during the technological process. The productive characteristics of process industry are as follows: the "mass flow"consisting of various raw materials, which is not the general sense of the "mass flow", its state, form and properties are changed with support and effects of input energy through some processing processes, such as heat transfer, mass transfer, momentum transfer together with some physical, chemical or biochemical reactions according to the specific technological process to form anticipated products. Process and operation of each procedure or device in the technological process of process industry are diversified, including chemical change, physical change, etc. And its operation modes include continuous, quasi-continuous and batch type, etc.

Process manufacturing industry includes chemical industry, metallurgical industry, petrochemical industry, building material industry, textile industry, food industry, medical industry, etc. Specifically speaking, these process industries usually own following characteristics:

- Raw materials used are mainly natural.
- Products are primarily used as raw materials for equipment industry; therefore, many categories of process industry possess characteristics of raw material industry. And of course products of some process industries can also directly be used as consumer goods.
- The production processes are mainly continuous, quasi-continuous, or of being developed into continuous, but some of them are of batch mode.
- Raw materials in abundant forms of mass flow and energy flow are transformed into products by plenty of chemical-physical changes/transforms in the production.
- The production processes are often accompanied by various forms of discharging process.

Process industries often discharge useful matter, energy, and at the same time pollutants even toxic substances in the discharging process. In order to solve pollution problems fundamentally caused by the production, such kind of industry needs to develop new green manufacture process (Yin, 2002).

Compared with the production mode of process industry, equipment manufacturing industry is often characterized by single part production, of discrete and assembly processing mode. Equipment manufacturing industry includes plenty of machinery and electric appliance industries, such as automotive industry, aircraft industry, shipbuilding industry, household appliance manufacturing industry for TV sets, refrigerators, air-conditioners, washing machines etc. Most of products of these industries can be directly used by consumers. Their common characteristics are as follows:

- Most of raw materials used are products of process industry.
- Most of products are directly used by consumers for better living conditions.
- Their production process is usually discontinuous or allowed to be discontinuous, even intermittent and pause; the products are usually produced by processing or assembling details. Their production is often carried through by "discrete mode".
- The raw materials are processed mainly by physical or mechanical treatments in such processes and physical changes are observed on them.
- Compared with the process industries, their discharging process is relative simple, the amount of discharged wastes is smaller, the pollution is smaller, and the pollutants are easier to control and treat.

2.3 Manufacturing Process and Process Engineering

Manufacturing process, also known as "production process" or "process" for short, often refers to the whole integrated system of manufacturing processes especially, which is made up of different procedures and different devices under the conditions of industrial production.

The integrated engineering knowledge system, which is made up of fundamental sciences, applied sciences and engineering sciences and related technologies involved in the abovementioned connotations of manufacturing process, is process engineering.

2.3.1 *Process and manufacturing process*

The so-called process can be regarded as the changes of things from the initial state to the final state under given outside conditions. Such changes include changes at different levels, on different scales and in various structures. The difference between process and manufacturing process is as follows: process refers to the general term of the changes from the initial state to the final state under given outside conditions, but viewed at an angle of space-time, manufacturing process usually refers to an integrated system of large scale or relative large scale (Lerou , 1996) (Table 2.1). While viewed from operational mechanism, manufacturing process often has the function of multi-factor integration and the feature of multi-level, multi-scale coupling-coordination, which embody in the procedures, devices and relevant unit operations of the manufacturing process. And it also has the characteristics of integrity, complicated structure and complicated phenomenon as well, it often contains multi-scale phenomena and multi-scale processes, most of which belong to the category of complex systems. The most important feature of complex process systems is having the "changing" structure, such structure is difficult to describe all the phenomena in the process fully by using the method of microscopic analysis; and also can not treated simply with average parameters as a structureless system. Now, it seems that the more applicable method is the spatio-temporal multi-scale, which is one of the effective methods to describe the structural features of the process at present. Therefore, the manufacturing process also possesses performance of analysis-integration and integration-reanalysis-restructuring performance based on the analysis-integration property.

Table 2.1 Processes at different levels and their ranges of space-time scale (Lerou, 1996)

Process	Time scale/s	Space scale/m
Molecular/Electronic	$<10^{-5}$	$<10^{-10}$
Hydromechanics/Transfer	$10^{-3}\sim10^{1}$	$10^{-9}\sim10^{1}$
Chemical reactions/Catalysis	$10^{-5}\sim10^{3}$	$10^{-11}\sim10^{-2}$
In metallurgical reactors(device)	$10^{-4}\sim10^{4}$	$10^{-3}\sim10^{2}$
At factories(process)	$>10^{4}$	$>10^{1}$

With respect to process manufacturing industry, the manufacturing process often contains the storage, transportation and pretreatment of raw materials and energy, the reaction processes and the processing of reaction products, and it also involves the auxiliary materials and energy supply system connected with reaction process for realizing the functions of manufacturing process. The broadening connotation of the manufacturing process can be also understood generally as the process including the selection, storage and transportation of materials and energy, the selection and design of products, the projection and innovation of process structure, the control, utilization and treatment of emissions and by-products, the treatment and elimination of toxic and harmful substances, up to the discarding or recovery (recycling) of used products.

2.3.2 *Process engineering*

The development of process engineering should be supported by the knowledge system of fundamental sciences and technological sciences, and intercrossing of the knowledge systems of related engineering sciences and engineering technologies.

From the beginning of 20^{th} century, the study in the process industry has been carried on mainly on microcosmic scale and at basic level, especially the theoretical study at the atomic and molecular level/scale of unit operations, such as chemical thermodynamics and reaction kinetics subsequently, etc. Such study often adopts the methodology of abstract and closed studying on small scale, aiming to recognize and reveal the possibility, rationality, effectiveness, limitation of the reactions and transformations in various unit operations.

From 1950s, the study on the transport phenomena (Levenspiel, 1962; Szekely , 1971; Geiger, Poirier, 1971) i.e. the study on the heat, mass and momentum transfer and the reaction engineering, had intended to promote the optimization of functions and the rationalization of designs in the unit procedures and devices, based on the understanding of the principles of unit operations and with a consideration of more physical factors. This is a kind of technological and scientific study of medium-scale, aiming to obtain the effectiveness, orderliness, continuity, compactness, etc. of the structure and function of unit procedures.

However, till now, the knowledge in the field of engineering sciences and engineering technologies for the process industry is not be sufficient for quantitative designing, amplification and regulation of the manufacturing processes, and can't make a theoretical canal for information technologies enter into these complex technological processes forthrightly and effectively. Therefore, in order to obtain the effectiveness, orderliness, continuity, compactness, etc. in various manufacturing processes (production technological processes) totally, it is necessary to carry out the study on complexity-simplification at level of manufacturing process with large scale and whole structure. In some aspects, such study also contains the study on the complex adaption system. With respect to various process industries, this is the knowledge of process engineering; it can also be said as the learning of engineering science and engineering technology at the level of manufacturing process. Certainly, for the integrity, complexity and related functions, structures and modes of the objects must be concerned when the process engineering is studied. of course, the knowledge of the relevant production, such as knowledge of equipment, energy economy, environmental protection, information and intelligent technologies, etc. should be considered inevitably.

2.3.3 *Process engineering and manufacturing process*

The object of the study on the process engineering is the topic in the field of engineering sciences and engineering technologies of manufacturing process in the process industry, on the basis of transformation of material and energy. Process engineering focuses on the description, simulation, projection, optimization, control and management of manufacturing process. It aims at study on the essence and the regular operation of manufacturing process to improve the process efficiency and facilities, to optimize the production flowsheet, to improve the product quality, to enhance information and intelligent application, and to eliminate pollutants for environmental protection. In short, it will guide the manufacturing to improve management and economic benefits at all levels.

The manufacturing process of process industry usually consists of several processing steps (procedures, devices or named units). The transfer, the transformation, or the storage and transportation of materials and energy are carried out by these units. Some of those are orderly and controllable, but some others are random, disordered and difficult to control. But the operation characteristics of manufacturing process often refers to series operation of units in the process, and all the units are operated integratively and synergistically; it is common that the output of the former procedure is the input of the next procedure, they link up and buffer-match each other.

In the manufacturing process, microcosmic change/transformation should be known for each unit (procedure, equipment, etc.); it can also be allowed to use the concept of “black-box” to characterize. The functions of the unit in the manufacturing process are usually to transform the input into the output, as the specific functions possessed by the unit. Not only the specific functions possessed by the unit, but also the interrelationship among the units should be given the attention, as various units are linked each other through a certain relationship. The concept of “relationship” mentioned here can be understood as logical relation of different forms. The relationship between the input set and the output set are formed by the relationship /connection between two units. The entirety of all the relationships in the manufacturing process is the structure of the manufacturing process. The meaning of “entirety” of all the relationships is not only the set of units’ ‘relations’ but also includes a definite arrangement between the units.

A series of behaviors and events taking place in the manufacturing process are inevitably accompanied by a lot of information. Therefore, process engineering in the process industry is usually a comprehensive integration system (Fig. 2.2) of mass flow, energy flow and information flow, and mass flow itself contains most part of energy flow and information flow.

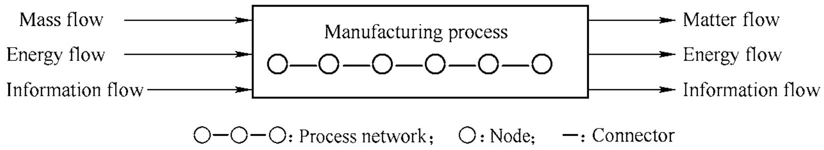

Fig. 2.2 Schematic of concept of process engineering in the manufacturing process

In the process manufacturing industry, specific patterns of process engineering are often expressed by different kinds of technological process, in which not only the input and output of materials and energy but also the matter, energy and related information inside the technological processes occur in the form of "flow".

The so-called "flow" may not be used only for fluids (liquids and gases) as familiar to us. Here, the concept of "flow" must not be confined to the flow concerned in hydrodynamics. It generally refers to the movement (i.e. flow) of certain resources and events among nodes and connectors in a certain network. Here, again the "network" may correspond to the manufacturing process in the factories of process manufacturing industry. It can also be embodied by the layout, etc. And the "node" corresponds to different procedures, devices and reactors in factories while the "connector" corresponds to transportation route, equipment and lifting facilities for the materials and energy among various procedures, reactors and workshops (branch factories) or some pipelines and storage vessels, etc. among reactors in the production enterprises. However, the "resources" often refer to raw materials, auxiliary materials, energy supply, equipment, information, etc. And the "events" generally refer to physical and chemical transformation, conversion, storage and transportation, process behavior, etc.

The technological properties of the manufacturing process are as follows:

- The function of the process is to achieve the goal (often a group of goals) of producing set material or energy conversion.
- Units in the process are the basic processing units for the storage and transportation, transmission or conversion of materials and energy.
- The mass flow, energy flow and information flow at input and output points of various units in the process are linked up according to certain logical relations.
- The entirety of process (manufacturing process system) can be always divided into several sectional processes (subsystems) with specific processing purposes; sectional processes can be further divided into several units, while units can even be parsed to several unit operations, etc. That means that multi-scale and multi-level research methods must be used flexibly and skillfully.
- The entirety of process has the property of comprehensive integration for various units, sectional processes, and new engineering effects can be occurred, which is called the "emerge" of the nature of system in complex sciences, by use of the reasonable and skillful comprehensive integration methods/measures; and this kind of engineering effect can also be regarded as formation of a certain

unique or new property.

Thus, the importance of the manufacturing process and process engineering for process industry is evident. At the same time it can be also recognized that the process technology (principle, method, combination and integration of steps) is the soul, and the equipment(device, reactor or apparatus) is the body, while the products is the embodiment of the process operation (efficiency, effect, benefit). As the manufacturing process shows up the different technico-economic targets for manufacturing industry faced, the process engineering studies the muti-objectire optimization system under constraints. Such objective functions of optimization include several aspects as follows:

- Input: optimization of raw materials, auxiliary materials, energy, human resources, investment, etc.;
- Output: optimization of products, by-products, emissions, cash recovery, etc.;
- In Side process: optimization of technical and economical indexes in terms of production efficiency, energy utilization, material yield, labor productivity, equipment operating rate, utilization of current funds, etc.

The importance of manufacturing process for enterprises of manufacturing industry lies in integrated optimization and comprehensive influence. The manufacturing process defines directly on the grade and, quality of products, production efficiency, product cost, delivery rate of products, availability of resources and energy, environmental load, linkage of eco-industral chains, capital benefits, labor productivity and other important aspects. Therefore, the manufacturing process is key solution for enterprises of process manufacturing industry to acquire market comprehensive competitiveness and sustainable development, and it has significant correlation with comprehensive influence power on various problems occurred in the process of existence and development of enterprises of process manufacturing industry (Fig. 2.3).

2.3.4 *Connotation and targets of process engineering*

The study of process engineering certainly involves chemical and physical changes of matter (raw materials, auxiliary materials, etc.) under the effect and support of energy and information. The contents of this study concern the motion of mass flow, and chemical and physical transformation, including microscopic and macroscopic mass flow, as well as energy transfer and conversion, the interactions among materials and energy, etc. All of those are of different levels and different scales. In fact, it mainly intends to study the structure of the manufacturing process (production technological processes), the analysis and integration of its functions and structure or the restructuring optimization based on the integrated optimization. Process manufacturing industry should produce the

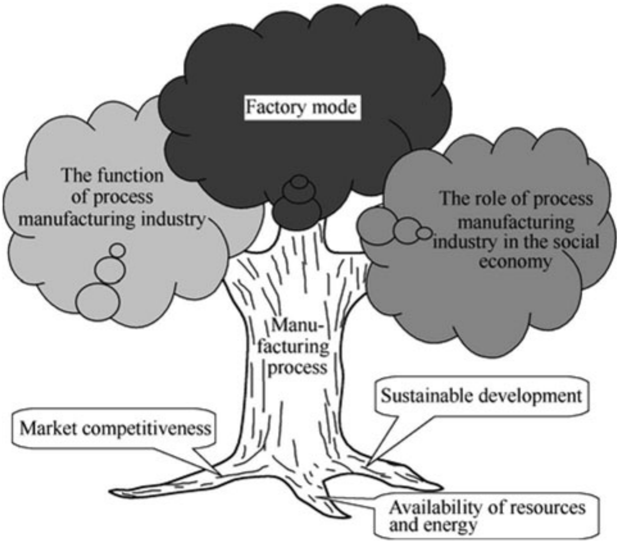

Fig. 2.3 Relational grade and comprehensive influence power of manufacturing process for process manufacturing industry

qualified, low-price and environmental friendly products, with the advanced technology, advanced equipment, the interface technigues among them, and also the rational way of transportation and storage. On this basis, the main purpose of the study on process engineering is to establish a green production process of high efficiency, and energy-saving. It studies not only the product manufacture function of process, but also the comprehensive functions to widen the manufacture and the problems regarding the mode, scale, structure, etc. of the manufacturing process and enterprises.

Process engineering mostly deals with heterogeneous systems, however, the majority of which are systems of nonlinear complex functions. To reveal the essence of these systems and to explore its operation rules are always the goal of engineers and scholars as means to realize the innovation, quantization, optimization and regulation of these engineering systems.

A comprehensive academic discipline was formed step by step with evolution and enrichment of this kind of knowledge. The beginning point of the study and exploration on process engineering is to recognize the optimization-integration problems on the mass flow, energy flow and information flow in the whole technological process on the level of the entirety of manufacturing process. The essence and operation rules of manufacturing process are helpful to guide production operation, engineering design and technical revamping of different process industries, process structure adjustment of an enterprise, improvement of product mix, rationalization of the production scale, coordination with environment protection, and the development trend of the enterprise/industry in the future, etc.

As a developing kind of science, the achievements of system science, complexity research, information technology, environment engineering, etc. should be absorbed and applied into various disciplines on technology, such as chemical engineering, metallurgy, food, and textile industry, etc.. The integration and dissolution of such disciplines must develop different new process sub-disciplines which are suitable for industries and their manufacturing processes.

The contents of the study on process engineering are as follows:

- The function of various components (units, procedures, devices, etc.) in process system and the relationship among components;
- The direction, path and efficiency of the mass flow, energy flow and the corresponding information flow in process system;
- The analysis-integration of process system and the level structure of it;
- The macro-operation dynamics of synergetic running in the process;
- The normalization and optimization models of the manufacturing process;
- The effect of boundary conditions on process running and structure adjustment;
- The process optimization, and the information engineering or intelligence technology;
- The manufacturing process and the eco-environmental engineering, etc.

2.4 Features of Manufacturing Process

The complexity and entirety should be emphasized specially to describe the general characteristics of the manufacturing process. They are formed by the variety of different unit functions, complicated species and abundant of quantity of the units in process, and the diversification of the relationships among the interfaces, etc.

2.4.1 *Complexity of manufacturing process*

What is complex? Complex means a problem consisting of various connected disorder parts. Variousness is often the representation of the quantity of things, while disorder represents jumbling and confusion in the species, shapes, level structures, scales, etc. Therefore, the term “complex” characterizes a great variety of puzzled numbers, structures and shapes of the components or things.

What is the complexity? The complexity is referred to the representation of the essence of events and their operation rules-operation characters. Further more, the complexity does mainly refer to process systems. In a complex system, the overall performance is not equal to the sum of partial performances, because the relationship between the overall performance and the partial performances in the “complex system is not a common linear one, and not a relationship of simple addition.

In the complexity science, the term "complexity" contains the characteristics (Holland, 2000) about variety-diversity on one side, and multi-structure levels on other side.

It is not difficult to understand that the nature and operation modes of various manufacturing processes in the process manufacturing industry may be characterised by complexity system. There are certain common marks in these manufacturing processes, which are existing and touchable "hidden orders" displayed behind their complex and diversified even changeful operations.

But it is impossible or not certain to make a complete and accurate explanation for the performance of whole complex system through the understanding of the performances of the components-subsystems as procedures or devices. This is the characteristic of the complex system (manufacturing process).

The cognition of complexity and complex systems makes people pay attention to and rethink on the methodology. When problem of complex systems like manufacturing processes is being studied and solved, there are still some shortcomings in the methodology of reductionism, which has been applied in the scientific and technological circles for centuries. It should be pointed out that the new methodology, i.e. holism, must be used simultaneously, although reductionism is still an important basis.

2.4.2 *Integrity of manufacturing process*

In the physical world, wholeness can be divided into several parts, and several parts can be also integrated to whole in different ways. Whole and part exist as a couple of philosophical category, which represents divisibility and unity of objective matters. The wholeness is the organic-order integration of parts, and the parts are indispensable links of the wholeness.

For understanding the manufacturing process, it is obviously that the integrity of the manufacturing process must be attached high importance based on the above cognition of the whole and part(units). Especially such a fact should be seen further from the characteristics of static structure and dynamic operation mode of the process systems. As according to the design and structure, the units (procedures, devices)are always the machines and facilities with the function of "body", however, their function running is often influenced by surroundings, by functions and operation of upstream or downstream procedures/devices, Therefore, the practical operation state or mode changes frequently. So, neither the units (procedures, devices) are simply regarded as the static machines and facilities, nor the function of them is regarded as one or some constant parameters. The design and construction of the manufacturing process should not be separating and superimposing various units simply and automatically, but unifying and integrating various units orderly to achieve some optimized objective functions according to certain technological ideas (principles, methods, technological routes, etc.). It is not difficult to realize that the functions and efficiency of the whole process are greater than the sum of its components when the process system is in order; but it is just on the contrary while the process system is in disorder.

With the cognition of the relationship of "whole and part" in the manufacturing process, several cognitive problems of manufacturing process can be discussed.

There are several aspects should be emphasized as follows when the manufacturing process is studied:

- The manufacturing process is an organic, ordered and coordinated wholeness; it takes large scale and multi-level structure. And the relations among its units (procedures, devices) are not simple superimposed, unconsolidated, but connected to each other with matching and coordination. This is the important cutting point in the study on process engineering. The optimization of the manufacturing process under certain boundary conditions is based on the analysis-optimization of set of unit's functions, the coordination-optimization of set of relationships among units, and the restructuring-optimization of set of units. This is the important target and content of the study.
- When the manufacturing process system and its units are operating orderly-coordinately, the functions and efficiency of the whole process should be better than the sum of that of its units, even a fully new function and performance of process emerged while these units integrated and matched under certain conditions. High attention on this aspect must be paid to optimize the process structure when the process engineering is studied. Contrarily, when the units are simple superimposed and stacked, the manufacturing process system operates disorderly, the function and efficiency of the whole process will be worse than the sum of that of its components, even the failure or partial failure of the manufacturing process system will happen. The task of the process engineering is to prevent and to correct the disadvantageous structure and inefficiency caused by the simple stacking or superimposing, but to apply engineering technology and engineering science reasonably in design, manufacture and operation.
- In the manufacturing process, it could not fully cognize and deeply understand its units (procedures, devices) without understanding of the integrity structure and the integrity-coordination operation law of the process. The study on the manufacturing process should not be limited to know the laws of manufacture from the units, but to study the essence of structure of manufacturing process and its operation dynamics and the analysis-integration of the manufacturing process at higher level and on larger scale. Just as there is an essential difference between the study on the human beings as living organism and the study on the human beings as a simple combination of various matter and molecules.

It is not difficult to understand that using the concepts of *structure* and *dynamic operation rule* to investigate and evaluate the manufacturing process is of great importance with cognition of the characteristics of manufacturing process, i.e. complexity and integrity. This is because as compared with functions and performance of each unit, the manufacturing process can obtain new function and performance through changing certain relations among units. However, the dynamic operation of the process of certain structure will present some characteristics under constricted boundary conditions. In the manufacturing process, a certain *structure* and *dynamic operation rule* can be found in processes at different levels with a viewpoint of engineering science.

2.5 Classification of Manufacturing Processes

The manufacturing processes in the process manufacturing industry can be classified according to the functions of the manufacturing process, the structures of the manufacturing process, the modes of the running behavior as well. Of course there are still other possible ways to classify (Gruhn, 1983).

2.5.1 *Classification according to functions*

In general, the functions of the manufacturing process appear to take following sorts:

- Function of matter transformation. Function of matter transformation is referred to changing the properties and performance of the substances by physical, chemical or biochemical reactions in the manufacturing process.
- Function of energy supply, storage, and conversion. In the manufacturing process, the running of the mass flow is proceeded by effecting and supporting of energy consumption, so the manufacturing process must be provided with the function of the energy supply, storage, and conversion.
- Function of the supply, storage and recycle of the auxiliary materials. There is often a need of the input of auxiliary materials, e.g. various assistant agents, water, air, etc., and the supply, storage and even recycle of them are also necessary.
- Function of the collection, treatment and regulation of the information. In the manufacturing process, the transforming, stocking and operating of mass flow, energy flow are inevitably bring about a lot of information, it is necessary to collect, treat and regulate them effectively.

It is more suitable to classify the units of the manufacturing process by the above process functions; but it is not suitable to indentify the whole manufacturing process.

It is usually to classify complete manufacturing processes by the main products or raw materials, and then the name of the manufacturing process characteriges its function. This classification method of the manufacturing process is used for a factory, such as:

- The chemical industry, including salt chemical industry, coal chemical industry, petroleum chemical industry, silicate chemical industry, etc.
- The metallurgical industry, including iron and steel making industry, aluminum processing indusing, copper extraction works, etc.

2.5.2 *Classification according to structures*

In the manufacturing process at the level of factory, the concept of the structure is mainly referred to the modes of the “connection”. In fact, to understand the concept of the structure entirely, it can’t be completely limited to the modes of the connect only. The modes of the connection among the units of the manufacturing process mainly have some basic forms as follows:

- Series connection;
- Parallel connection;
- Circumambulatory (bypass) connection;
- Feedback connection.

1. Series connection. The series connection often refers to the connection in which output stream of one unit is the input stream of next unit in manufacturing process. Furthermore, as for each unit, mass flow only passes along the running direction for once. Certainly, in the manufacturing process of series connection, the number of the units can be more then two. The series connection is mainly used to realize the matter transformation incessantly and provides certain conditions for the process. The mode of series connection is usually adopted in following cases:

- The expected transformation can’t be accomplished in one unit in principle.
- The process must be divided into several steps to keep certain limit values of process parameters, such as a certain temperature, a certain pressure, etc.
- Multi units are much superior than the single unit for the process.

From this sense, the series connection is usually used for realization of the multistep process. It is commonly applied to the main process of manufacturing industry. For example, the steel manufacture is a multi step process on viewpoint of whole plant level, so the steel manufacturing process as a whole takes series connection.

Fig. 2.4 shows the mode of the series connection, the electric arc furnace (EAF) route for the long products of one-to-one relationship in steel industry is the most typical. Unit Ⅰ is an ultra high power EAF; unit Ⅱ a ladle furnace (LF); unit Ⅲ a billet caster and unit Ⅳ a bar (wire-rod) rolling mill.

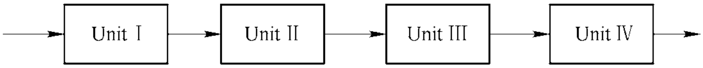

Fig. 2.4 The schematic diagram of the series connection

The mode of the series connection is presented by some other forms of the manufacturing process too, for example:

- Concurrent series connection form, see Fig. 2.5.

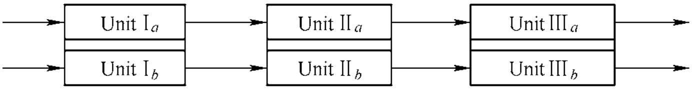

Fig. 2.5 The schematic diagram of the concurrent connection

This kind of concurrent series connection process is embodied in the steel plants with thin-slab casting process. The process is composed by two 150t ultra high power EAFs (EAF × 2), two 150t LFs (LF × 2) and two thin-slab casters (CC × 2). The flow directions of the concurrent units in this series connection process are the same, to make the downstream hot rolling mill operate continuously at full capacity.

- Counter current series connection form, see Fig. 2.6.

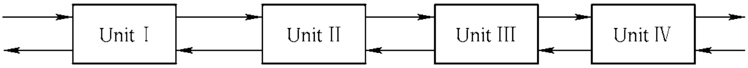

Fig. 2.6 The schematic diagram of the counter current connection

This kind of counter current series connection process is embodied, for example, in the FINMET, the gas-based process for direct reduction iron (DRI or HBI). The iron-rich lump ore or pellets go in positive-direction, while the natural gas goes in converse-direction. The flow directions of the units in this kind of connection are opposite to take full advantage of reduction potential and thermal energy of the natural gas (Fig. 2.7).

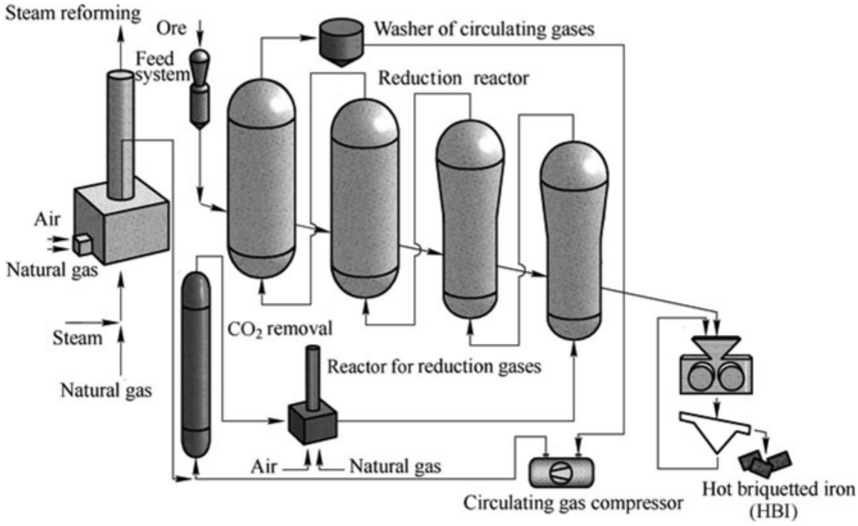

Fig. 2.7 The flow chart of the gas-based process of direct reduction iron

- Jumping connections are shown in Fig. 2.8 and Fig. 2.9. These are varieties of the series connection process.

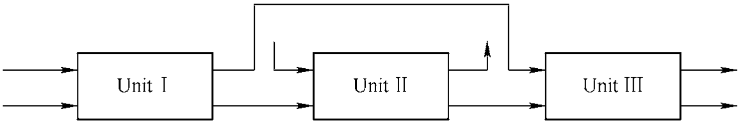

Fig. 2.8 The schematic diagram of the concurrent jumping connection

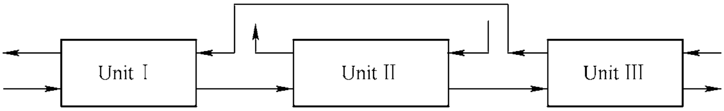

Fig. 2.9 The schematic diagram of the counter current jumping connection

Fig. 2.8 is the concurrent series jumping connection. It is embodied in the steel plants where the technologies of ingot casting and continuous casting coexisted, namely, the steel plants produce steel ingots and continuously cast blanks at the same time, and there is a need for the steel ingots to be rolled into blooms or billets of different sections in the blooming plant. All the rolled together with the cast blooms/billets are the semi-products for the finished products. Only a very small amount of cast blooms/billets may be processed by the blooming mill into more suitable sections and then into to finished products rolling mill.

Fig. 2.9 is the counter current series connection process. This form is rare in the chief process of the steel plants, but it can be seen in some heat exchanger systems.

2. Parallel connection. In the manufacturing process, the parallel connection mode is usually used together with the series connection. The series connection mode always takes the dominative at factory-level of process manufacturing industry; the parallel connection mode is often the supporting form adopted at the level of procedures or branch factories to enlarge the principal connection. The parallel connection modes can be distinguished into three kinds in general(Fig. 2.10), that is the input side parallel connection, the output side parallel connection and the original parallel connection.

Analysing the functions of the parallel units, the parallel connection mode can be divided into two kinds, namely, the parallel connection among same functional units and the parallel connection among different functional units.

The purposes of using the parallel connection mode among same functional units are as follows:

1) When the extent/capacity of a unit can't satisfy the requirements of input/output for whole manufacturing process, to improve the extent of the process

system, several units of same kind parallelly connected to satisfy the demand of manufacturing process. It is usually seen in the steel manufacturing process, such as two BFs or three BOFs operate in parallel, etc.

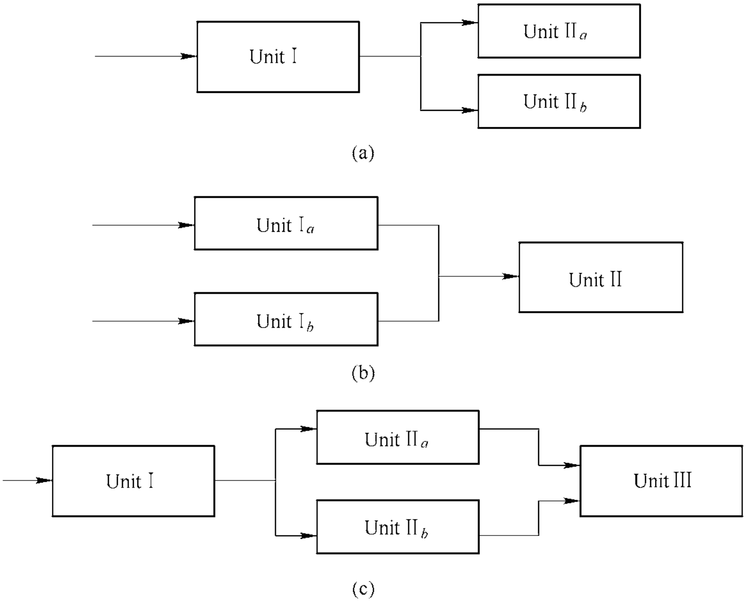

Fig. 2.10 The schematic diagram of the parallel connection mode

(a) The input side parallel connection mode;

(b) The output side parallel connection mode;

(c) The input and output stream-side parallel connection mode

2) Sometimes, the manufacturing process has to decrease its productivity by chance; the parallel connection of units is adopted to satisfy this requirement: In this case, one of parallel production lines can be stopped. For instance, several reheating furnaces are normally used in hot rolling mill to heat the billets; when the market is poor, one reheating furnace is stopped to reduce the production.

3) It is inevitable that some units in the manufacturing process should be paused for maintenance, inspection or temporary failure, the parallel connection can ensure the manufacturing process operate continuously. For example, in the BOF steel shop, the operation mode of converters “3 by 2” or “2 by 1” is adopted.

4) To ensure the reliability of manufacturing process, one line in the parallel connected can play a spare role, to make the production steady and reliable. There are always spare unit for BF airblast engine, main crane, power resource machine in the steel plant.

5) To reduce the harm of interminence by serious accident on the manufacturing process, only one unit continues taking over the task of the manufacturing

process partly as two units operate normally. This can be often seen at the integrated iron & steel enterprises with the process of BF-BOF-hot rolling. The relative example would not be given here.

The purposes of using the parallel connection mode among different functional units are as follows:

1) The various products from one manufacturing process must be processed separately; it usually appears in chemical manufacturing processes. Such kind of example is existed in steel plants as well. For example, there are several continuous casters for the production of billets, slabs or rounds with sections in a steelmaking plant, and then they are processed by wire/rod rolling mill, strip rolling mill or seamless tube mill separately.

2) In some systems of the manufacturing process, the different raw materials for next unit should be prepared separately, and the preparation units operate in parallel connection mode. For example, in the iron-making process, the functions of sintering section, palletizing section, coking section and coal pulverizing section are different from each other, these units with different functions operate in parallel connection mode in one BF shop.

3. Circumambulatory connection (bypass connection). This is a connection close to the concurrent series connection practically, see Fig. 2.11.

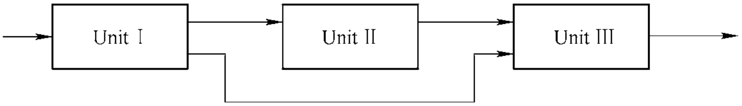

Fig. 2.11 The schematic diagram of the circumambulatory (bypass) connection

The circumambulatory connection mode is often seen in the manufacturing process. For example, in the steel-making process, there are many modes of transportation connection between CC casters and reheating furnaces sometimes. When the slabs are hot direct charged and rolled, the slabs enter into hot rolling mill directly bypassing stocking yard and reheating furnace. Nevertheless, when the slabs are cold or even hot charged, the blanks should enter into reheating furnace at least, or even the stocking yard, and then into hot rolling mill to roll into products; this is the circumambulatory connection in various degrees.

4. Feedback connection. Generally speaking, feedback connection is used for the recycle of material or energy in the manufacturing process. The recycle of material is good for improving the utilization and yielding rate; while the recycle of energy is to recover the energy, from the residual and waste heat, backwards to the manufacturing process, to improve the utilization rate of energy.

Usually, two or more units are included in a feedback connection, see Fig. 2.12.

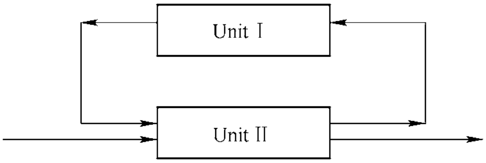

Fig. 2.12 The simple schematic diagram of the feedback connection

There are many feedback cycle connection forms of material and energy in the manufacturing process of the steel industry. For example, the crops and scraps from rolling plant are returned to the steel-making plant; the scales from rolling plant are supplied to steel-making plant and sintering plant; the BOF slag can be used for the sintering; the power generated by using the COG and BFG can be supplied to whole plant; the recycled waste heat; circulating water, etc. can be used also; see Fig. 2.13 and Fig. 2.14.

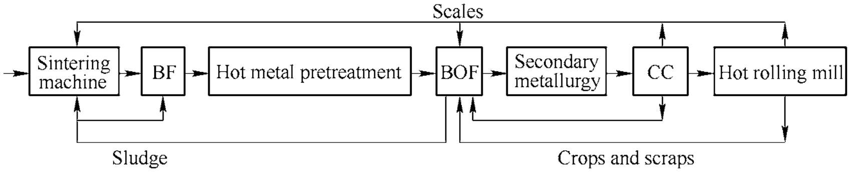

Fig. 2.13 The diagram of the feedback connection of iron resource among units in steel manufacturing process

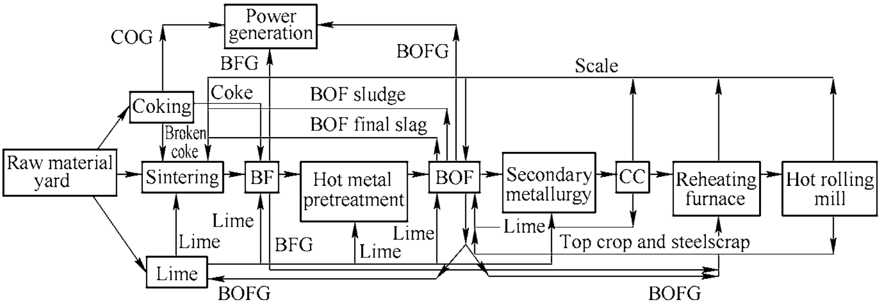

Fig. 2.14 The feedback connection of energy/material in steel manufacturing process

2.5.3 *Classification according to production running modes*

As a function of time the matter output of products is the important operation characteristics of manufacturing process. Accordingly, sometimes the manufacturing processes could be classified by the character of the output of product flow as

- continuous manufacturing process,
- quasi-continuous manufacturing process, and
- batch manufacturing process.

1. The operation features of continuous manufacturing process. In the process

manufacturing industry, the operation characteristics of the continuous manufacturing process could be expressed as follows. The output of finished products of certain characteristics doesn't change with time significantly within a certain time-interval, this kind of manufacturing process belongs to continuous. It should be pointed out that the numerical value of the output of finished products in the continuous manufacturing process may have some changes in different time-intervals. This variation is always realized by the change of surrounding conditions or operation loads, or caused by the change of operation loads due to the change of external conditions.

The continuous manufacturing process couldn't be implemented wholly and thoroughly in steel plants, though it can be realized in some enterprises of chemical industry. However, the continuous operation has been realized in certain degree in some unit systems of the steel manufacturing process. For instance, the BF ironmaking process is actually a subsystem of continuous operation.

2. The operation features of quasi-continuous manufacturing process. In the process manufacturing industry, the quasi-continuous manufacturing process could be characterised as follows. The output of finished products gets fluctuations and some undulations with time in a certain time-interval, neverthelss, the average value can be used to represent the output of the process. This kind of manufacturing process belongs to the quasi-continuous. If many units are connected and matched together or some operated in the cyclic mode, then the change of operation state of these units will make output of manufacturing process fluctuate with time even pause. This kind of manufacturing process can be also viewed as quasi-continuous process.

The BF-BOF-hot rolling process in steel plants basically belongs to quasi-continuous process, but some units in which belong to batch process.

The classification of manufacturing processes according to the running modes of products mentioned above is just in terms of the time-characteristic factor of the manufacturing process. But the continuity of manufacturing process are affected not only by the time-characteristic factor. It will be further discussed in the following chapters.

3. The operation feature of batch manufacturing process. The operation feature of the batch manufacturing process is that the products are output in batches, periodically. Such operation is shown by some units in the manufacturing process of steel industry. Whatever steelmaking furnace possesses typical feature of batch operation, even the output form of the hot continuous rolling mill is of batch type when it is viewed with longer time scale.

2.5.4 *Classification according to technological features*

The classification modes of manufacturing processes could be detailed further when they are classified by the technological features of the manufacturing process. In terms of the technologies, they are always classified by extent of the operation temperature and pressure of the process. Therefore, the manufacturing processes can be classified as follows:

- High temperature and ultra-high temperature process;
- Intermediate temperature process;
- Room temperature process;
- Low temperature and ultra-low temperature process;
- Ultra-high pressure process;
- High pressure process;
- Intermediate pressure process;
- Atmospheric pressure process;
- Low pressure and vacuum process.

When the manufacturing processes are classified by extent of the operation temperature and pressure, these two factors can be combined for the classification sometimes, such as the high temperature-atmospheric pressure process, the high temperature-vacuum process, the high pressure-high temperature process, the room temperature-atmospheric pressure process, etc. The advantage of this kind of classifying is that the feature of equipment and the state of the technological operation could be understood obviously; especially the protection requirements of the materials which are bound to be used and the manufacturing process could be warned. Such classification mode of manufacturing processes is often paid attention by the circles of engineering technicians.

References

Gruhn G (1983) System Verfahren Stechnikl (the upper volume). Translated by Lu Zhenwei. Chemical Industry Press. Beijing: 39-51

Geiger G H, Poirier D R (1973) Transport phenomena in metallurgy. Addison-Wesley Pub. Co. London

Holland J H (1995) Hidden order: Adaptation builds complexity. Addision-Wesley, New York

Lerou J L, Ng K M (1996) Chemical reaction engineering: A multi-scale approach to a multi-objective task. Chem.Eng.Sci. 51(10): 1595-1614

Levenspiel O (1972) Chemical reaction engineering. 2nd ed. John Wiley & Sons, New York

Szekely J (1971) Rate phenomena in process metallurgy. Wiley Interscience, New York

Yin R Y (2002) Energy-saving, clean production, green manufacturing and sustainable development of steel industry. Iron and Steel 37(8): 1-8 (in Chinese)

Zhu G F (2003) Chinese manufacturing in the globalization era. Social Science Academc Press, Beijing: 235 (in Chinese)

Chapter 3
Engineering Science in Steel Manufacturing Process

The knowledge systems of metallurgy/engineering disciplines comprise three levels, i.e. fundamental science, or the solution of problems on the molecular or atomic scale; technological science, or the solution of problems on the scale of procedures, and devices; and engineering science, or the solution of manufacturing process problems on the system level as well as problems of coordinating and optimizing the relationships between each procedure and device. The development of the metallurgy began with research on the atomic/molecular scale, and gradually expanded to research on the scale of technological science and up to research on the scale of overall integrated processes. Metallurgical process engineering focuses mainly on engineering research on the macroscopic scale.

From the viewpoint of technical processing, the steel manufacturing process is a manufacturing system that consists of many procedures of different characteristics and functions. From the viewpoint of its physical essence, the process is a multi-factor "flow" that operates in a dynamic and orderly manner in accordance with given "programs" and within a complex network structure. This is an open, irreversible process, or in other words, a process of matter and energy converting and dissipating

The human being has been using ironware and firing iron ores with charcoal to iron products for thousands of years. There is a long history from reducing iron ores to puddling wrought-iron, to melting pig iron, further to steelmaking by hot metal. Hammering the cast ingots into forged steel and afterward improving its performance by a simple heat treatment also passed through a long period. As a whole, ferrous metallurgy belonged to ironsmiths' workmanship before the mid-nineteenth century. The yield, the quality, the production efficiency and the product cost depended on natural conditions, especially on smith masters' workmanship and their organizing ability. Since the mid-nineteenth century, the manufacture of liquid steel in bulk quantities has been turned up from the workmanship.

R. Yin, *Metallurgical Process Engineering*

Then the modern technology and science of metallurgy especially the process engineering are being developed by the 20th century (Xu, 2002).

3.1 Transition of Theory and Engineering Practice for Metallurgical Process

The modern ferrous metallurgical process includes different procedures. Those are: iron ores preparation and reduced into hot metal (sintering-coking-ironmaking); hot metal pretreatment, decarburization of hot metal into molten steel (steelmaking); subsequently, secondary refining of melt into clean steel in time with special compositions and appointed temperature; then solidification, of this qualified molten steel, continuously into billets and/or slabs (except for a few mold casting) with predetermined size as well as controlled microstructure and temperature (without surface defect); and finally hot and cold rolling, of continuously cast billets/slabs into various steel products. The performance, shape, size and surface of these products meet the demands of users, and whose cost and price have market competitiveness (Fig. 3.1).

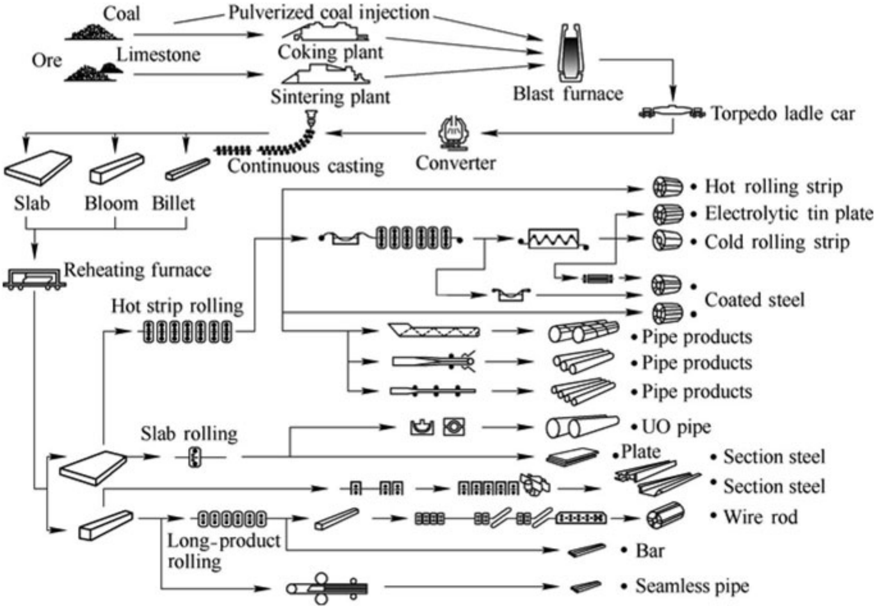

Fig. 3.1 Flowsheet of manufacturing process of blast furnace-converter-continuous casting-rolling

Another flowsheet of modern metallurgical process is that the ferruginous source is based on the steel scrap, including home scrap of downstream manufacturing and of steel plant's self. The process starts with smelting steel scrap by electric furnace into molten steel similar to the converter metal (the reduction period has been eliminated in the modern electric furnace). And the following procedures are also secondary refining, solidification-forming, reheating, and continuous rolling or forging, which is similar to the subsequent procedures of the blast furnace-converter route. Finally, the steel products with market competitiveness are obtained.

The formation of modern metallurgical process passes over a long time of evolution and perfection. The beginning and formation of the theoretical framework, the invention, the exploitation, the adoption and the innovation of the technologies, and the combination, the integration, the evolution and the perfection of the production, have appeared alternately and promoted continuously each other during a history about 150 years.

The ferrous metallurgical process contains several scholarships such as pyrometallurgy, solidification-crystallization, plastic deformation and performance control of material. It is characterized by numerous procedures, complex route and long flowsheet and so on. So the development is supported on multidisciplinary theoretic researches with intersection between each other. It is a typical analysis-combination-reanalysis-integration developing course.

3.1.1 *Formation and progress of the fundamental science on metallurgy*

As described above, each procedures such as ironmaking, steelmaking, casting, rolling and heat treatment of steel, always have been carried out by the experience, the workmanship and the organizing ability of smiths since a long time. However, the workmanship or the skill has been inherited from master to apprentice, and easily lost. Generally speaking, before the 20th century, the cognition of these procedures only was based upon the accumulation of workmanship or skill experience (for instance, watching “duration and degree of heating”, watching “spark”), and wasn’t guided by scientific theory.

From the historical overlook, it can been seen that the development of ferrous metallurgical process from workmanship or skill and experience to scientific theory starts with the operation of each unit (procedure, device) in the process, such as oxide reduction during ironmaking, decarbonization during steelmaking, deoxidation during refining, nucleation and grain growth during freezing, deformation-slip-dislocation of crystal grain during plastic deformation, recrystallization during phase transformation.

The 20th century is a key period when the ferrous metallurgy developed into a science, especially an engineering science. In the 1930s, H. Schenck (1945), M. Temkin (1945), J. Chipman (Elliot, Meadowcroft, 1965) and other researchers applied the theory of chemical thermodynamics to metallurgy step by step, and formed the metallurgical physical chemistry. In the thermodynamic manner the problems in the metallurgical process are mainly studied as chemical reactions between atoms/molecules, including the possibility of the reaction direction, the limit of the reaction, the selectivity and ordering among different reactions as well as the change of the enthalpy and the chemical equilibrium. Upon the aid of chemical thermodynamics were, the essence of metallurgical reactions and the rules in the metallurgical process understood with historic meaning for metallurgy. This is classed among fundamental science, which is mainly based on the level of atoms or molecules in problem. The methodology of "white box" and "black box" may be adopted. The background of a problem is treated as black box firstly——assumed as an isolated system. Then all the objects on the level of atoms or molecules are analyzed and studied by the method of "white box", This method makes the mentioned objects simplification and typification. These studies within fundamental science are very important to explain all kinds of processes and phenomena on metallurgy-material engineering and to understand their essence. So the metal production had developed from the experience to a science year by year.

The chemical thermodynamic theory of metallurgical processes has been studied systematically, which is focused on the following aspects.

A. Basic laws of oxidation-reduction in metallurgical reactions

Because in the extraction of metals the raw materials are iron ores, which are mainly oxides, partly carbonates, the reduction reaction is sure to be encountered. The steelmaking process, which is distinct from the ironmaking, is an oxidation smelting. In fact, neither a reduction reaction nor an oxidation reaction proceeds alone. This is the unity of opposite between oxidation and reduction. When any chemical reaction takes places, oxidation occurs, and reduction does too. In the same chemical reaction, one element is oxidized, and another element is sure to be reduced. Oxidation-reduction has to be happened simultaneously in a chemical reaction process.

To study the basic laws of oxidation-reduction in the metallurgical processes (Wei, 1980), we drew attention to the following aspects of chemical thermodynamics:

- Standard Gibbs free energy of formation of oxides (ΔG^{o}) and the relationship with temperature;
- Decomposition pressure of oxides and oxygen potential;
- Direct reduction and indirect reduction;
- Standard Gibbs energy of oxidation of elements in molten iron ($\Delta G^{\ominus}$);
- Isotherm of practical metallurgical reaction;
- Study of activities of reactants and products in chemical reaction;
- Study of phase diagrams etc.

Through a series of basic study on oxidation-reduction of metallurgical processes, many theoretical achievements have been summarized and may be used to analyze kinds of phenomena and regularities in the practical metallurgical production. And then, these results are helpful to improvement of production techniques and the equipment innovation.

1. The relationship of standard Gibbs free energy of formation of oxides ($\Delta G^{\ominus}$) with temperature. Due to the chemical compositions of various oxides are different, in order to compare easily, the standard Gibbs free energy of formation of oxides is converted into the value per 1mol O_2. For example, if an oxide is represented by M_xO_y, its representation formula is written as:

$$\frac{2x}{y}\mathrm{M}+\mathrm{O}_2=\frac{2}{y}\mathrm{M}_x\mathrm{O}_y \tag{3.1}$$

When above reaction reaches equilibrium, the equilibrium constant K is given by:

$$K=\frac{(a_{\mathrm{M}_x\mathrm{O}_y})^{2/y}}{(a_{\mathrm{M}})^{2x/y}\cdot p_{\mathrm{O}_2}} \tag{3.2}$$

where K is the equilibrium constant, a is the activity of reactants and products, p_{O_2} is the partial pressure of oxygen, in atm (1 atm≈101.3 kPa).

And the standard Gibbs free energy of formation of oxides is given by:

$$\Delta G_{\mathrm{f}}^{\ominus}=-RT\ln K \tag{3.3}$$

The relationships between $\Delta G_{\mathrm{f}}^{\ominus}$ and temperature T, which are plotted into a graphic form by H. J. T. Ellingham at 1944, called Ellingham diagram. With the enrichment of thermodynamic data, the diagram was revised and supplemented many times later. Fig. 3.2 was plotted by M. Olette in 1970s (Wei, 1980), after revised.

It can be illustrated in Fig. 3.2 that: when an element is oxidized into oxide at constant temperature and pressure, the lower the value of $\Delta G^{\ominus}$, the more stable the oxide. In other words, the element is easier to be oxidized.

2. Decomposition pressure of oxides and oxygen potential. The decomposition of oxides is the reverse reaction of their formation as:

$$\frac{2}{y}\mathrm{M}_x\mathrm{O}_y=\frac{2x}{y}\mathrm{M}+\mathrm{O}2 \tag{3.4}$$

The equilibrium constant K of this reaction is that:

$$K=\frac{(a_{\mathrm{M}})^{2x/y}\cdot p_{\mathrm{O}_2}}{(a_{\mathrm{M}_x\mathrm{O}_y})^{2/y}} \tag{3.5}$$

where p_{O_2} is the decomposition pressure of an oxide (in atm). Both a_{M} and $a_{\mathrm{M}_x\mathrm{O}_y}$ are equal to 1, so

$$K=p_{\mathrm{O}_2} \tag{3.6}$$

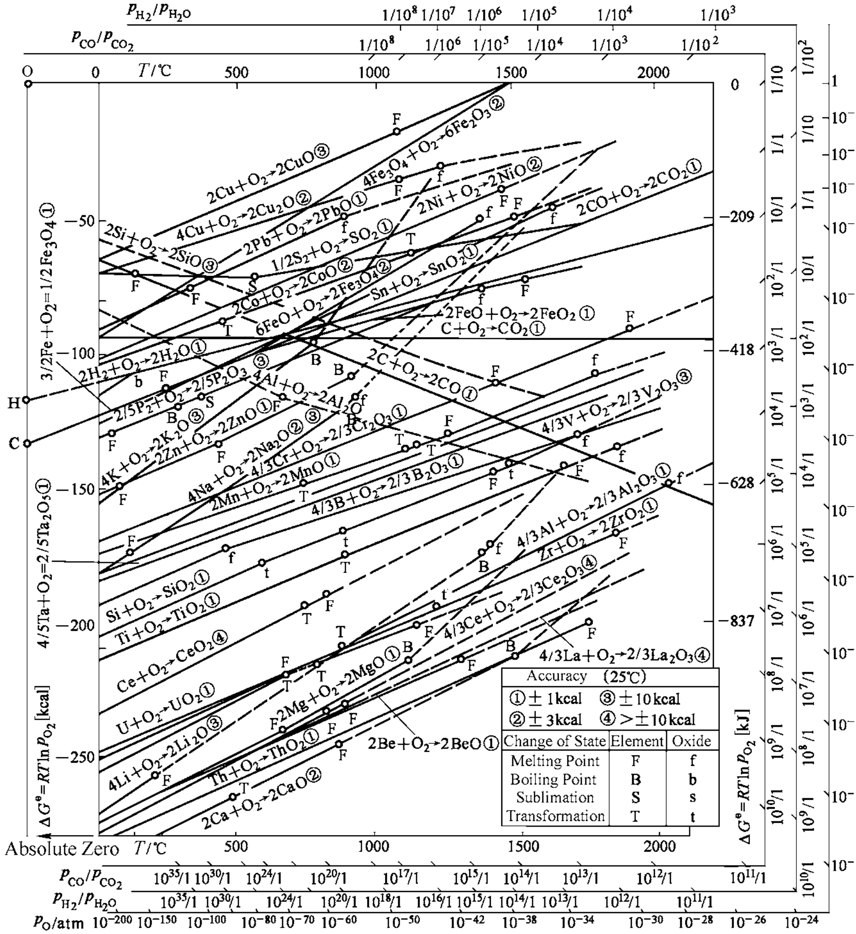

Fig. 3.2 Relationship between standard Gibbs energy of formation of oxides $\Delta G^\ominus$ and temperature

Let $\Delta G_d^\ominus$ be standard Gibbs free energy of decomposition of oxide, and $\Delta G_f^\ominus$ be standard Gibbs free energy of formation of oxide (all per 1mol O_2). So it yields

$$\Delta G_f^\ominus = -\Delta G_d^\ominus = RT\ln p_{O_2} \tag{3.7}$$

Fig. 3.2 actually also shows the relationship between $RT\ln p_{O_2}$ and T, which reveals indirectly the relationship between the decomposition pressure of oxides and the temperature.

The $RT\ln p_{O_2}$ is regarded as the oxygen potential in the literature. i.e.:

$$\text{Oxygen potential} = RT\ln p_{O_2} = \Delta G_f^\ominus = -\Delta G_d^\ominus \tag{3.8}$$

The oxygen potential (or the decomposition pressure of an oxide) is regarded as a criterion to predict the stability of oxides or the order of oxidization-reduction of elements.

3. Direct reduction and indirect reduction. In the blast furnace, the reaction that iron oxide is reduced into iron by solid carbon (coke) is called direct reaction; but the reaction that iron oxide is reduced by CO formed in the furnace is called indirect reaction.

Because the contact opportunity between iron oxide and solid carbon (coke) is limited, the direct reduction actually consists of two gas-solid reactions which are the reduction reaction by CO and the solution loss reaction of carbon (coke combined with CO_2 into CO). However, it can be seen that in Fig. 3.2, FeO can not be reduced by CO at ironmaking temperature. But in the practical operation of blast furnace, both direct reduction and indirect reduction may all occur. The percentage of the indirect reduction can reach 40%~50%; moreover, increasing the percentage of indirect reduction is beneficial to reduce the fuel consumption of blast furnace. Here the results in practical operation are different from the calculations by standard Gibbs free energy. In such cases, it must be interpreted by the isotherm of chemical reaction.

4. Standard Gibbs free energy of oxidation of element in liquid iron ($\Delta G^{\ominus}$). In oxidizing smelting and secondary refining of liquid steel, elements often dissolve each other into metal solution. For steel-making process, generally, solute element M dissolves in the liquid iron.

When the Gibbs free energy of dissolution of a certain solute element M in liquid iron is studied, a solution with mass percentage of solute equals 1 ([%M] =1) is usually taken as a standard state. The element M in liquid iron is represented by [M], for instance:

$$\mathrm{Cr}_{[s]} = [\mathrm{Cr}] \tag{3.9}$$

$$\begin{aligned} \Delta G^{\ominus} &= 19246 - 46.86T \quad \mathrm{J/mol} \\ &= 4600 - 11.20T \quad \mathrm{cal/mol} \end{aligned} \tag{3.10}$$

Namely, as 1 mol solid Cr dissolves in liquid iron into the solution of 1% [Cr], the change of standard Gibbs free energy of dissolution ΔG^{o} is expressed as above.

Certainly, the following expressions can be worked out easily,

$$\frac{4}{3}\mathrm{Cr}_{[s]} + \mathrm{O}_2 = \frac{2}{3}\mathrm{Cr}_2\mathrm{O}_3(\mathrm{s}) \tag{3.11}$$

$$\Delta G^{\mathrm{o}} = -754626 + 171.13T \quad \mathrm{J/mol} \tag{3.12}$$

$$\frac{4}{3}[\mathrm{Cr}] + \mathrm{O}_2 = \frac{2}{3}\mathrm{Cr}_2\mathrm{O}_3 \tag{3.13}$$

$$\Delta G^{\ominus} = -780287 + 233.61T \quad \mathrm{J/mol} \tag{3.14}$$

$$\frac{1}{2}O_2 = [O] \tag{3.15}$$

$$\Delta G^{\ominus} = -117150 - 2.89T \quad \text{J/mol} \tag{3.16}$$

The change of standard Gibbs free energy of dissolution of elements in liquid iron has been studied. They are useful to show the order of direct oxidization of some common elements in the bath during steelmaking-refining (see Fig. 3.3).

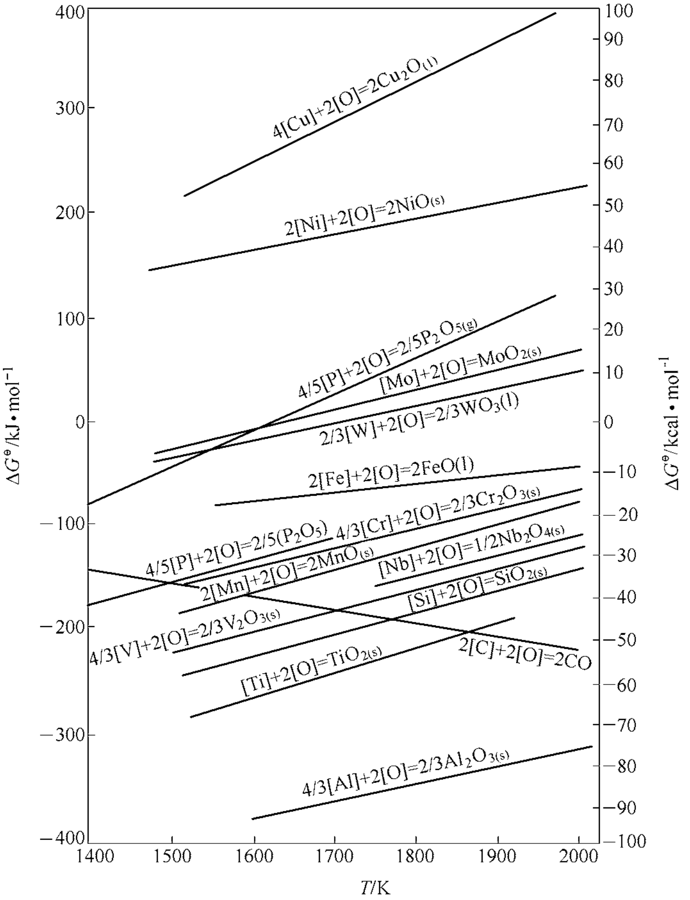

Fig. 3.3 Standard Gibbs energy of oxidation of elements in liquid iron

5. On isotherm of the real metallurgical reactions. The variation of standard Gibbs free energy of chemical reaction ($\Delta G^{\ominus}$) can be taken to predict whether the chemical reaction proceeds. For some oxidation-reduction reactions, $\Delta G^{\ominus}$ can be applied to predict which one occurs first, and then other chemical reaction follows; i.e. $\Delta G^{\ominus}$ can be applied to predict the order of oxidation-reduction of elements in metallurgical process. But it must be pointed out that this just only is applied to the standard state, and not to real conditions effectively. It can be seen that, as a

criterion of chemical reaction, $\Delta G^{\ominus}$ has some limitations and applies to following appointed conditions:

1) Partial pressure of all gas phases in the reaction is 101.3 kPa (1atm);

2) Solid and liquid matters in the reaction are pure substance;

3) Element in liquid iron is 1% [M] as standard state;

4) Oxide dissolving in molten slag is pure substance as standard state.

Because the chemical reactions of the production occur in real condition, which doesn't accord with and is even apparently different from the appointed standard state, the Gibbs free energy change in actual state must be calculated according to isotherm of chemical reaction. The real Gibbs free energy change ΔG is taken as criterion of direction of the metallurgical reaction.

The change of Gibbs free energy according to isotherm of reaction in the solution can be described as:

$$m[\mathrm{A}] + n\mathrm{B}_{(\mathrm{g})} = e(\mathrm{C}) + f\,\mathrm{D}_{(\mathrm{g})} \tag{3.17}$$

$$\Delta G = \Delta G^{0} + RT\ln J = -RT\ln K + RT\ln J = RT\ln\frac{J}{K} \tag{3.18}$$

$$J = \frac{a_{(\mathrm{C})}^{\mathrm{e}} \cdot p_{\mathrm{D}}^{\mathrm{f}}}{a_{[\mathrm{A}]}^{\mathrm{m}} \cdot p_{\mathrm{B}}^{\mathrm{n}}} = \frac{\text{activity product of reaction products}}{\text{activity product of reactants}} \tag{3.19}$$

J is the ratio of activity product of reaction products to activity product of reactants under the actual conditions.

6. Study of activities of reactants and products in chemical reaction. Experimental study and production practice prove that, elements participating in metallurgical reaction, because of different atomic structure of each element, are interacting with some others in liquid iron. The intensity of these kinds of interaction changes with different atomic property, concentration and surrounding factors. The result is that, the concentration of components in the metallurgical reaction cannot be applied directly to thermodynamic calculation, but its effective concentration — "activity", namely, its concentration multiplies correction coefficient — "activity coefficient", is applied to the thermodynamic calculation accurately. The Henrian activity coefficient f_i of the species i in liquid iron is obtained by means of determination of the interaction parameter of j on i in liquid iron.

When some elements such as C, Mn, and Si dissolve in liquid iron, Henrian activity coefficient of [C] in liquid iron can be calculated by following formula.

$$f_{\mathrm{C}} = f_{\mathrm{C}}^{\mathrm{C}} \cdot f_{\mathrm{C}}^{\mathrm{Mn}} \cdot f_{\mathrm{C}}^{\mathrm{Si}} \cdots \tag{3.20}$$

where $f_{\mathrm{C}}^{\mathrm{C}}$ is the activity coefficient of [C], when there is only the element C in liquid iron; $f_{\mathrm{C}}^{\mathrm{Mn}}$ is the activity coefficient of [Mn] on [C], when the element Mn also dissolves in liquid iron; $f_{\mathrm{C}}^{\mathrm{Si}}$ is the activity coefficient of [Si] on [C], when the element Si also dissolves in liquid iron.

It can be written logarithmically as

$$\lg f_C = \lg f_C^C + \lg f_C^{Mn} + \lg f_C^{Si} + \cdots \tag{3.21}$$

where

$$\lg f_C^C = e_C^C[\%C] \tag{3.22}$$

$$\lg f_C^{Mn} = e_C^{Mn}[\%Mn] \tag{3.23}$$

$$\lg f_C^{Si} = e_C^{Si}[\%Si] \tag{3.24}$$

where e_C^C, e_C^{Mn} and e_C^{Si} are the interaction parameters of C, Mn, Si on C, respectively.

Above formulas can be concluded into a general mode:

$$\lg f_i = \sum_{i=2}^{n} e_i^j[\%j] \tag{3.25}$$

The values of e_i^j interaction parameters of j on i in liquid iron at 1600℃ can be consulted (Wei Shoukun, 1980), so the activity a_i of element i in liquid iron can be calculated as

$$a_i = f_i[\%i] \tag{3.26}$$

In the metallurgical thermodynamic calculation, the concentration of every oxide in slag can be represented in mole fraction x_i, and its activity coefficient is represented as γ_i. Based on a lot of experimental results, researchers have worked out numbers of iso-activity coefficient diagrams (γ_i or $\lg\gamma_i$) or iso-activity diagrams(a_i)of ternary slag system, which is useful for reference when the activity of components in slag should be calculated.

B. Thermodynamics of crystal nucleation during solidification (Worrell and Chipman, 1964)

The theoretical basis about formation of nuclei in crystallization of liquid metal is the nucleation thermodynamics. The crystal nucleation is a process that some groups of atoms (molecules) grow up gradually and form orderly crystalline cells, and then make surrounding atoms (molecules) accumulate on them and solidify continuously. There are two types of nucleation: spontaneous and non-spontaneous. The spontaneous nucleation (also called homogeneous nucleation) is a process that some free atomic groups with energy fluctuations grow up spontaneously and form nucleus. The non-spontaneous nucleation also called heterogeneous nucleation is a process that a nucleus forms on the interface with an external particle.

In the process of spontaneous (homogeneous) nucleation, the driving force of nucleation is caused by the undercooling of the molten metal. When a nucleus with volume of V is deposited, it is accompanied with a variation of volumetric Gibbs free energy ΔG_V, and the interfacial Gibbs free energy ΔG_i will increase due to the birth of new interface. The thermodynamic expressions are given by:

$$\Delta G_V = \frac{-V\Delta H}{T_0}\Delta T \tag{3.27}$$

$$\Delta G_i = A\delta_{\text{LS}} \tag{3.28}$$

where V is the molar volume of nucleus; ΔH is the change of enthalpy of solidification, $\Delta H \approx \Delta H_{\text{m}}$ (latent heat of solidification); ΔT is the degree of undercooling; T_0 is the equilibrium temperature of solidification of metal; A is the area of liquid-crystal interface; δ_{LS} is Gibbs free energy of liquid-crystal interface, i.e. the interfacial tension.

Therefore, the change of Gibbs free energy in the process of spontaneous (homogeneous) nucleation can be expressed by

$$\Delta G = \Delta G_V + \Delta G_i = \frac{-V\Delta H}{T_0}\Delta T + A\delta_{\text{LS}} \tag{3.29}$$

The additional interface energy of the nucleus would not lead to that the total energy increases. So the homogeneous (spontaneous) nucleation may occur by

$$\frac{-V\Delta H}{A}\Delta T + \frac{\delta_{\text{LS}}T_0}{\Delta H} \leqslant 0 \tag{3.30}$$

If a deposited nucleus is supposed as a sphere, its critical radius should satisfy:

$$r^* \geqslant \frac{2\delta_{\text{LS}}T_0}{\Delta H\Delta T} \tag{3.31}$$

A nucleus originates more easily, when the free energy decrement ΔG is maximum. So the critical radius of nucleus r^* can be deduced from $\frac{\partial(\Delta G)}{\partial r} = 0$.

The nucleation energy will be

$$\Delta G^* = \frac{16\pi\delta_{\text{LC}}^3}{3(\Delta G_V)^2} \tag{3.32}$$

Under the circumstance of heterogeneous (non-spontaneous) nucleation, a nucleus often forms on the surface of solid particles in liquid or kinds of interface (the wall of container). Certainly, not every kind of solid particle has the surfaces to fit nucleation. The new phase of the nucleus must satisfy a premise condition that it has to wet the surface of solid particle.

If a spherical cap nucleates on the surface of a solid substrate, the following relationship of the interfacial tensions exists.

$$\delta_{\text{LS}} = \delta_{\text{SC}} + \delta_{\text{LC}}\cos\theta \tag{3.33}$$

where δ_{LS}, δ_{SC}, δ_{LC} are the interfacial tensions of liquid-substrate, substrate-crystal and liquid-crystal, respectively. θ is the contact angle between crystal and solid substrate.

The change of Gibbs free energy of the process becomes

$$\Delta G = -V\Delta G_V + \sum A\delta \tag{3.34}$$

where V is the volume of the spherical cap nucleus; A is the surface area of the spherical cap nucleus.

$$V = \frac{\pi}{3} r^3 (2 - 3\cos\theta + \cos^3\theta) \tag{3.35}$$

$$A = 2\pi r^2 (1 - \cos\theta) \tag{3.36}$$

$$\Delta G = \left(-\frac{\pi}{3} r^3 \Delta G_V + \pi r^2 \delta_{\mathrm{LC}} \right)(2 - 3\cos\theta + \cos^3\theta) \tag{3.37}$$

Owing to $\frac{\partial(\Delta G)}{\partial r} = 0$, the critical radius of heterogeneous nucleation r_{C}^* can be calculated as

$$r_{\mathrm{C}}^* = \frac{2\delta_{\mathrm{LS}}}{\Delta G_V} \tag{3.38}$$

Substituting into the formula of ΔG (3.37), the heterogeneous nucleation energy will be determined as:

$$\Delta G^* = \frac{4\pi\delta_{\mathrm{LC}}^3}{3(\Delta G_V)^2}(2 - 3\cos\theta + \cos^3\theta) \tag{3.39}$$

C. Thermodynamics of solid phase transformation

In the manufacturing process, with solid phase transformation the properties of metals will be improved. When solid phase transformation occurs, the change of Gibbs free energy of the system ΔG contains not only the Gibbs free energy of the process and the surface energy of new phases, but also the strain energy caused by the difference of specific volumes between new and old phases as well as the coherent interfacial energy for keeping coherent phases. And the surface energy of new phases has two sorts as chemical surface and structural surface. Thus, the change of Gibbs energy of the system ΔG during transformation can be expressed by

$$\Delta G = -V\Delta G_V + A\delta + E_{\mathrm{S}} + E_{\mathrm{C}} \tag{3.40}$$

where V is the volume of new phases; ΔG_V is the change of Gibbs free energy per unit volume; A is the surface area of new phases; δ is the surface tension of new phases; E_{S} is the strain energy; E_{C} is the coherent interfacial energy (Xu,1964).

D. Thermodynamics of recrystallization

The recrystallization occurs in the deformed metal during it heating to enough high temperature. By further nucleation and growth, the crystal grains in equilibrium come into being again. After recrystallization, the crystal structure of new crystal grains are the same as parent, but the orientation are different. The recrystallization nucleation occurs on slip band, deformation band, grain changing boundary and grain boundary predominantly.

The classical theory of recrystallization nucleation is similar to the phase transformation nucleation. The variation of Gibbs free energy of nucleation in metal during the recrystallization process can be expressed by

$$\Delta G = ZV + A\delta \tag{3.41}$$

where Z is the strain energy per unit volume; V is the volume of new nucleus of recrystallization; δ is the surface energy; A is the surface area of new nucleus.

The nucleus is supposed as a sphere, thus

$$\Delta G = -\frac{4}{3}\pi r^3 Z + 4\pi r^2 \delta \tag{3.42}$$

It must be pointed out that, all listed above nucleation thermodynamics of molten metal at solidification, of crystal metal at phase transformation and of metal at recrystallization belong to behavior of atoms/molecules in the atom group level. It is the theory of microcosmic process.

E. Kinetics of metallurgical process and chemical reaction

The metallurgical analysis based on the thermodynamics of chemical reaction will be involved in the kinetics of the reaction at the same time. The kinetics of chemical reaction, at first, discuss the rate and mechanism, the pathway and control step of a reaction based on the concepts of molecular/atomic motion and molecular structure. There are two theoretic systems are formed and developed as follows:

- Molecular effective collision theory (kinetic theory of gases);
- Absolute rate theory, i.e. theory of transition state or activated complex (quantum mechanics and statistical thermodynamics).

Kinetic theory of chemical reaction is considered at molecular-atomic scale. It isn't involved how the reactants arrive in the reaction site and how the products leave the reaction site. This kind of reaction kinetics is based on the premise that the reaction system is homo-dispersive. The microcosmic mechanism, the steps and the rates of the chemical reaction are studied, which is actually the microcosmic kinetics in molecular-atomic level. In the metallurgical problem, most metallurgical chemical reactions proceed at the phase interface. Therefore, the description of the overall rate and mechanism of reaction must deal with mass transfer that the reactants arrive at the interface and the products leave the reaction site. Commonly, the metallurgical reaction kinetics is named as "macroscopic" kinetics (Xiao and Xie, 1997). This kind of "macroscopic" is relative to the "microscopic" homogenous reaction, but it is still investigation in molecular-atomic scale. It includes comprehensive understanding of mass transfer nearby the reaction site only. These sorts of investigation belong to the fundamental science on metallurgy.

3.1.2 *Technical science issues in unit device and procedure level of metallurgical process*

The processes such as refining reaction, melting, solidifying, reheating, deformation, transformation and recrystallization in practical production of metallurgical plants, all proceed in unit device of industrial scales. For these reaction processes, the rules of thermodynamics and kinetics are the same to the theory in molecular-atomic level. However, because of size increasing, the concentration distribution of matter, the temperature distribution, and the distribution of residence time in device are different from that in the laboratory apparatus. This difference is relevant to geometrical factors of devices.

There are many reactions on interface among different phases in the metallurgical production, and the dispersion systems such as bubbles, drops and particles in liquid bath are often used to enhance efficiency of metallurgical process. The size, quantity, position and residence time distribution of above all kinds of fine particles change with increasing of device size. To make the laboratory research results scale up to industrial production process efficiently, and to minimize the pilot experiments which consume a lot of human and material resources, the kinetic study in unit device or procedure level , namely, reaction engineering, is generalized.

The unit device as reactor is taken to be “black box” in early time of reaction engineering. That is to say, without regard to the internal details of all kinds of process in device, the phenomena of flow and mixing in the reactors are mainly analyzed and predict by response to stimulus signals at outlet and inlet; the regularities are generalized by statistical analysis of a great mass of empirical data. The reactor theory is formed according to above studies. For example, a continuous reactor of plug flow has peak efficiency, as the back-mixing or the short circuit does not occur in it. These concepts are applied not only to design of a reactor but also to that of mutual link age character among procedures. Thus, adjacent procedures or devices should be rationally laid out for mass flow in order, avoiding cross or reverse operation.

With the development of the computational fluid dynamics (CFD), quantitative analysis and calculation of flow pattern, heat transfer and mass transfer in reactor are realized. As a heterogeneous reaction, in the interface (reaction site) the reaction rate of metallurgical reaction as “source” or “sink” coupled with the mass flux can be quantitatively analyzed. Due to quantitative description of “transport phenomena”, the reactor isn’t taken as “black box” any more, and the process in it will be distinguishable and cognizant.

Transport phenomena—momentum, mass and energy transfer is a kind of knowledge for the rate process, and also can be regarded as generalization of the rate phenomena for common observation and study, because among transport phenomena there is an obvious similarity—the concept of the rate.

The purpose of study on transport phenomena is to understand the influence of physical processes such as flow, mixing, heat and mass transfer etc.on metallurgical reaction process in reactor, and some general regularity. The purpose of application of transport phenomena is known to understand the mechanism of all kinds of transport phenomena in reactors; to improve the operation and design of the metallurgical process and device; to establish physical-mathematical modeling for the studied metallurgical process; to simulate the metallurgical process with the help of computers; thus, to combine the numerical technology with metallurgy. Applying transport phenomena and reactor theory, in short, is possible to solve rationality and effectiveness of unit operation or unit device in the practical metallurgical production. It is also worth to take notice of that the system studied about “transport phenomena” is not isolated but has mass and energy exchange with surroundings.

The heterogeneous reactions at high temperature in a dispersion system are the important features of metallurgical reactors. Therefore, the size distribution and the relative quantity of bubbles, drops and particles and also the performance of their interface (interfacial tension, adsorption, interfacial wetting and interfacial electrochemistry) need be studied for the metallurgical reaction engineering. The ratio of extractive phase (including volume ratio and mass ratio) as well as the mass balance and heat balance at interface conjoin the reaction kinetics with the quantity of extractive phase. Then the total mass transfer and heat transfer in the dispersed system can be obtained.

Moreover, the reactor type of batch operation plays an important role in metallurgical plants, so the stirring and mixing is of great significance to process efficiency. Improvement of operation efficiency and increment of time frequency of the reactors will be favorable for the constitution and smooth running between procedures in the manufacturing process.

With reaction engineering the technological characteristics and the function improvement of typical metallurgical reactors should be also studied attentively. By method of physical-mathematical modeling and numerical analysis with computer, the characteristics of a certain sort of metallurgical reactor or system and its operation are investigated analytically, while new technique or new equipment are developed. Optimization of device design and its operation will be instructed by these investigations. Certainly, for the technical innovation and the operation optimization of metallurgical reactors in the current production practice, the corresponding technical and informational support can be offered from metallurgical reaction engineering also.

As one of the technical science in unit device and procedure level, metallurgical reaction engineering is the argument on mass and energy transfer processes and macroscopic kinetics in metallurgical reactor in this scale. In comparison with microcosmic mechanism in molecular-atomic scale, reaction engineering is more close to the metallurgical production practice. However, in term of the whole metallurgical production manufacturing, it should belong to the mesoscopic (medium-scopic) kinetic problems still.

The earlier works on metallurgical reaction engineering started at the midage of 20^{th} twentieth century. After 1950s, metallurgists applied the viewpoints, theories and methods of chemical reaction engineering to metallurgy under different conditions respectively. At 1972, *Metallurgical Reaction Engineering* by I. Muchi and A. Moriyama (1972) was published in Japan, and during the same period scholars of several country published monographs about metallurgical reaction engineering, such as *Rate Phenomena in Process Metallurgy* by J. Szekely (1971), *Transport Phenomena in Metallurgy* by G. H. Geiger and D. R. Poirier (1973), *Rate Processes of Extractive Metallurgy* by H. Y. Sohn and M. E. Wadsworth (1979). From 1980s, Chinese metallurgists applied actively the theory of reaction engineering to analyze many kinds of problems about metallurgical reactors, and their results were summarized into *The Series of Metallurgical Reaction Engineering.*➊ Metallurgical reaction engineering contains: transport process theory, macroscopic reaction kinetics, metallurgical reactor theory, modeling and simulation of metallurgical reactors and so on.

The objects of the process analysis in metallurgical reaction engineering are all kinds of metallurgical reactors, such as the sintering machine, the blast furnace, the torpedo car, the pretreatment equipment, the converter, the electric furnace, the ladle, also the secondary refining equipment, the continuous casting tundish and the caster. As an analysis method reaction engineering is based on theory of transport phenomena. All kinds of transport phenomena and their mutual relationship are synthetically studied in the reactors. Some concepts such as flow, mixing and distribution function are used under some assumed and simplified conditions. Through heat, momentum and mass balance, the mathematical model of the reactor process is formulated. And then, after solving the mathematical model, operation characteristics of the reactor under different conditions and regularity of each process parameter are obtained. Subsequently, with optimizing operation parameters, the rational parameter of reactor size and structure are determined, and optimizing design of the reactor process is realized. That is an engineering analysis of the technological science, which is different from fundamental science such as metallurgical physical chemistry.

Whereas, in the metallurgical plants, the optimum condition for one metallurgi-

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➊ The Series of Metallurgical Reaction Engineering were published by Metallurgical Industry Press, Beijing, 1996~2002, there are all 21 books about rate phenomena, process modeling and reactor analysis in ferrous and nonferrous metallurgy.

cal reactor may be not suitable for the whole metallurgical production. Therefore, with the improvement of technology and the development of production, it is necessary to induce the larger-scale investigation——study of the integrated engineering at higher scale for the metallurgical production process——the metallurgical process engineering.

3.1.3 *Formation and progress of metallurgical process engineering*

From the brief review of the engineering theory and practice of the metallurgical process in the Chapter 3: 3.1.1 and 3.1.2, it can be seen that developing ways were coursed as following: in 1920s, people started to study the metallurgical process with the theory of physical chemistry, that is, actually to study the possibility and the limit of oxidation-reduction reactions and the mechanism of reaction kinetics in pyrometallurgy, which is of instructive value to unit operation to a great extent. However, it relates only the chemical reaction processes themselves to operation, and doesn't consider the influence of some factors such as space, time, geometrical shape, flow and mixing in reactor. Its investigation follows classical method, i.e. it is assumed in an isolated system which has no mass and energy exchange with surroundings, and the equilibrium reversible process is taken as a criterion to study the conversion process in the system.

In 1960s, the influence of the physical factors upon the unit operation, unit procedure and unit device was further cognized and generalized in the chemical engineering. Involved physical processes were generalized as the transport phenomena. i.e.:

1. The transfer of momentum is a physical basis of all flow dynamics;
2. The transfer of mass is a physical basis of all mass exchange and separation;
3. The transfer of energy is a physical basis of heat transfer and heat exchange.

By the methods of physical and mathematical modeling and numerical analysis the complex processes in the metallurgical reactors at high temperature were quantitatively studied with success. It promotes a sub-discipline construction of the metallurgy beyond the shackles and the limitations of conventional experience. The hydrodynamics of melts in metallurgical reactor is studied with the knowledge "transport phenomena". The parameters of the rate controlling step are analyzed and studied. The direction of operation optimization of the metallurgical process are obtained. All those make a great influence on the project, forecast and control of the metallurgical procedures, the metallurgical devices and the metallurgical operations indeed. This is an actually macroscopic kinetics of metallurgical process in device and procedure scale.

Combining the chemistry (metallurgical physical chemistry) of metallurgical operation with the physics (transfer processes in unit device), the engineering of unit operation and unit device is formed through analysis with classification and summarization in cross-coupling domains, This knowledge (reactor theory) promotes the improvement of the device design and the technological operation for the metallurgical process. However, above knowledge is still limitative by investigation on the unit operation and the unit device (reactor) scale. The knowledge concerning the scale of whole manufacturing in a plant has been seldom referred before and is urgent to study now. The knowledge on this scale will guide the structure adjustment and the process optimization of the steel plants and decide their developing mode. To solve this problem of large-scale type and high-level horizon, application of theory and methodology of the system science and engineering must be needful. But the theory and practical problems of steel plants in manufacturing process level can't be solved directly in accordance with the system engineering, because the field of system engineering is comprehensive application of the natural science, the social science and the engineering technology with intersection and synthesis. The core of system engineering is organization, management and decision-making (Xu, 2000). The engineering science of the whole manufacturing process in a steel plant relies on new theoretic understanding of the physics and the operation regularity in the entire metallurgical manufacturing process. Therefore, to formulate and theorize metallurgical engineering science in manufacturing process scale is in urgent need. The formation and development trend of this engineering science is shown briefly in Fig. 3.4.

In general, metallurgical process engineering is a large-scale integrated theory in the manufacturing process level, and its object is an opening, far from equilibrium, irreversible and complex process system. It involves the analysis-integration of the metallurgical production process, the control of multi-dimension mass flow in manufacturing process, and the operation dynamics of production process. It also includes the engineering theory of process design of metallurgical plants, the structure and mode of the metallurgical enterprises (steel plants), and also the engineering science and technology about the eco-industrial chains.

3.2 Connotation and Physical Essence of Metallurgical Process Engineering

The multi-level analysis of science, physical essence of manufacturing process of metallurgy, target of the metallurgical process engineering, research scope and methodology of metallurgical process engineering and the influence of metallurgical process engineering on steel enterprise are described in this part briefly.

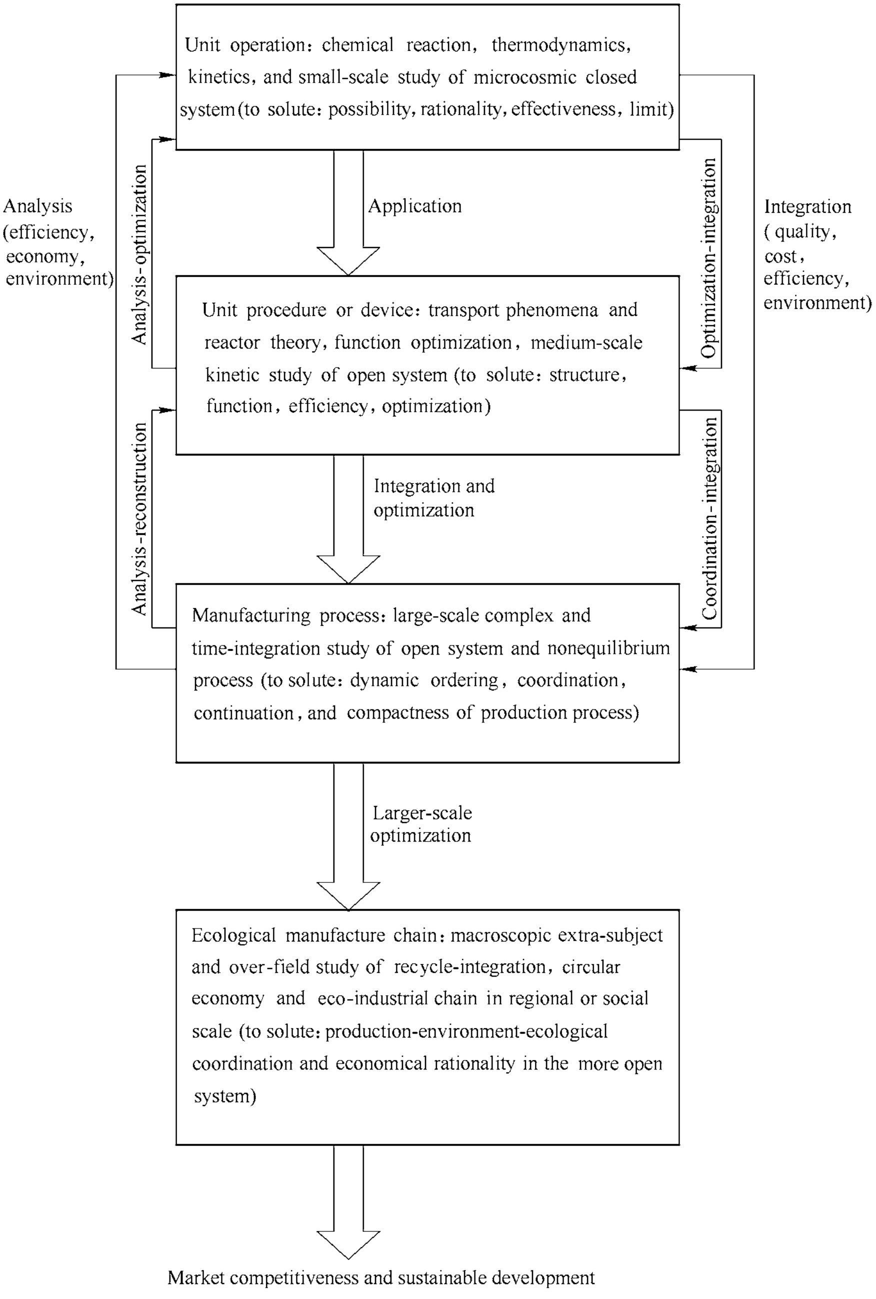

Fig.3.4 Development schema of metallurgical process engineering

3.2.1 *Multi-level analysis of science*

A. General trend of scientific investigation natural science

In the paper *The Challenge of Physics*, Lee Tsung-Dao pointed out, generally speaking, the development of the physics early in part of the 20th century can be generalized simply to emphasize simplification and induction. It was believed that the matter structure should be understood, as long as elementary particles were found. However, in the mid-twentieth century, people realize that even if only elementary particles were clear, we still couldn't understand fully the great problems of the whole physical universe—the contradictory of symmetries and asymmetries, the invisible quark, the dark matter and the quasi-stellar objects……. These were beyond elementary particles. Therefore, in the development of physics in the 21st century, the entirety and unification were being more emphasized. Microcosmic elementary particles and macroscopic space vacuum have to be studied as a whole. Cosmos was full of challenges which we still hadn't understood. He said, the influence of breakthrough in these domains should be bigger than the influence of several great breakthroughs in the early days of the 20th century.

Chemical engineers and scholars put forward to connect science-technology-process-product-market as shown in Fig.3.5. namely, to achieve the harmonization of science-product-market-environment by all ways from atom to economy. At the same time, biologists try to connect the study of different scales and levels in molecule-cell-tissue-organ-biomass for a new breakthrough. There are some marks of these cognitions in Table 3.1.

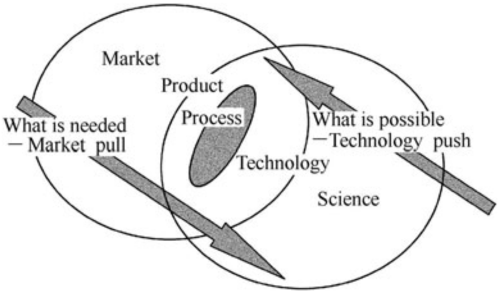

Fig. 3.5 Process engineering: business model

Table 3.1 Trend of integrated fundamental researches

Physics	Quark-Proton-Nucleus-Atom-Molecule-Glass state-Condensed state(Crystalline)- Macroscopic vacuum
Biology	Atom/molecule-Cell-Tissue-Organ-Biosystem
Chemical and metallurgical engineering	Atom/molecule-Reaction-Device-Process-Product-Environment-Market

The study on biology begins with organism entirety to cell from top to bottom. And that, it goes deeply from cell to molecule by aid of chemistry. On the contrary, the study on chemistry starts from the scale of atom or molecule, to inorganic macromolecules and to organic polymermolecules, and then touches the complex system of the organism gradually. They encounter in the domain above molecular but below cell level (Guo, Hu, Wang, et al, 2002) and bring out new subdiscipline.

So a question surely will arise that how we ought to do and to take a great advance for metallurgy. From academic viewpoint, metallurgy had passed through a way from experience to science. But on the goal of industry, this change only proceeds over two stages that, the influences of chemical composition, temperature and pressure was understood to regulate unit operations (such as desulfurization, deoxidation, and decarbonization etc.)at first, and secondly, the principle of transport phenomena and physical-mathematical modeling of processes in device or procedure scale was understood to some extent. Certainly, these two developmental stages are milestones in the history. However, it should be thought about how are the ways in the metallurgy discipline. One way goes up from atom, molecule, device, working procedure to entire manufacturing process. Anotherway, downwards, starts from market demand for diverse steel products. Two ways above mentioned, and even the way of nature—environment—manufacturing process—products—recycle, are intersected in the manufacturing process level of steel plants. So the essence and regularity of the metallurgical manufacturing process are necessary to study. Now the metallurgy discipline is facing a new challenge and needs a change. The reason for change is that the classic theory and method aren't enough to realize the dynamic control for design and operation of metallurgical manufacturing process quantitatively. At the same time, the current theory and method don't make effectual use about information technology and ecological conception penetrating into the steel production in plants. Thereby, will over a new way of atom — reaction — device — process — product — environment — ecology think entirely? It seems that the topic on structure problem of the complicated, opening, nonequilibrium and irreversible process system at different levels and scales exists as commonchallenge to science. in the 21st century. It is necessary to study the scientific problems at different levels and scales with generalized view for the fundamental research. We could enter into a wiser situation only in the way to understand the knowledge different scales and levels and to link them.

To solve above-mentioned problems, at first, that has to get the cognition both deeply and scientifically, then the technical effect must be obtained and the market benefit or social advantage will be promoted.

B. Multi-level analysis of metallurgy

All the sub-disciplines of metallurgy became the theory in level of atom or molecule scale for a long time. It means the key fundamentals of the conversion process at different temperature (thermodynamics and kinetics of chemical reactions, theory of solidification, crystallography, physical change and phase transformation of metals, plastic deformation of metals) and the knowledge of heat transfer (heat transfer theory) etc. It belongs to fundamental science still. The knowledge related technical device, operation technology and automatic control does belong to technological science. These fundamental and technological sciences are applied to unit operation scale (such as a certain chemical reaction, one kind of phase transformation) or unit device and procedure level (such as blast furnace, steelmaking converter, refining ladle, etc.). Now, the functions, the structure and the efficiency of the whole manufacture (production) process must be emphasized to solve problems on the developing stratagem, the effective control of operation, the market competitiveness, and the sustainable development of entire enterprise. To express clearly the physical essence of entire metallurgical manufacturing process, an engineering science theory which is applied to study the integrated property, function, structure, efficiency of the manufacturing process of the plants should be developed. This is engineering science in manufacturing process level—metallurgical process engineering.

The essence and the major intension of metallurgical process engineering belongs to the scope of metallurgy/material engineering. Metallurgical process engineering doesn’t equal to system science, just as the physics and the ecology can’t be generalized into the system science, and can’t be dealt with simply as the problem of system engineering. Metallurgical process engineering roots in metallurgy and metallic material engineering, and assimilates the achievements and some concepts of physics (irreversible thermodynamics, dissipation theory, synergetics) and chemistry (multi-scale effect in substance conversion). In the metallurgical process engineering the projection and the coordination of diverse processes as reaction, plastic deformation and phase transformation, the matching and connection of procedures and devices with various functions in manufacturing process as well as the combination and structuring of “resources” and “events” of different scales in manufacturing process should be considered and analysed. In the metallurgical process engineering, the objects are the problems about property, structure, function, operation rule and efficiency in the open, nonequilibrium irreversible system. In the way of research, the method and concept of system science (including the science of complexity) are often adopted. When observing and solving the problems, both the reduction and integration are needed. People pay attention either to process analysis of different scales and levels, or to study on process integration of different scales and levels, and also to formation of optimum process network dynamically among different levels. Further research and reanalysis of already integrated process is necessary even for reconstruction and optimization of the manufacturing process.

In the knowledge chain of science—technology—engineering—industry, metallurgy-material engineering consists of three levels, i.e. fundamental science—to solve mainly the problems on the molecular or atomic scale; technological science—to solve the problems on the device or procedure scale; engineering science—to solve the problems on integrative manufacturing process scale as well as combination, matching and optimization problems among procedures and devices in the process entirely. Take iron- and steelmaking as an example, it can be seen that level relationships to each other in Table 3.2.

Table 3.2 Analysis of level relationships in term of science of steel manufacturing process

Classification	Research scale	Research approach		Level	System character	Control means
		White box	Black box			
Fundamental science	Atom/ Molecule	Atom/ Molecule	System background	Microscopic	Isolated system: no mass and energy exchange with surroundings, reversible process—equilibrium	—/ PLC
Technological science	Procedure/ Device	Procedure/ Device	Molecule/ Process	Mesoscopic	Open system: mass and energy exchange with surroundings	PLC/MIS
Engineering science	Process/ Integrative system	Process/ Procedure relationship	Molecule/ Field	Whole/ System	Open system: mass and energy exchange with surroundings , irreversible —far from equilibrium	MIS/ CIMS

As shown in Table 3.2 that the problems of fundamental research of metallurgy-material engineering is mainly on the atomic-molecular scale of microcosmic level. By means of the white box and the black box, it discusses the typical objects, and treated in an isolated system of no mass and energy exchange with surroundings. Results of these researches are very important to explain and to understand the smelting-refining processes in essence, which makes metallurgy-material production scientific. The cognition on the atomic and molecular scale had been solved successfully. In the production practice, steelmaking plant faced not only the problems on atomic and molecular scale, but also the problems of larger-scale with more complex boundary conditions and multicolored phenomena. Thus some theoretic research results with level of technological science such as "transport phenomena theory" and "controlled rolling-controlled cooling" appeared. These kinds of theoretic results are studied under the condition of open system which has energy-mass exchange with surroundings. This methodology is beneficial to control unit operation and improve design parameters. Evidently, it is a sort of knowledge on mesoscopic level for the steel production.

Since 1990s, the challenges and opportunities for the modern steel enterprise weren't a single problem of product quality or performance, but multi-target problems of cost, product property, process control, process emission, environment, ecology, optimizing and selection of resource and energy, as well as cyclic utilization. To solve this group of multi-target problems, the essence, the structure and the operation characteristics of steelmaking manufacturing process must be studied and cognized entirely.

Problems on the macroscopic level—integrated process system scale of the steel manufacturing process belong to knowledge category of engineering science. It is formalized based on developed fundamental science (microcosmic level) and technological science (mesoscopic level) of metallurgy-material engineering, and it also assimilate the recent achievements of system science, theory of dissipation and synergetics, combining with modern concepts of information technology and ecology. The engineering science is a common knowledge to the process manufacturing industry. While, entering the 21st century, the process manufacturing industry faces the challenges of economic globalization, as well as the opportunities of increasing information technology and serious environment burden, so this kind of integrated and complex knowledge must be studied and mentioned.

3.2.2 *Physical essence of manufacturing process of metallurgy*

The metallurgical production, especially manufacturing process in the steel integrated enterprise, is a sort of complicated system of open, nonequilibrium irreversible processes. It forms a synergetic-integrative and dynamic-orderly operation process which is made up of some different procedures, such as storage and transportation of raw materials, preparation of raw materials, ironmaking (reduction of iron), steelmaking (oxidation of carbon), second refining of molten steel, solidification of molten steel, reheating of cast slabs/billets, steel rolling-pressure working with phase transformation, cold rolling and surface treating of finished steel, the materials transportation, as well as the storage, transmission and conversion of energy resource etc. Moreover, the connection and interaction behaves as a nonlinear relationship among various processes, procedures and devices. That is to say, the steel manufacturing process is an open, nonequilibrium, irreversible complex process system which consists of unit procedures with various structure-functions through nonlinear coupling.

This sort of complex process system includes many unit operations with different functions, structures and operations. Meanwhile, it bears different significances of multi-level (atom and molecule, procedure and device, process section, whole process), of multi-scale, in order or chaos (function, time and space), for linking-matching (static), and for coordinating-buffering (dynamic). This system strives for dynamic orderly structure and continuous (quasi-continuous) compact operation.

As a kind of open complex process, this sort of system not only embodies in the complexity of composite units and their structure, but also the complexity of input and output of mass flow, energy flow and information flow in the whole manufacturing process and the complexity of the integrated (macroscopic) operation dynamics in the process system.

The features of the steel manufacturing process are as follows:

1. The process is an integrated operation system which consists of many interrelated procedures with various performances and functions. Each procedure in the process behaves different functions. So the process which is made up of procedures through interrelating and integrating takes new functions that each procedure hasn't.

2. The whole process and all kinds of component procedures and devices are open systems having mass, energy and information exchange with surroundings; namely, the information is being exchanged with the imported mass and energy and the exported products, by-products, emission and energy continuously. Openness and exchange are necessary conditions that this sort of process has survived, thus developing into order.

3. The whole process and all kinds of component procedures are far from quilibrium state. When the whole process is a nonequilibrium state, the interaction between procedures and devices is nonlinear coupling, which embodies in integrity and complexity of the process.

4. The main subject in the process are some "flows", especially mass flow such as ferruginous mass flow in the steel manufacturing process. In the operation of the process, the information carried by the "flow" is multi-factor'. The information is taken as some basic variables mainly, such as chemical composition factor, physical phase state factor, temperature factor, geometry factor, surface feature factor, space and location factor, time and time sequence factor.

5. A certain procedure in the process has succeeded the upstream procedure in functions of genetic factors from the multi-factor flow, but making some factors an abrupt change—"mutation" of "quality" or "quantity" and fitting in harmonic with surroundings. The functions of "inheritance" (transfer), "mutation" (variation, conversion), "adaptation" and "coordination" (self-organization) can embody in one or some factors in the "flow".

6. The nonlinear coupling relationship among procedures in the process is represented by the way such as mutual cooperation (addition, multiplication etc.), mutual promotion (multiplication, exponential etc.), mutual restriction (subtraction, division, negative exponential etc.) and mutual influence (functional relation). Namely, there is not any linear relationship among procedures but either multiplication effect of positive feedback or saturat ion effect of restricted growth namely negative feedback.

The character of nonlinear relationship among procedures also embody in nonlinearity of mass exchange and energy exchange, nonlinearity of space transformation, and nonlinearity of time course.

7. The nonlinear coupling and the nonequilibrium play an important role on "self-organization" of process system. So-called "self-organization" is forming and then perfecting in orderly state of process system spontaneously on one's own.

8. There are "fluctuations" in behaviors of each procedure of the process. When one or some parameters in the process system are in a critical state, the "fluctuations" can trigger off the reconstruction of components of the system and then the "mutation" of behavior of the process. So the effect of "fluctuations" in procedures or process at "critical point" is important tremendously. Numerous types of dissipative structure and orderly state will emerge by them.

Generally, from the viewpoint of physical essence, the steel manufacturing process, which consists of many procedures with various functions, is a kind of multi-factor "flow". The "flow" streams with specific "order" in a complex process network structure (such as general layout of steel plant). Many physical and chemical conversions are accomplished and all prospective techno-economic-social indexes may be reached. Actually, it is an open and irreversible process, namely, the conversion and dissipation of matter and energy.

Discussion on metallurgical process engineering must abandon the closed thinking mode with conservative boundary conditions, and turn to an opening thought which is considering the open, far from equilibrium, nonlinear coupling and fluctuating system. The incessant reform, evolution, and development of the system should be studied and the new concepts will be formed, so the method has to be changed. As the research subjects are different from the categories of fundamental science about the metallurgy, the openness, irreversibility, nonequilibrium and dynamic order appear in the metallurgical process. Researchers-metallurgists must change their views from isolated system, reversible process and thermostatic state to open system, irreversible process and nonequilibrium state. The formation of a dynamic orderly structure through "self-organization" being existed in the process system is the topic for research.

As a discipline of the engineering science, metallurgical process engineering needs some ideas, theories and methods of system science but doesn't restrict itself within the limitation of system engineering. Thermodynamics, kinetics, theory of dissipative structures, synergetics and ecology are all important theoretical bases and tools of the metallurgical process engineering. In fact, for the research and development of metallurgical process engineering, the relationship between system science and process theory as thermodynamics, kinetics, dissipative structure, synergetics, ecology etc. isn't a kind of subordination but of combination, integration and intersection. Therefore, it can't be considered that process engineering belongs to the system engineering as soon as the "system" is concerned. In theory the system engineering can't cover all kinds of knowledge, and in practice not every problem can be solved with the only method of system engineering completely. There is a wrong way that all the complex problems can be generalized into system engineering or be packed in “one basket”—system engineering. It should be pointed out that: after all, the engineering science and the process technology in the metallurgical production belong to the category of metallurgy-material engineering, because some problems such as physical essence, mutation of function/structure, synergetic operation and process dissipation in the metallurgical production as well as the structure, function and operation regularities of metallurgical manufacturing process cannot be studied and solved, just through the system engineering alone. In essence, metallurgical process engineering belongs to the category of metallurgy-material science and it solves the problems of engineering science and process technology in the manufacturing process level of a metallurgical enterprise.

Since development of the metallurgical manufacturing process, the structure optimization, the dynamic ordering and the synergetic operation should be the effect and goal of technical innovations and integration in the steel plant, and also should be an important cutting-in point of engineering research on the whole process entirely. In the industrial practice, it is impossible that the structural variation of the process would be realized as a “mutation” through one-shot technico-economic measure to organize a structure of whole process with new functions at once. In contrary, in practice (especially in the technical reform of existing plant), to improve partial functions a certain order parameters of a section or a processing procedure (i.e. subsystem) would be changed to a critical value, thus the structure and function of this section or procedure (subsystem) could be varied (reordered). And then, the order parameters (one or several) of some sections or procedures (subsystems) should be changed by taking measures—with the principle of synergy and connection in regular series (including in technology and on investment). Following this, on a larger scale (such as from the converter to the hot rolling mill) the dynamic orderly structure will be formed through nonlinear interaction—synergetic effect and self-organization effect among subsystems. Finally, there is a whole dynamic orderly structure of metallurgical production. Thus an open, nonequilibrium, dynamic orderly process—continuation/quasi-continuation, compactness, synergic operation of a modern steel manufacturing process appears.

Above cognitions are not only necessary to describe the physical essence and structural evolution of metallurgical manufacturing process but also a roadmap to technical reform and investment decision of a steel enterprise, and even to projection and construction of the new plants.

3.2.3 *Targets of the metallurgical process engineering*

The metallurgical process is a kind of complex process system. Studying on metallurgical process engineering, it should be focused on aiming at the macroscopic process in large scale of chemical and physical changes of matter system (mass flow of production), mass-and energy-consumption and their efficiency, transport-storage-buffer of mass flow and energy flow in process, and input and output (including emission, etc.) of process system. And it should be focused on study of integrity and essence of manufacturing process, i.e., study on structure-function-efficiency etc. of metallurgical manufacturing process at engineering science level. Then the study of structure-function-efficiency of metallurgical manufacturing process will be extended into the green manufacture and eco-efficiency of society as a large-scale system to take account of engineering science, process technology, economic benefit and ecological benefit.

As above, the metallurgical process is a sort of complex process system. Really, complexity exists in various kinds of process and process engineering widely. Study on all kinds of behaviors, characters and effectiveness of the whole integrated process in the process manufacturing industry are still in the groping way. as:

1. It is a sort of very complex system, and the thermodynamic nonequilibrium state and the kinetic behaviors of the process in various scales and levels are often nonlinear coupling.
2. This sort of process system is often multi-component, multi-phase and in complex states with their own open boundary conditions.
3. In this sort of process, there are different component numbers of the same level, different relationships of interaction between components, complex relation among components of various levels and scales, as well as demand for "self-organization".
4. In this sort of process, there are often a lot of control factors, such as control of matter property, control of energy and temperature, control of time and time sequence and so on. During the operation, the mutual influence, mutual competition and mutual restriction among these control factors exist. Therefore, a certain order parameter or some ones dominating behaviors of subsystem of the process even the whole system often arise.
5. Various types of process structures which are in multi-levels and multi-scales (time scale, space scale, mass scale and energy scale and so on) are formed with different sets such as of components, of components' relations and of levels' relations.
6. The process of various structures determines the structure of plant, i.e. the mode of plant.

The purposes of study on the metallurgical process engineering are considered to understand the structure and behavior of the integrated process, to promote synergetic optimization of the function of process system, mainly, of function at high-level and large-scale, to achieve the multi-objective optimization of the metallurgical process system and to get an environment-friendly relationship to com-

community.

In general, metallurgical process engineering involves with fields of engineering science, production technology, engineering and design, decision-making and investment and so on.

1. Content of engineering science—metallurgical process engineering. Lots of aspects are as follows:

- Physical essence of process;
- Structure analysis and structural evolution of steel plant under the process integration;
- Analysis and optimization of functions of processing procedures;
- Coordination and optimization of set of procedure functions and set of procedures' relationships;
- Reconstruction and optimization of set of procedures;
- Combination of process science and information technology;
- Operation dynamics of metallurgical process;
- Extension of functions of metallurgical process.

2. Production technology. To achieve integrative optimization of metallurgical manufacturing process, the following problems must be considered:

- Core problem: the multi-factor mass flow control system, i.e. harmonization, consistency, coordination and management of three items: matter state transformation, matter property control and mass flow control;
- Basic parameters and derivative parameters in the manufacturing process;
- Integrative control of mass flow, energy flow and information flow;
- "Criticality-compactness-continuation" effect;
- "Generalized loop engineering"—flexible buffer engineering;
- Simulation and regulation of operations of the manufacturing process.

3. Engineering and design. The strategic guiding principle of engineering design of new manufacturing process should be the rational choice of plant mode and then system matching and optimization of processing procedures. The plant mode with special, serial and competitive product strategy instead of universal product-mix should be considered. Design of plant under different conditions should be made as:

- For new system, rational choice of plant mode and innovation of process system;
- For existing plant reform, correct selection of optimum plant structure and coordination-optimization among each sections and whole plant.

So far as technology is concened, the fundamental theory of processes has not changed, but the feature of the process technology has changed greatly. There are:

- Ironmaking procedure: combination of raw material preparation, ore reduction and energy conversion;
- Steelmaking procedure: analysis and optimum integration of operation func-

tions to form an efficient and quasi-continuous unit procedures supplying liquid clean steel;

- Solidification procedure: key procedure of continuity and compactness of steel manufacturing process by means of high speed and near-net-shape casting;
- Rolling procedure: minimum compressive ratio in deformation with high speed continuous rolling based on optimized control of surface quality, dimension accuracy, metal structure and its property.

Conclusion is, in short, that the technological process ought to be optimized and adapted for the product pattern, thus different process types for flat products production, long products production, pipe products production would build respectively with a corresponding reasonable economical scale.

4. Decision-making and investment. To aim at market competitiveness and sustainable development, to search for investment orientation and to make right decision, the following problems will be considered:

- The overall arrangement of industries (or enterprises) vs. its market, resource, energy, environment;
- Judgment of investment direction;
- Assessment of investment in sequence;
- Optimization of fund amount per unit product;
- Evaluation and choice of initial investment and total investment of the system;
- Analysis of investment opportunity and the time benefit of schedule;
- Estimation of risk analysis and breakeven point;
- Analysis of mechanism and mode to get finance.

3.2.4 *Research scope and methodology of metallurgical process engineering*

Metallurgical process engineering is a macroscopic engineering science, where the physical essence, structure and whole behavior of process are mainly studied. The purpose is to understand fully the driving force of interrelated matter and energy flows including storage in metallurgical manufacturing process; as well as to study a series of problems concerning function-structure-efficiency, space and plan arrangement, control of time and time sequence, emission control and optimum recycle in the manufacturing process.

In physical essence the metallurgical manufacturing process is an open, irreversible and nonequilibrium process system. The essential research of metallurgical process engineering includes study on operating situation and boundary conditions; study on fluctuations including instability or nonuniformity and nonequilibrium of components (subsystems such as procedure, device, workshop and so on) and interactive nonlinear relationships among components in the process; study on self-organization induced by above phenomena and cooperative relation; further study on operative dynamics of process system and even new structure emerging based on self-organization and synergistic effect.

The investigation on structure and behavior of whole process includes studying on structural characters and behaviors on different levels and scales, formulating dynamic orderly operation structure by analysis-optimization of set of procedure functions, by coordination-optimization of set of procedures' relations and by reconstruction-optimization of set of procedures, as well as identifying its entirety and complexity. To study the dynamic-instable "flow" characteristics and regularity of the multi-factor mass flow in the process network according to certain program, in other words, the coupling of matter state transforming, matter property controlling and mass flow controlling in production should be considered also. The essence and regularity of process coupling embody in complexity and time-factors' evolution in the process system.

Problems about technology during study on metallurgical process engineering include that, the structures and functions of the whole steel manufacturing process and its unit procedures and devices, the efficiency of mass flow, energy flow and information flow in production, even extending to the time-space optimization. The operations, the devices, the processing procedures and even the structures and functions of the whole process have been varied from simpleness to complexity, and return then to simplification in the developing course of metallurgy. Certainly, this new simplification appears after improving of ordering degree of whole process structure, as greatly distinguished from the original simple and disordering.

For a long time, concerning the structures and functions of production people have been not used to study on the irreversibility and the complexity. It is not skilful to simplify the complex problems through studying on the irreversibility of mass-and energy-exchange and the complexity of structure-function in the process. In fact, the *complexity* mainly comes of uncertainty on classification of things and events, on the level-scale measure of the process structure and on interactions among different levels and scales. The complex problems can be simplified if these above are cleared gradually. The purpose of study on this sort of complex and large-scale process system should not complicate the problems, but get a new simplification i.e. process simplification, procedure simplification, structure simplification and control simplification on the base of understanding the evolution from simpleness to complexity. This new simplification reflects deeply understanding of the physical essence and the operation regularity of the production. The process engineer must study the complex system with simplification method, especially, the complex process system on large-scale and engineering level by means of simplifying in deep cognition.

The complex manufacturing process is analyzable and integratable frequently. Moreover, its analyzable and integratable performances embody in either one and the same level or different levels of complex system. Therefore, the manufacturing process is shown to be of multi-levels' character on structure.

The intellectualization of complex process system includes the feedback of process structure and interaction among structures or levels. We should think about them, understand them, study and solve the problems actively on engineering science level. Actually this topic must be involved in the theory of self-organization based on dissipative structure and synergetics.

The fundamental approach of research in metallurgical process engineering is overall study and description of the physical essence of the process and process structure, analysis and integration of the whole process, and investigation from a certain special theme to generalized universality.

The object of study on complex problems in the metallurgical process is put these complicated (even uncoordinated) factors, such as chemical composition factor, physical phase state factor, geometry factor, surface feature factor, energy and temperature factor as well as, time and time sequence factor, through coordinating-coupling in production by means of analysis-integration and self-organization of dissipative process (sometimes through mutation or emergence) to form an optimized process structure (section structure or whole structure). It deserves notice that structure is a core problem in studying complex process. Studying process structure is helpful to unify interfaces of mass, energy and information in process, integrate mass-energy-information, flow and their synthetic optimization. Dynamic order, quasi-continuation and even continuation of the whole process will further arisen through sequent coordination and ordering. For the operation of whole metallurgical production, research in ordering and coordination is important supporting point of quasi-continuation/continuation. Quasi-continuous/continuous production process is commonly chain of optimum structure-function-efficiency, so it has high production efficiency, stable product quality, low energy consumption and less emission, which is friendly to environment and ecology. Meanwhile, it should be taken notice that: at the boundary between chaos and order there are complex and abundant information, even including on economy and management. Therefore, study on metallurgical process engineering should be able to combine holism with reductionism, and be skillful either in analyzing or in integrating. The purpose of studying metallurgical process engineering is also optimum simplification of physical model of process, to make the information technology effective on the large scale and high level of complex structure process (e.g.CIMS MIS).

The scope of metallurgical process engineering further extends for the construction of open, cyclic, controllable eco-industry system including "artery system" (material processing flow) and "vein system" (emission and recycle flow) of manufacturing process; as well as, to carry out different life cycle assessment (LCA) and recycle of social wastes to promote the eco-industrial chain linkage.

When studying this sort of complex system of metallurgical process engineering, it is must distinguished multi-scale problems from multi-scale methodology. The multi-scale methodology can't be adopted to substitute for everything. Study on multi-scale problems, at first, should make clear regularity of lower scales or adjacent scales, and then enter into trans-scale study to predict the regularity of mentioned scale level. Study on correlation and unification of trans-scale problems through different levels is an important method of studying complex process engineering. However, multi-scale methodology actually contains two aspects: one is multi-scale forecasting, i.e. forecasting from low scale level to high scale level; the other is multi-scale controlling, i.e. controlling low scale level according to the demand of high scale level. Certainly, both are necessary, when the problems need be solved on the aspect of practical production and design (Hu and Liu, 2002).

There are a series of complex problems in the metallurgical production frequently. In practice, these complex problems often show as a series of *technical bottlenecks*. To solve *technical bottleneck* problems in large-scale complex process system, it has to be realized under a given period, and permitted financial-material resource, that we ought to ponder over *time sequence*, *motility* and *structural emergence* existed among these technical bottlenecks. The *time sequence* refers to the rational steps of solving technical bottleneck, i.e. to solve someone firstly is suitable and the later part of solving is more efficient, when a series of *technical bottleneck* problems are faced. So-called *motility* indicates that in the metallurgical production process, when former *technical bottleneck* is solved, the *technical bottleneck* often *moves* into another technology problem; this *motility* of *technical bottleneck* will always exist until regularly progressing of the whole production process——forming a new process structure. The *structural emergence* indicates that in the course of solving a series of *technical bottleneck* problems in the complex process system the new structure which has optimizing function and higher efficiency will be generated at a certain level in one or some sections, taking a certain new function because of "synergetic effect" under proper treatment.

Metallurgical process engineering has been studied and integrated into an engineering science on whole process scale, based on great accomplishments of fundamental science and applid science of involved procedures and devices of steel manufacturing process. The steel manufacturing process influences either the mass-energy conversion of production or the emission to environment, As an engineering science, metallurgical process engineering aims at function optimization, structure optimization and efficiency optimization of process system through optimizing the whole manufacturing process; and then, the extensive problems such as mode -structure of enterprise, market competitiveness and availability of the resources as well as environmental protection would be solved.

3.2.5 *The influence of metallurgical process engineering on steel enterprise*

Beyond the 20th century, the steel industry especially in developing countries there is an opportunity for further developing on the one hand, and it also is facing the challenge on the other hand, mainly involved in two aspects of the market competitiveness and the sustainable development. To solve these problems as a whole, the steel enterprise must consider the philosophy of the manufacture process optimization on a sound basis.

For the process industry such as chemical industry or the metallurgy, especially the steel industry, manufacturing process is characterized by broad correlativity and strong permeability (Fig. 3.6). A number of market competitiveness factors like comprehensive cost, product quality, product mix, production efficiency and investment benefit, as well as many aspects of sustainable development such as availability of resource and energy, emission and its influence on environment, the construction of eco-industrial chain and recycle of bulk social waste, are related to correct selection of manufacturing process. The manufacturing process of steel plants also influence their function positioning and the social-economic role which will play.

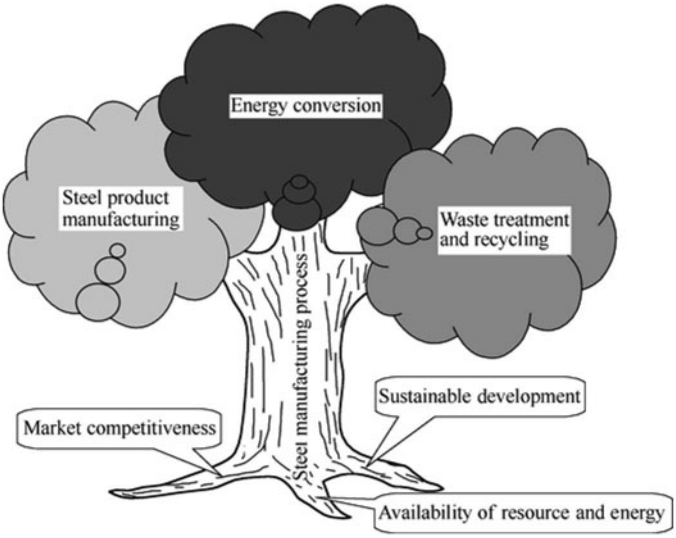

Fig. 3.6 Correlativity and permeability of the steel manufacturing process

Modern steel plants should be positioned together at the function of steel product manufacturing, the function of energy conversion and the function of waste treatment and recycling. But structural diversity of manufacturing process influences the mode of steel plants partly, such as long product plant, flat product plant, pipe product plant and also BF-BOFintegrated complex or EAF mini-mill etc. Metallurgical process engineering is just the knowledge of large scale, aiming at the manufacturing process of entire enterprise. Therefore, it has the relation to integrated optimization of practical production, and orientation of future development, technical reform, decision-making and efficiency of investment, environment and industrial ecotype reforming and so on.

For existence and development of a steel enterprise, the problems concerned with metallurgical process engineering has direct relationship to following aspects:

1. Essential study and identification of the chemical and physical changes, the transportation and buffering, as well as the form and efficiency of matter and energy conversion of the multi-factor mass flow, but also input, output and emission of process system in metallurgical manufacturing process, will influence comprehensively on structure-function-efficiency of process system in the steel plants.

2. Based on the analysis-integrated study of the metallurgical manufacturing process at engineering science level, the optimization of steel plants' mode, and then the design principle, design method, their operation and management principle will be determined, which represents common regularity, principles, objectives (group) and new concepts.

3. Beyond the mode and type of steel enterprise the study on green manufacture and industrial ecology of society——much larger system should be developed, i.e. both economic benefit and eco-efficiency should be considered. It is helpful to position the role playing by a modern steel enterprise in society-economy and to feed back for optimization of mode of steel enterprise, which can adjust and improve the metallurgical manufacturing process again.

The change of global and regional demands (including quantity and quality) of steels, the variation of market price of steel products and the substitution-competition among steel with other materials, promote the inevitable technical reform of numerous old plants and the corresponding investment. At the same time, some new steel plants will be constructed surely. The questions are these business will be guided by which idea, and what technology and knowledge (especially engineering science) will be applied to construct the whole metallurgical manufacturing process. Then it is possible to decide the investment direction, to analyze the specific fund amount, to judge the investment in sequence, and to choose the investment occasion. All of them are vital strategy matters for the survival and development of a steel enterprise.

4. The development of steel industry of the 21st century will be combined with the information technology and the ecological adaptability closely. Therefore, it is necessary to further think about the social-economic position of a steel enterprise.

The steel production process is characterized by gigantic throughput of materials and energy as well as a long processing chain. In the future circular economic society there are three-aspects of function within a steel plant, (Yin, 2000 b), i.e. the function of steel product manufacturing, the function of energy conversion (supplying clean energy, vapor and hot water for the society), and the function of waste treatment and recycling (especially treating the steel scrap, the plastic waste, the scrap tire and also the sewage and rubbish of the community). The important part of eco-industrial chain and an important link of future circular economic society will be undertaken by the steel enterprise.

5. Metallurgical process engineering, mainly aimed at the study on steel manufacturing process, leads to coordination-optimization of the relations among different procedures and devices, and then to reconstruction-integrated optimization of the whole manufacturing process based on analysis-optimization of functions of unit operation, unit procedure and unit device. It is helpful for the combination with information technology, and to realize computer control of process and computer control to enterprise management. Then joining with the models of product booking and customer analysis, the degree of information technology and artificial intelligence will upgraded greatly.

6. Concerning the environmental problems, the steel manufacturing process is a "root". To solve the environment problems of steel enterprise should study the environment protection and the ecological recycle chain combined with steel manufacturing process based on metallurgical process engineering, i.e. should study the source of environment problems, essential strategy and recycle linkage in the manufacturing process of steel plants, but can not pay attention to end-pipe treatment technology only (Yin, 2000 a; Yin, 2002). So the wide scope of metallurgical process engineering with environmental science becomes general engineering technology field of metallurgy-materials engineering as a basis, combined with information technology and ecological ideas. The route of study on this field continues from fundamental science to technological science, then to engineering science, finally to industrial application.

7. Concerning manufacturing process of steel enterprise it should call special attention to the relationships about structure, function, efficiency, with procedures and devices in the production process. Where, process and efficiency are macroscopic relatively, but structure and function are of multi-level and of multi-scale. In the steel production process, "static structure" is the arrangement and the combination of procedures/devices and their space position by certain rule. But in practical operation, the state and the behavior of structure are varied with time. It belongs to dynamic structure concerned in the steel production is referred to problem of multi-level, consisting of micro- (chemical composition, atoms in position, etc.), meso- (processing reactor, device, etc.), and macrostructure (workshop, plant, manufacturing process, etc.).

For a long time, the study on steel manufacturing process and structure of steel enterprise and the cognition about those are insufficient, and sometimes even indistinct. Simple accumulation and superismposing of relevant procedures and devices are carried out oftentimes with an empirical mark. Indeed, if the character, function and efficiency of entire structure of production process have been deeply studied, then abstract-generalization and accurate description have been systematically made on engineering science level, it must be benificial to the logical thinking of engineering design, guiding idea of technical reform of steel plant, as well as the decision of business transformation or construction of new enterprise.

We had accumulated many practical experiences in the production, construction and technical reform, engineering design and scientific research for the steel plants in long period. According to the needs of production practice, the technical reform and sustainable development of the steel plants, the exploration of the essence, structure and entire operation regularity of metallurgical manufacturing process on engineering science level is already an urgent task ahead.

3.3 Ken and Topics of Fundamental Research of Metallurgical Engineering Science

In the 21^{st} century, the fundamental research of metallurgy can't focus on the microstructure level of atom and molecule scale as in 1930s, but should open our vision to engineering level and deal with thought of holism. Metallurgical process engineering should base itself on the entirety to pay attention to the unification of analysis-integration among fundamental research, process technology and engineering science and to master every part. It must promote the structure optimization of entire process and "emerge" a new structure. The roadmap of thinking logic should be as following:

Metallurgical manufacturing process—open, irreversible, nonequilibrium, large-scale complex system

↓

Processing and fluctuations, nonlinear interaction, integration—self—organization

↓

Emergence, operation and evolution of dynamic-orderly structure

↓

quantitative deseription description quantitative description and informationization

↓

New field of fundamental research

Details and concrete contents of study need to be explored and exploited by metallurgists at home and abroad. Following aspects are worthwhile thinking.

1. In the complexity of metallurgical process system.

- Open, irreversible, nonequilibrium dissipation;
- Fluctuations in different levels and scales and their amounts;
- Nonlinear relationship of interaction among units;
- Performance, relationship and characteristics of flow, process network and

program in the process system;

- Coupling and evolving of multi-factor flow on time axis;
- Diverse controlling mechanisms and their correlation and competition;
- Multi-level and multi-scale structures, description of them.

2. In dynamic-orderly structure.

- Layout and combination of units and their space-time distribution;
- Order parameters of different scales and different levels and their effect on structural property—“emerge” phenomena of structure and function;
- Dynamic operation and coordination of structure;
- Exploration and construction of new process structure;
- Engineering design rule—from concept and principle to structure and mode.

3. Increasing quantitative and informational degree.

- Description of the complex entirety, multi-scale decomposition and association;
- Controllability and control mechanism of the complex entirety;
- Study on trend to extreme of integrated optimization(or study on optimization trend);
- Simulation and computational method in the complex entirety.

4. In the new field of fundamental study.

- Level relationship and integration among fundamental science, technological science and engineering science in the field of metallurgy-material engineering;
- Process optimization and integration of different levels and scales on time axis——simulation and regulation of metallurgical process;
- Iron-carbon metallurgy and hydrogen metallurgy, hydrogenextraction;
- The influence on metallurgical processes of a number of physical parameters (electricity, magnetism, undercooling, ultrasonic and high pressure etc.);
- Operation dynamics of metallurgical manufacturing process;
- Metallurgical manufacturing process and eco-industrial chain;
- Metallurgical manufacturing process and steel with structure of nanometer-scale particles.

References

Ellingham H J T (1944) J. Soc. Chem. Ind. (63):125

Elliot J F, Meadowcroft T R (1965) Steelmaking—the Chipman conference,June 1962. [C] The MIT Press, Cambridge, Massachusetts, 4-7

Guo M S, Hu Y, Wang K, Li J H, et al(2002) Multi-scale effect of substance transformations. Heilongjiang Education Press, Harbin, 25-257 (in Chinese)

Hu Y, Liu H L (2002) Multi-level and multi-scale methodology for structures occurring in chemistry and chemical engineering. In: Scientific front and future. (Proc.5th Fragrant Hill Academy Conference), China Environment Science Press, Beijing, 38-55 (in Chinese)

Temkin M (1945) Mixtures of fused salts as ionic solutions. Acta Physico-chemica USSR (20): 411-420

Schenck H (1945) Physical Chemistry of Steelmaking. BISRA

Wei Shoukun (1980) Thermodynamics of metallurgical processes. Shanghai Scientific & Techincal Publishers, Shanghai, 1-93 (in Chinese)

Worrell W L, Chipman J. (1964) Trans.TMS-AIME. (203):1682

Xiao X G, Xie Y G (1997) Basic principles of metallurgical reaction engineering. Metallurgical Industry Press, Beijing, (in Chinese)

Xu G Z (2000) System Science. Shanghai S & T Education Pub. House, Shanghai, 353 (in Chinese)

Xu K D (2002) The 20th century—ferrous metallurgy advanced towards engineering science from skill. Shanghai Metals 24(1): 1-10 (in Chinese)

Xu Z Y (1964) Principles of metallography. Shanghai Scientific & Techincal Publishers, Shanghai, 467-473, 417(in Chinese)

Yin R Y (2000 a) Green manufacturing vs steel industry. Iron and Steel 35 (6): 61-65 (in Chinese)

Yin R Y (2000 b) Times cosideration for technological process of steel industry ASIA STEEL, Volume A: General, 1-11

Yin R Y (2002) Energy-saving, clean production, green manufacturing and sustainable development of steel industry. Iron and Steel 37(8): 1-8. (in Chinese)

Chapter 4

Analysis and Integration of Manufacturing Process of Metallurgy

A description of the dynamic-orderly state of the entire steel manufacturing process requires the use of a number of basic parameters that run through the procedures of chemical metallurgy, solidification, and physical transformation. These basic parameters consist of quantified indexes of matter (weight, flowrate and density), temperature, and time. That is to say, steel manufacturing procedures are designed to bring about the connectivity, compatibility, continuity, and stability of the entire steel manufacturing process by means of regulating and controlling these basic parameters.

Since the 1990s, a series of technological improvements have, to a certain degrees, affected the structure of the steel manufacturing process. These technological improvements are manifested as the analysis optimization of its set of procedure's functions, the coordination optimization of its set of procedures' relations, and the subsequent reconstruction optimization of its set of procedures inside of process.

Modern steel manufacturing process has grown into a large system of process engineering technological system, which includes energy conversion, resource utilization, product quality control and new steel solutions for a better world, environmental protection, ecological engineering, and some more aspects. So far as the process own self in concerned, it is progressing in the direction of quasi-continuation/continuation, compactness, simplification, high-efficiency, comprehensive utilization and environment-friendliness. Steel manufacturing process has a feature of which the scale is a big capacity of million tons per year, but the level of control technology and equipment of the key parts can be compared with any processing technique of new materials (National Research Council, USA 1990). Steel industry is among the most productive, efficient, and technologically sophisticated industries in the world (Kavanagh, Carson, Dasgupta, et al, 1998). In the

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21st century, the steel enterprises are facing challenge for market competitiveness and sustainable development.

For more than a century, method of analysis is the majority in studying on the steel manufacturing process. The steel production process has been separated into many procedures like the raw material preparation, the coking, the ironmaking, the steelmaking, the solidification, the rolling and the heat treatment of metals. All of them formed separate academic branch to study and then collected directly. A lot of problems, such as process in batches and intermittence of mass flow, temperature up and down repeatedly, high consumption of energy and resource, large amount of emission and time loss of operation have existed for a long decades. So it has urgent need to establish a theory based on the whole production process in entirety to solve the optimization and integration of material, energy and information flow. This is the study on the analysis-integration optimization of the steel manufacturing process. From the new theory, a new idea and directions would be put forward to provide the support for healthy development of the steel enterprises.

4.1 Steel Manufacturing Process Is a Complex Process System

As a kind of manufacturing process, steel production is a complex process system, which is composed of different procedures, devices and relevant supplementary parts. They are mutual correlated, supported and restricted with each other, and they are operated serially and integrated in the process.

4.1.1 *Feature of the steel manufacturing process system*

One main feature of the steel manufacturing process is the multi-component, including multi-procedure and multi-device, etc.. The unity of diversity and also the identity of difference are included in multi-component of the process. For example, reduction smelting, oxidation smelting, solidification, plastic deformation and phase change are all one component of the process and they are different and diversified. Based on this kind of diversity-difference, the steel manufacturing process should be organized and integrated to be a whole, and the specified function that is a multi-target group would be realized through the whole process. Another feature of the steel manufacturing process is mutual correlation and mutual restriction among the components. Different but non-correlative components (events, procedures and devices, etc.) can not construct a process and don’t regard as any efficient operation. One more important feature of the steel manufacturing process is the integrity because of above two features. The steel manufacturing process must be a unified entirety which integrated by all procedures, devices and relevant facilities in the process. This process system has the whole structure, whole character, whole status, whole behavior, whole function, whole efficiency, etc. Entirety of process can be expressed as

$$\sum = \langle A, R \rangle$$

where, $\sum$ is process entirety;

A is collection of all components;

R is collection of all relations among components.

Integrity (entirety) is a more important property of steel manufacturing process and studying on entirety must involve its structure. What is structure? Process structure is the sum of total components and correlations among components in the process system. And the collection of relations among components under definite set of components could be also the structure of process system.

For a steel plant, the structure of steel manufacturing process can be mainly expressed as a number of procedures and devices, their capacities, arrangements and layout planar or three-dimensional. It should be called *static structure* (*frame structure*). Of course, the steel manufacturing process should have an operation mechanism (operation macro-dynamics). Operation mechanism of process reflects the *dynamic structure* of the process. It characterizes the collection of relations and restriction among procedures and devices in the process.

Process system with specific structure would perform specific functions. The functions originate from behaviors of the process system. And they also have the important characteristics of the relationship between the process system and surroundings. Any behavior in the process system would have influences on surroundings, but the better influences can be called a function-activity of the process system. Surroundings are an object of the activity. Activity is the contribution to the evolution of the object made by the behavior of process system (Xu, 2000).

Steel manufacturing process consists of some organizational relevant components. As integrity, the steel manufacturing process should take new function different from some components and their sum. So the function of manufacturing process behaves in its entirety. The integrated function of steel manufacturing process is closely related to its structure, but the function depends not on the integrated structure only. Function of steel manufacturing process is on the influenced and restricted by outside surroundings. Under given surrounding environment (e.g. some boundary conditions), process system with different functions could be built by same components but different structures. Outside surroundings change and reaches a critical value, even if the process system is made of same components and same structure, its function will be influenced and restricted.

We have to cognize the difference between *function* and *performance* of steel manufacturing process. *Performance* is the feature and capability appeared during mutual action and mutual restriction inside the system and relating to external about the steel manufacturing process. Performance is not equal to function in general. *Function* is a special performance which expresses the displaying effective action to the external world. For example, the combustion efficiency of an engine is the *performance* of it and the driving power provided by the engine is its *function*. So the performance of the steel manufacturing process is the origin of function and provides a possibility to display its function. The function can only be displayed during the operation of process system. These are many performances in the same process system. Every performance could develop relevant function or several performances are combinated to form one function. So, the diversity of the process performance determines the diversity of the process function.

The structure and function of manufacturing process would be changed along direction of time arrow (especially a large-scale time e.g. one year, ten years or one century). That is the *evolution* of the manufacturing process. Evolution of the manufacturing process is general in character. You may find that any manufacturing process technology is always possessing rapid or slow evolution if you use large enough or proper time scale to measure it.

Motivation of process evolution comes from not only inner factors of the process, but also some factors of outside surroundings. The inner factors mean the improvement of the component's function and performance, as well as the reaction, competition and contradiction among components, procedures and devices. For example, replacement of open hearth by basic oxygen furnace leads to enlargement of blast furnace, which results the change of production scale of the process. Especially, some changes of correlations and restriction of components (e.g. application of hot metal pretreatment and secondary metallurgy), guide the change of process structure, function and other properties. Correlative pattern and the correlativity among the components would be varied due to the change of components' number in the process and the enlarging or shortening of the production capacity. The outside driving factors include change of surrounding condition (e.g. oil price rising), variation of mutual influence and interaction between environment and process system, such as implementation of some environmental law and stricter emission requirement for steel plants. That guides the change of the process structure and property and even the change of integrity function and property resulted by innovation or elimination of some components in the process. Generally speaking, manufacturing process evolve driven by both inner and outside factors. For steel manufacturing process, the outside factors include market, price, resource (energy) , environment, law and regulation, and the inner factors include technological progress, technical innovation, production experiences, and management, etc.

As integrity, the steel manufacturing process has evolved with broad scope or narrow scope of evolution. Narrow scope of evolution means only change from one structure to another. For example, open hearth—ingot casting—blooming in some steel plants has been eliminated and fully continuous casting system has been built, and the structure of these steel plants was evolved. Broad scope of evolution talks over the emergence, the growth of manufacturing process——from zero to maturity, for example, from an iron ware master shop to an integrated steel plant. Topics about development from un-maturity to maturity, and from one structure to another, are also noticed. For example, hot metal pretreatment and secondary metallurgy were the special refining devices with "off-line" operation in the early stage. They have been gradually developed to matured on-line operation procedures in manufacturing process and the structural change of manufacturing process of steel plants has been occurred. In another hand, discussion on aging, degeneration, elimination and shredding is included in steel manufacturing process, for example, replacing old procedures as open hearth—ingot casting—blooming, eliminating cupola for steelmaking and removing reversible rolling mill from the production line. Problem on permanence of steel manufacturing process belongs to broad scope of evolution. During the existence period of steel manufacturing process, process system must possess quantitative changes in feature even no qualitative conversion. For example, many small BF—BOF—bar mill processes in China limited to 0.3~0.6 Mt/a, but their capacity reached suddenly to 1~2 Mt/a after applying fully continuous casting technology in 1990 s.

On historical viewpoint the steel manufacturing process was developed not only toward extension from simplicity to complexity, but also toward high-efficient restruction from complexity to simplicity. It should be stressed that this kind of simplicity through ordering, coordination and compactness is not degeneration but evolution.

4.1.2 *Complexity of steel manufacturing process*

Steel manufacturing process is a complex process system. The complexity embodies in many aspects such as multi-unit, multi-phase, multi-level, multi-scale, opening, far from equilibrium, non-linear and dynamic-orderly. Due to collection of these complex characters, the complexity of process structure must be formed.

Essentially, steel manufacturing process is consisted of conversion and evolution of such factors: matter, energy, time and space. The complexity of static structure and dynamic structure of steel manufacturing process originates just because the differences in matter behavior, energy efficiency, time-order series and plane-space layout.

As one kind of system of first category, the structure of steel manufacturing process can be studied on following two aspects:

1. Frame structure and operation structure.

1) Frame structure means the basic connection method among units before pro-

process operation and after its stop. Actually this is the static structure of system. Static structure of steel manufacturing process relates to set of procedures and set of procedure's functions.

2) Operation structure means the way of mutual reliance, mutual support and mutual restriction among procedures during the operation of process system. It is actually the dynamic structure of system. Dynamic structure of steel manufacturing process relates to set of the procedures' relations and set of compositive procedures.

2. Spatial and time-characteristic structure.

1) Spatial structure means the arrangement or assembly way of processing units in space.

2) Time-characteristic structure means the correlation of processing units during time flowing.

In a steel plant, to adjustment and optimization of spatial structure of the process system should be paid attention during invested construction and technical innovation, and the relatively secluded time-characteristic structure must be studied more clearly. Synergetic optimization of spatio-temporal structure must be considered comprehensively. In course of operation, because and the spatial structure as static structure is fixed relatively, the optimization of operation structure, even sometimes on the time-characteristic structure or spatio-temporal structure would be the major concern during production.

It can be seen that the complexity of steel manufacturing process structure is expressed not only as multi-unit, multi-phase, multi-level, multi-scale, opening, nonequilibrium, non-linear and dynamic-orderly, but also as the complicated static structure and dynamic structure resulted by the set of procedure's functions, the set of procedures' relations and the set of process procedures. Of course, it is related to the complexity of the spatio-temporal structure as a whole.

4.1.3 *Flow and order of steel manufacturing process*

For the process manufacturing industry, manufacturing process is a kind of multi-factor *flow* in the open system. Under some surrounding conditions, the manufacture process dynamic orderly operate according to a certain *program* and realize some purposes in the *network structure* formed by different procedures with their joints. Steel manufacturing process is a typical one of the manufacture processes.

Engineering science issue of the manufacture process should be focused not only on its structure, function, integrity and complexity mentioned in above sections, but also on the *flow* and *order* of the process system more deeply.

1. *Flow* in steel manufacturing process. The operating behavior, pathway and trajectory of the process flow, including mass flow, energy flow and information flow, have close related to the structures in different levels in the process system.

Generally, in the steel manufacturing process, the energy flow and the information flow are mixed with in the multi-factor mass flow. The evolution and progress of steel manufacturing process were shown as the quasi-continuation and continuation of the flow. In other words, quasi-continuation, continuation, coordination and compactness are interested target state of the steel manufacturing process. The target state manifests the process optimization about matter, energy, time and space in the system, or coordinated-optimized assembly and operation of matter and energy in a rational space and time in the steel manufacturing process. Attractiveness is the key element in the objectives. Status without attraction to steel plant can not be the target of evolution of process system. Target state of development of the steel manufacturing process in its entirety can be seen clearly from the technological progress, technical innovation and technological integration. It must be a multi-objective group, moreover, does't single target. At the same time, the strategic and the long-term attractiveness of the objective state must be considered.

The dynamic operation of the flow is attracted toward status of quasi-continuation/continuation, coordination and compactness. So, the optimization of the set of unit's functions, the optimization of the set of procedures' relations (interaction, mutual support and mutual restriction), and the reconstruction optimization of sets of units and their relations in the manufacture process become the real important problems.

The flow itself possesses complexity too. Flow in the steel manufacturing process consists of many kinds of factors, such as chemical composition factor, physical aggregate factor, geometry factor, surface feature factor, energy factor, time-sequence factor, spacial location factor, etc. So, in the complex process system, as the important characteristics of optimization of macro operation dynamics of manufacture process, the connecting-matching, the coordinating-buffering, even the heredity-mutation of these factors among units play the key role in quasi-continuation/continuation. To some extent, process optimization means well-coupling and coordination of relevant factors of the flow on the node of the process network. That is the better the coupling-coordinating is made, the closer the flow operation result goes to the expected objectives, the higher the efficiency of the process system would be.

Problems about the coupling-coordination (major space-time coordination) of every factors of the flow in process network structure at nodes (procedure, device, even workshop, etc.) and at connectors (pipe, roller, conveyor, railway, hot metal ladle, torpedo, steel ladle, etc.) should be attended and deeply studied on the flowing aspects:

1) Composition of the coupling factors and their character on different nodes in the process network structure.

2) Coupling degree of different factors in the flow at every node of the network

structure. It relates to the rationality of the set of procedure's functions, reliability, stability and efficiency of the set of procedures' relations.

3) Subordinations in coupling route of different factors inside the flow of the network structure. That means the coupling orientation on different nodes. In other words, what is the coupling principal axis? For example, the factor A couples to B or the factor B couples to A.

It can be seen that the problem of coupling of multi-factor flow is an important cut-in-point when we study the operation dynamics of mesoscopic (procedures, devices, workshops, etc.) and integrated process structure (whole manufacturing process, steel enterprises, etc.). At the same time, studying on the coupling-coordination-integration-evolution of multi-factor flow in the steel production process has not only theoretical value, but also practical value, and especially has influence on the optimization of time-space structure and increase of material and energy efficiency of the multi-factor flow. Thanks to the coupling-coordination of multi-factor flow, it must result the optimization of dissipation of process system. That will enhance the operation efficiency of material, energy, time and space of multi-factor flow in the manufacturing process running.

2. *Order* in steel manufacturing process.The *order* should be studied together with study on *flow* of the steel manufacturing process. The order aquals *program* of certain significance.

The order is a common used concept. According to the explanation in *Chinese Encyclopedia*, *order* is an arrangement that expresses *early or late* and *big or small* according to priority. Order also means the array in a queue according to some rule or regulation. In accordance with above features, there is a strict definition of partial ordering (i.e. order in general) that the *order* is regarded as a binary relation with transitivity, anti-symmetry and reflexivity.

In the process system, the order degree of two or more units with partial ordering relations can be compared, but any units without partial ordering relations can not be compared. Then the order and disorder are used for describing the state of events in the process system. *Order* means well-regulated correlation or conversion among events and their internal factors, i.e. there is partial ordered relation mathematically about units (sub-systems). *Disorder* means the mixed bag and rule-less combination among events and their internal factors. There is no rule in operation and conversion.

Order is made as a macro-recognizable sign. To one's mind only order phenomena can be identified on macrocosmic level. When we study something (involving macro-manufacturing process, even microcosmic crystal lattice and atoms), array order of every factor in the thing should be found, and the relations among some things would be defined according to this *array order*. To identify order or disder in a process system, either the structure order—to put events in sequence in the structure or the function order—to realize some one function after another must be considered generally. Concerning the *structure order*, we discuss three categories as follows.

1) Space order. It means the regularity of spatial distribution of the process system or its sub-systems (procedures, devices or even workshops). Any process system has its definite spatial distribution. The spatial distribution would not be disordered and random.

2) Time-characteristic order. It means the successively time course or the periodical change during the process operation. This determinate time course can be called time-characteristic order.

3) Spatio-temporal order. It means the cyclical variation of the process system on the four-dimensional coordinate. If we study the operation of some process system only from the aspect of time or from space, the feature of periodic change of the system is not obvious. But if we observe it combining with time and space together, the regular periodic change could be found. Annual rings of the plants and many kinds of waves are the example.

Following deep study, besides above three kinds of order, the function order (i.e. function structure) should also be studied. Some new functions of the process system should be included in the study on function structure.

So far as the static structure (frame structure) is concerned, the steel manufacturing process shows space ordering. The workshops, procedures, and devices should be arranged orderly in the space. So, the adjustment and optimization of the space ordering in the steel manufacturing process should be paid more attention to while the construction of a new plant and the technical revamping of an old plant.

Concerning the dynamic operation structure, manufacturing process possesses time-characteristic order. But in the practice, time-characteristic order has some non-stability and uncertainty. Under some circumstances, the manufacturing process in some steel plants has spatio-temporal order. The spatio-temporal order must be analyzed carefully for operation process especially in a universal steel plant with complex series-parallel structures.

Of course, the steel manufacturing process gets obvious *function order*. Steel manufacturing process often arranges and operates according to the function order as storage and preparation of raw materials and energy—reduction smelting—oxidation smelting—alloying and refining—solidification—reheating—deforming and phase transformation. The function order embodies both in the static structure and dynamic structure.

Generally, it is an important fundamental work for the technology progress and innovation to study and know the connotation, the essence and the rules of the *flow* and *order* of the steel manufacturing process.

The evolution of steel manufacturing process takes the routes which are from simplicity to complexity and then from complexity to simplicity and compactness.

This simplicity and compactness was resulted from further recognition of the complex process system. This deep understanding is based on the essence and rules. Actually, it is an embodiment of an progress of the orderly operation of multi-factor flow. This is the progress from lower to higher position and the distillation from practice to theory.

4.2 Steel Manufacturing Process—A Dissipative Process

There are large numbers of order phenomena appearing in nature and society. Order phenomena can be classified as two types. One is equilibrium structure formed by static order operation. For example, the crystal structure is a equilibrium static structure formed by arrangement of atoms following special rule. Another is nonequilibrium structure or dissipative structure (Xu, 2000) formed by dynamic order operation.

Dynamic orderly phenomena often appear in the nature, for example, the four seasons in every year. Summing up the dynamic orderly phenomena of different fields with inductive method, it can be seen that there is obvious difference between the dynamic order and the static order. It is important especially to investigate the difference according to the system evolution, including process system, and the mechanism in the system. The major difference between dynamic order and static order would be discussed below.

From the structure pattern, static order is motionless (*died*) and macro-invariant equilibrium structure. It is collocated by microcosmic particles (sub-systems) according to a specific rule. Dynamic order dissipative structure is "*live*" structure. In viewing this structure, on-line operation of every sub-system is incessantly moving in microcosmic/mesoscopic scale and the numerous micro-actions form the macrocosmic steady structure. As dissipative structure is a "*live*" structure, it has time-characteristic order feature and spatio-temporal order feature, besides spatial structure orderly.

From mechanism of formation and conditions for steadiness, static equilibrium structure needs a definite environment, such as fixed temperature, pressure and so on. If the parameters are not the same between the system and environment while structuring, they will exchange mass and energy with surroundings and then reach to the same as well as in constant, the process system forms equilibrium static structure. In case of equilibrium structure formed, the system becomes no any exchange with environment. Dynamic orderly structure is formed under the circumstance of far from equilibrium and with mass-energy interaction between the system and outside. As the dynamic order has formed, exchange between system and external is still needed. Under the opening condition as above, the *living* dynamic orderly structure has kept. If the exchange between system and outside environment is weakened or stopped, the formed dynamic orderly structure would be destroyed. It means that a *living* structure must be kept with metabolism, otherwise the dynamic orderly structure is going to be vanished.

From viewpoint of movement, static order structure doesn't change with time, every part of it keeps quiescent. The static order is expressed as collocation by a specific rule, and its spatial pattern is unchangeable with time. The dynamic orderly *living* structure means a definite form and rule macroscopically, but its subsystems is changing forever on the micro viewpoint.

Prigogine studied the conditions of forming dynamic-orderly structure——dissipative structure (Shen, et al, 1987) and he pointed out that in order to form a dynamic-orderly structure——dissipative structure of the system, including process system, the necessary conditions are following:

1. Open system. The second law of thermodynamics indicates that process spontaneously proceeds to the direction of entropy increase in an isolated system and result of evolution in isolated system must be equilibrium state of the maximum entropy. The process evolving spontaneously to equilibrium means developing to the direction of higher symmetries and lower ordering degree in the system and ultimately goes to completely disorder state. But the dynamic-orderly structure——dissipative structure, evolves to the direction of lower symmetry and higher ordering. Therefore, opening is the necessary condition for a system to evolve into ordering.

The entropy change of an open system can be decomposited into an entropy source term dS_i and an entropy flux term dS_e as

$$dS = dS_i + dS_e$$

where, dS_i is entropy change produced inside the system, i.e. entropy created during the process, without relation to environment; dS_e is change in entropy of the environment, more generally, for any reversible change involving energy and matter exchange between system and environment.

If there is no exchange between a system and environment, it is an isolated system and $dS_e = 0$. For an open system, dS_e does not equal to zero, dS_e could be positive or negative value and it depends on the exchange condition between system and environment. But dS_i must be positive or zero, $dS_i > 0$ for irreversible change inside the system, $dS_i = 0$ for reversible change which doesn't take place in the industrial production.

The total entropy change is equal $dS_i + dS_e$ in an open system, only if

$$dS_e < 0$$

and $$|dS_e| > dS_i$$

we have $$dS = dS_i + dS_e < 0$$

It can be seen that only for the open system there is sufficient exchange of matter and energy with outside environment, and the absolute value of entropy flow can be more than the entropy production occurred by spontaneous process in the system, we enable the whole system to attain a state of lower entropy and maintain an ordered configuration.

2. Far from equilibrium. Equilibrium is the most uniform disorder state existed steadily after experiencing long time in an isolated system. If the system deviates from equilibrium, its state changes along a line directed by the smallest entropy increment principle developed by Prigogine. In the linear region of nonequilibrium, i.e. the state equilibrium nearby, the final evolutional result of system reaches the state of smallest entropy production——nonequilibrium stationary state. And if the environment condition will be close to the isolated system, this nonequilibrium will become an equilibrium state smoothly. But dosed system can't construct order structure never.

Only if the system is far from equilibrium and each of irreversible forces and flows are in nonlinear region, the system could evolve to an order structure. Far from equilibrium is the necessary condition for forming order structure of the system(Yin, 1997). When the system is far from equilibrium forced by environment condition, the more the opening degree is, the stronger the influence from environment on system has, and the system is driven from near equilibrium region to a far from equilibrium non-linear region and the order structure formed. Otherwise even the system opens, the order state can not be reached.

Actually, above two conditions which make system become dissipative structure are related to the entropy value and near or far from equilibrium separately.

3. Non-linear interaction. There are interactions among the sub-systems(devices or procedures) of the process system. These interactions are non-linear commonly. They don't obey the superposition theorem. So, the new property would emerge during formation of a system, including process system, through non-linear interactions of these sub-systems.

The non-linear interactions are internal cause of forming order structure system. To analyze the interaction mechanism is the most important work for building an evolution model of the system. If dissipative structure occurs, there must be non linear interaction in the system and the evolution equation is non-linear. Anyway some approximately simplifying treatment is usually needed to formulate and verify the model, but while simplifying, the linear differential equation can not be used for expressing the system evolution.

4. Fluctuations. Property fluctuations (e.g. fluctuations of energy) ever appear in equilibrium state. Scale of fluctuations is inversely proportional to the square root of particle number. For the system composed of great numbers of particles, the fluctuations can be ignored. When the system deviates from equilibrium, fluctuations can make the system return to equilibrium again. Fluctuations are the destroying factor on equilibrium state and also the maintaining factor for stable equilibrium state of the system in the meantime. So, it can be said that fluctuations is an initial driven power for the system to evolve from initial stationary state to the dissipative structure. If there are no fluctuations, a system can not dis-

engage spontaneously from initial unstable stationary state and never makes a new dynamic-orderly dissipative structure. As discussed problems in the dissipative structure theory take regard of the system composed of sub-systems in very large numbers, the internal fluctuations induced deviations of state variables from their steady values exist in deed. The condition of forming dissipative structure is always satisfied. So the fluctuations wouldn't be mentioned in the practice, though they play an important role of transmission from unorder to order.

The above four conditions are interrelated, because:

Firstly, if a system does not open to outside, the system can not exchange mass, energy and information with environment and can not be far from equilibrium state. Any non-linear interaction among sub-systems of the system can not deviate the state from equilibrium, and the fluctuations only make system keeping equilibrium stably but not directing to order state.

Secondly, if the system is not far from equilibrium, the system is still near by equilibrium and the exchange with environment only takes a small disturbance. The system would not have essential change even it opens to outside.

Thirdly, non-linear interactions (e.g. between batch operation and continuous or quasi-continuous operation) is the fundamentals of qualitative change in the system because the system can not become a dissipative structure based on the linear interactions and followed superposition theorem.

Fourthly, there are a great number of fluctuations generally in the system composed of many sub-systems. Fluctuations are the basis for transmitting the system from a stationary state solution to another, and making it qualitative conversion.

It should be realized that steel manufacturing process is a large process system which pursues dynamic order and continuous operation. The issue of the operation dynamics of steel manufacturing process is to study the fluctuations, nonequilibrium and non-linear relations among sub-systems, especially the influence of the order parameters exited in the coordination relations, getting integration of an opening, far from equilibrium and irreversible system. So, the process would be directed to dynamic ordering because of its self-organizing action in some degree and of different types. In this kind of open system, the fluctuations of process in procedures and devices, the irreversibility and far from equilibrium state, especially the multi-factor mass flow in the operation process, have been automatically coupling together along the time axis due to nonlinear relations among procedures. It can be proved that self-organization of multi-factor mass flow can only result by non-linear relations among procedures in the operation process, i.e. the inner entropy increment inside system makes the open system developing to the direction of dynamic-ordering.

From above definition and description of the dissipative structure we know that the steel manufacturing process is a dynamic order process structure. In this structure, multi-factor flow (mass flow) operates with a specific *program* in the process network composed of procedures and devices. The operation way of multi-factor flow in the procedures and devices possesses non-linear character since it may be quasi-continuous/continuous or may be batch. For every procedure and device, the "intensity", "rate" and "coherency" of the multi-factor mass flow always vary in fluctuations. The different type of matter, energy and information exchanges between the whole process system and surroundings makes steel manufacturing process nonequilibrium. So it can be considered that the steel manufacturing process is characterized as dissipative structure defined by I. Prigogine. For studying this kind of industrial process production with dissipative structure, we should start with the function structure and then extend to spatial structure, time-characteristic structure and spatial-temporal structure. After deeply understanding the whole steel manufacturing process, we can make further optimization and adjustment of the structure and function of sub-systems and their mutual relations based on the entire optimization of process.

4.3 Essence of Steel Manufacturing Process

Steel manufacturing process consists of such procedures, as the storage and transportation of raw materials and energy, iron ore preparation(including sintering and palletizing), coking, ironmaking, steelmaking, secondary refining, solidification, reheating and rolling, deep-processing. They are either batch operation or quasi-continuous production. It can be seen that manufacture of steel is a process system composed of many procedures and devices with different functions. We should study what mechanism and what coordinating way should be used over these different functional procedures and devices to realize the spatial structure, time-characteristic structure and even function structure on the level of whole manufacturing process. Steel manufacturing process is a multi-factor, multi-level and multi-target engineering system of integrating mass flow control, energy flow control and information flow control. Essentially, the fundamentals of the function structure of steel production process are combination, penetration, synergy and management of matter state transformation, matter property controll and mass flow controll with time, temperature and space. Actually, steel manufacturing process is a multi-factor system of mass flow control, which can be summarized as:

$$S_{\mathrm{mf}} = \sum_{j} \int\int\int (P_j + A_j - B_j)\mathrm{d}Q\mathrm{d}T\mathrm{d}t + C_j$$

where S_{mf} is the multi-factor mass flow system, P_j is the mass flow (mainly ferruginous mass flow), such as iron ore, hot metal, molten steel, slabs/billets, rolling pieces, A_j is the energy and additives charged to the production process, B_j is the emission and waste produced in the mass flow, Q is the weight, flux and concentration of mass flow, T is the temperature of mass flow in the process, t is the time experienced by the process, C_j is the intermittent factors occurred in the process, j is an unit procedure in the production process or the number of procedure order.

4.3.1 *Basic parameters and derivative parameters for steel manufacturing process*

For describing the entire behavior of the steel manufacturing process, the new concepts different from former familiar microcosmic description are needed. Certain new parameters for describing the dynamic-orderly state of whole steel manufacturing process must be applied instead of the old parameters for procedures and devices.

Steel manufacturing process includes the various processes of chemical metallurgy, solidification and physical metallurgical transformation. To penetrate and coordinate the different functions of successive procedures, the more generalized parameters need to be found for describing and controlling the whole steel manufacturing process.

Basic parameters are independent variables. These parameters must satisfy following conditions:

1. Basic parameters can run-through every procedure and device in the steel manufacturing process.

2. Basic parameters do present quantifiable and continuously differentiable character in whole process.

3. Basic parameters can be expressed with one and the same form and same unit in whole steel manufacturing process.

Analyzing the different procedures, it can be seen that three hinds of parameters, i.e. quantity index of matter (weight, flow rate or density), temperature and time are the basic parameters and have influential on numrous changes, such as reaction change, state change, shape change, composition change and property change in whole steel manufacturing process. And the quality, sort, grade and aggregate of the ferruginous mass flow of steel manufacturing process are all the derivative parameters induced by above basic parameters. Fig.4.1 shows the relationship between basic parameters and derivative parameters of mass flow in steel manufacturing process system. Finally, the collection of all units and the collection of units' relations would influence the management and investment effect as output, consumption, cost and efficiency, as well as the environment burden. These influences and the relationship among above parameters are shown in Fig. 4.1. Some indexes at the bottom are the targets or direction of production management of the steel enterprise.

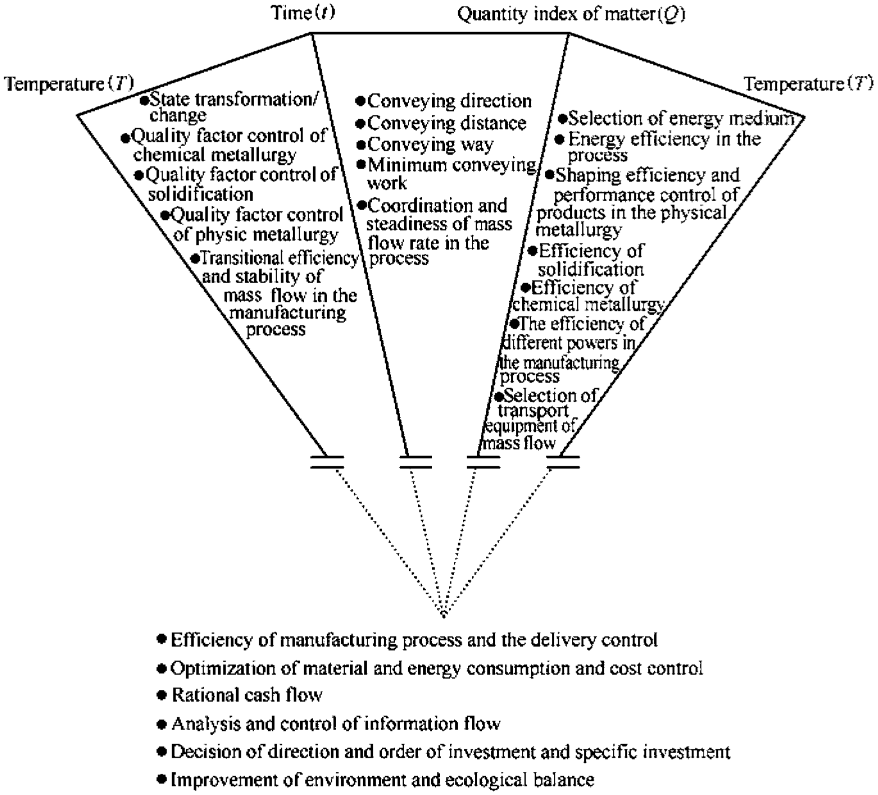


Fig. 4.1 Relationship analysis among basic parameters and derivative parameters in the system of steel manufacturing process

The cybernetic engineering of multi-factor mass flow of steel production process aims at realizing connection, matching, continuation and stability of whole steel manufacturing process through comprehensively governing the basic parameters of mass flow (quantity index of matter, time, temperature, etc.).

4.3.2 *Operation mode of steel manufacturing process system*

Since 1970 s, because fully continuous casting technology was used in steel plants, the operating and controlling of mass flow, energy flow and information flow in the steel production process had been greatly improved. The quasi-continuous operation got realized gradually, while some parts operated even continuously.

Analyzing the steel manufacturing process, to realize quasi-continuous / continuous control means that systematically evolve toward a coherent continuous system composed of “rigid units” and “flexible units”. So the modern steel plant could be modeled as the coherent manufacturing process system composed of "rigid units" and "flexible units". That is

$$\Sigma_v = \{F, R\}$$

$$F = f(\Sigma Fl,\ \Sigma Ri)$$

where, Σ_v is the coherent process system,

F is the set of procedure's functions,

R is the set of procedures' relations of process system,

$\Sigma\, Fl$ is the set of functions of "flexible units",

$\Sigma\, Ri$ is the set of functions of "rigid units".

In the steel manufacturing process, the above "rigid units" or "flexible units" are only the relatively abstract in different meaning and functions. In practical operation, the basic parameters of "rigid units" possess some *elasticity* (these basic parameters may undulate in some range). "Flexible units" do not infinitely flexible as there is some *limit* for the flexible operation. Because the "elasticity value" of "rigid units" in operation and the limit of flexible operation of "flexible units" are various, the relations of linking-up and matching of the successive procedures are quite different and with non-linear nature. Consequently, the practical operation mode of steel manufacturing process has been a syntonous action of different kinds of elastic chains/semi-elastic chains.

The elastic undulation of "rigid units" and the flexible operating limit of "flexible units" as well as the combinating relations of parameters expressed these performances characterize the coherence of whole process. This coherent character has originated from the fluctuations, non-linear interaction, opening and nonequilibrium of the process. The change of coherency would result the change of coherent dissipation value in the process system (dissipative structure). It ultimately influences on the material and energy consumption, cost, quality, productive efficiency, investment as well as the environmentfriendliness, etc.

4.4 Metallurgical Process Engineering v.s. Analysis and Integration of Steel Manufacturing Process

For a long time, the theory of metallurgy has emphasized the discipline branches based on analytic research of process, consideration of the general correlation entirely and the integration/continuation of system is not enough. So, the effectiveness of using high-techs, such as process information system, to change the traditional industries has been lessened in some degree. Therefore, problems of engineering science over present disciplines, i.e. Metallurgical Process Engineering, as a general theory of manufacture, should be studied and searched beyond the 21st century. The investigation of the essence, structure, function and analysis-integration of the manufacturing process becomes very important in view of science or economy.

4.4.1 *Evolution and structure analysis of steel manufacturing process*

After the Second World War, especially since the 1970s, the steel manufacturing process had been changed from batch operation to quasi-continuous/continuous step by step. The process technology had become quasi-continuation, continuation and compactness, and then led the product mix to specialization. That was the direction of structure adjustment of steel plants mainly. Meanwhile, instead of the simple way to enlarge production scale and to divide or to superimpose the procedures, it advanced towards the function analysis not only, but also the comprehensive integration and the process structure optimization in accord with it. Fig. 4.2 is the schematic diagram of the evolution of BF-BOF-Hot rolling process.

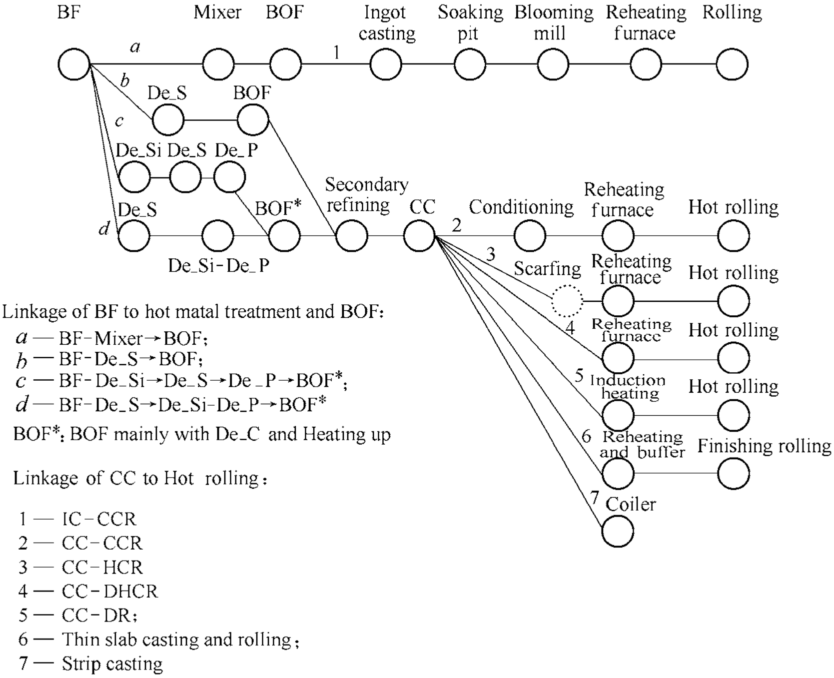


Fig. 4.2 Evolution of steel manufacturing process

Steel manufacturing process is a system consisting of many procedures of different functions and performances. As for a certain procedure or device in the process, it not only receives the "genetic factors" given by the previous procedures, but also makes "mutation" of the relevant factors in the multi-factor mass flow of the current procedure; in addition, they must adjust themselves to environmental parameters for coordination with them. Those are the keynote content and the evolution route of procedures' functions in the steel manufacturing process. The evolution of the manufacturing process for one century or more shows that the fundamentals of the entire manufacture process are the improvement in functions and performances of the procedures or the devices, i.e. it leads to optimization of the set of procedures' functions in the manufacturing process system. Optimization of the set of one certain procedure's functions will often change the functions of upstream and downstream procedures and then originates the analysis-optimization of the set of procedures' functions. The change of the relations between the neighboring procedures even among much more procedures will be brought inevitably at the same time, so the coordination-optimization of the set of procedures' relations in the whole process system should be formed further. Based on analysis-optimization of procedures' functions and coordination-optimization of procedures' relations, eliminating old procedure/device and forming new one in the process, and then the reconstruction optimization of the set of procedures in the process would be promoted. Thus some old procedures were eliminated by the reconstruction optimization of the set of procedures of the process, because they are not adapted to the redevices of analysis-optimization of procedures' functions and coordination-optimization of relationships among procedures. While some new procedures or devices emerge as the breakthrough in technology, then the integration-reconstruction of the set of procedures/devices in the process system has been realized.

From the evolution of BF—BOF—hot rolling process route (Fig.4.2), it can be found obviously that the steel manufacturing process of modernization should not be simplistic packing, superimposing and piecing together of various units, but realize their specific functions by the reasonable, dynamic orderly process structure. Therefore, the analysis-integration of different unit procedures/devices should be guided by the dynamic optimization of the process entirely. That is:

1. To select, distribute, coordinate the optimum functions of every procedure or device, and then to establish the set of procedures' functions with analysis-optimization.

2. To establish, distribute, coordinate the relationships among many procedures or devices, and then to build the collection of relations among procedures with coordination-optimization.

3. To organize the new collection of processing procedures for new process based on analysis-optimization of the set of procedure's functions and coordination-optimization of the set of procedures' relations, that is to build the reconstruction-optimization of the procedures in the process system.

The process structure may be referred to the collection of compositional procedures with different functions and the collection of relationships among various procedures in the manufacturing process under regular conditions. The connotation of process structure is not the simple accumulation and quantitative proportion of various procedures, but mainly the ability for adaptation/coordination of the set of procedures' functions and the set of procedures' relations, the dynamic control of the process operation and the internal activity of the manufacturing process.

Comprehensive study on the analysis-integration of the steel manufacturing process is to find the optimum structure with optimum function of the process system led by the requirements of the target groups of the manufacturing process (Yin, 2000). As shown in Fig. 4.3, the basic content involves the analysis-optimization of the sets of procedures' functions, including unit functions, the coordination-optimization of the set of procedures' relations, including neighboring and distant, and the reconstructurion optimization of the set of procedures in the process.

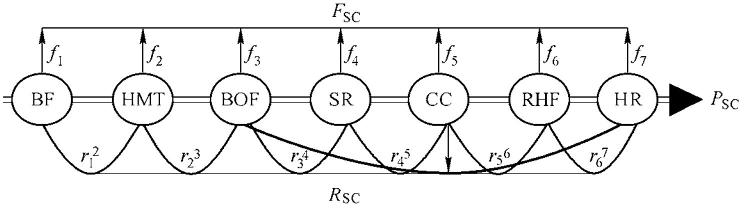


Fig. 4.3 Schematic of concept of analysis-integration of steel manufacturing process

BF—blast furnace; HMT—hot metal pretreatment;
BOF—basic oxygen furnace; SR—secondary refining;
CC—continuous casting; RHF—reheating furnace;
HR—hot rolling; F_{SC}—set of procedures' functions; R_{SC}—set of procedures' relations;
P_{SC}—set of procedures in the process system; f_i—set of functions of unit procedure;
r_i^j —set of relations between procedures

Based on the above, formulating the physical models reflected the process structure and nature of functions, the mathematical modeling of process operation and its control would be established. Its system block diagram is shown as Fig. 4.4.

4.4.2 *Analysis-optimization of the set of procedures' functions*

By procedure's functions we refer to the behaviors of the procedure in the manufacturing process and its major role, especially the mutation action as transformation, conversion, etc. In the steel manufacturing process, functions of many procedures are usually multivariate, while a certain function can be realized in several procedures. Thus, problems on realized degree, optimum coupling, mutual supplement, mutual replacement and comprehensive integration of these functions under different outside conditions have arisen. For example, the evolution of procedure's functions of the oxygen converter along with the technological progress is obviously, the original about 10 functions were lessened to 2~3 main. Functions of desulfurization, dephosphorization and desilication are transferred to hot metal pretreatment, while degassing, alloying, nonmetallic inclusion modification and melt refining are mainly undertaken by the procedure of secondary metallurgy. Analysis-optimization example of procedure's functions of BOF steelmaking is shown as Table 4.1.

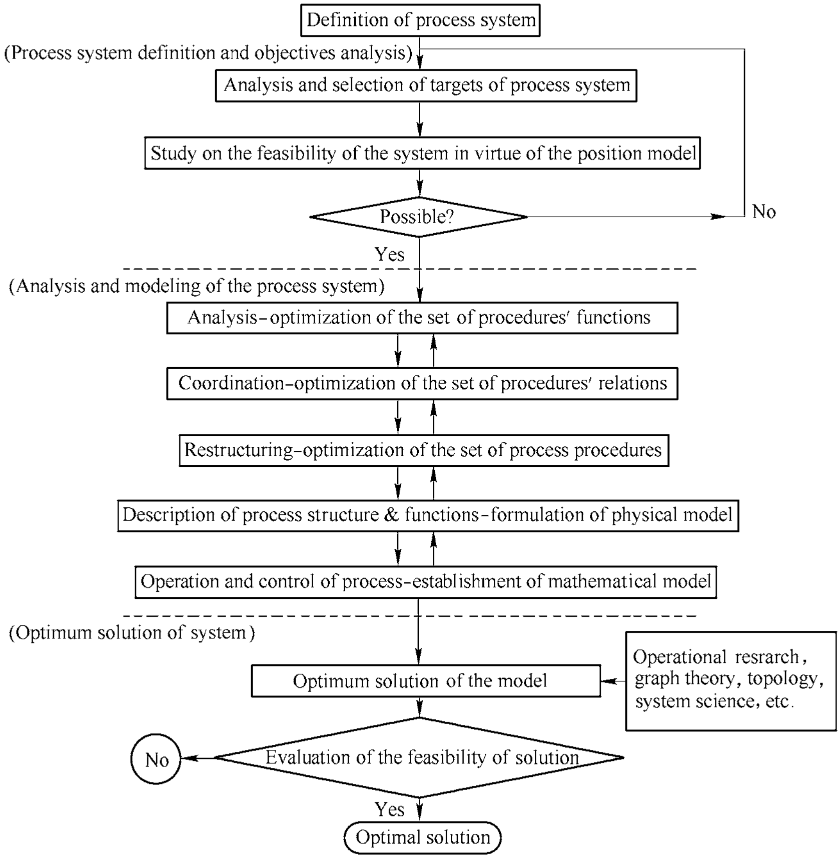


Fig. 4.4 The block diagram of analysis-integration model of steel manufacturing process

Table 4.1 Function analysis of the procedures in steelmaking process

Refining function	Hot metal pretreatment	BOF	Secondary refining
Desiliconization	⊙ ←	○	
Desulphurization	⊙ ←	○ →	◎
Dephosphorization	⊙ ←	◎	

Continues Table 4.1

Refining function	Hot metal pretreatment	BOF	Secondary refining
Decarburization	◎ ←	⊙	- - - → ⊙(*)
Heating-up		⊙	→ ◎
Degassing		◎	→ ⊙
Inclusion modification		○	→ ⊙
Deoxidation		◎	→ ⊙
Alloying		◎	→ ⊙
Purification	⊙ ←	◎	→ ⊙

⊙ Main procedure for realizing the function; ◎ Next important procedure for realizing the function; ○ Degenerated function in this procedure; (*) For IF steel, vacuum decarburization is more important.

Attention should be paid to the collections of procedure's functions. They should be divided at least into the set of functions of unit procedure and the set of procedures, functions of process system (or of process section). The functions of BOF steelmaking have given above as an example of collection of functions of unit procedure. However, the set of procedures' functions of process system is acquired by analysis-integration of process. The way to do it involves the analysis on many procedures of different functions firstly, and then the selection, distribution or replacement of realizing mode and a share of one or more functions in different procedures are arranged. Finally, the collection of procedures' functions of system through analysis-optimization under the guidance of the principle of dynamic programming entirely is formed. For example, the sulfur removal can be proceeded in such procedures as ore sintering, blast furnace (BF), hot metal pretreatment, basic oxygen furnace (BOF), electric arc furnace (EAF), secondary metallurgy etc. But through the technical comparison and economic evaluation all the oxidation procedures (BOF, EAF, etc.) should not be used for desulfurization, while the procedures as hot metal pretreatment, blast furnace, ore sintering. can remove sulfur reasonably. However, the special desulfurization treatment should be done in secondary metallurgy for control of the shape and property of sulfide inclusions in steel. That is the significance and the value of the analysis-optimization for the set of procedure's functions of process system.

The set of functions of unit procedure is referred to conversion, transformation, transport and storage of materials and energy charged on this one procedure, and the special behavior and action required in realization of the given targets of it. However, the optimized matching and the reasonable linkage with other procedures should be also considered. While let the reasonable matching and linkage of various state parameters of the conversion, transformation, transport and storage of materials and energy among units in the process being clear more effectively, the coordination of time-sequence factors and a correct space layout must be solved simultaneously.

If the set of procedure's functions in the steel manufacturing process is expressed by F, while a function of a certain unit procedure in the process system is expressed by f_{ij}, then an expression is obtained as follows:

$$F=\{f_{ij}\}$$

where F is the set of procedure's functions in the manufacturing process system; f_{ij} is the function "i" possessed by certain procedure "j"; i is or the number of function, $i=1,\cdots,m$; j is the number of unit procedure, $j=1,\cdots,n$.

So, the any one set of procedure's functions $\{f_{ij}\}$ can be expressed to form with equal dimensions mathematically. If one procedure doesn't possess one certain or more functions, then this function can be represented in matrix with 0. Therefore, the set of procedure's functions of system F in the steel manufacturing process can be expressed as

$$F=|f_{ij}|=\begin{vmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ f_{m1} & f_{m2} & \cdots & f_{mn} \end{vmatrix}$$

One certain or more functions were distributed in several procedures of process system, the optimum of such distribution would be characterized by such basic parameters running through whole process as the matter quantity index (includes mass, flux, concentration), temperature and time as:

$$f_{ij}=f(W(\Sigma w_k),T(\Sigma T_k),g(t))$$
$$C_{f,ij}=f'(W(\Sigma w_k),T(\Sigma T_k),g(t))$$

where, F is the set of procedure's functions in the process system; f_{ij} is the function "i" possessed by certain procedure "j"; $C_{f,ij}$ is the distributive share (0~1) of the function "i" in the procedure "j"; i is the function number; j is the number of unit procedure in the manufacturing process; W is the matter quantity index (includes mass, flux, concentration, etc.); w_k is the relevant factors influenced on matter quantity index; T is the temperature of the flow of metals in the process; T_k is the relevant factors influenced on temperature of metals; $g(t)$ is the time-characteristic parameters and their expression form.

4.4.3 *Coordination-optimization for the set of procedures' relations in steel manufacturing process*

The collection of relations among procedures in the steel manufacturing process should consider not only the linkage and matching of time-sequence factor, space-location factor, energy-temperature factor, property-feature factor, as well as of functions and equipment capacities (tonnage) of procedures (include neighboring and distant), but also the rationality of transportation ways (the transport facilities, transport status, and the layout of transport routes). That means the "minimization" of attenuation of mass flow of metals, of temperature undulation of the mass flow, of waste emission in process, of processing time and of manufacture inventory; as well as the product quality and performance satisfying to use. It would be realized by coordination-optimization for the set of procedures' relations.

Sometimes, one certain procedure(e.g. continuous casting) plays the keynote role in the evolution of the manufacturing process, after which the neighboring procedures can develop forward then. The practices from 1970 s had proved that replacement of ingot teeming—blooming procedure by continuous casting procedure in the steel manufacturing process of BF—BOF route had promoted the evolution of the collection of relations among the procedures in whole production process. However, as the pursuits in continuation, compactness, rhythm and synergy were brought about, the connotation of the set of the procedures' relations was more and more abundant. Contents on this aspect will be further discussed in the Chapter 7 "Operating dynamics in the production process of steel plant".

Analysis-optimization of the set of procedures' functions is the basis of coordination-optimization of the set of procedures' relations. From viewpoint of stationary, procedure's functions can be summed up into "capacity" function (e.g. output, productivity, transport power, etc.) and "intensity" function (e.g. quality, property of products and semi-products). Therefore, the relationships among procedures are always summarized as the connection and linkage of "capacity" and matching of "intensity". The relevant procedures in the steel manufacturing process should take the relations of time-sequence characteristics during dynamic operation (as the layout was fixed, so the space-location relations were relatively fixed as well). A series of relationships in short range or long range and relations among procedures may be established through analysis-optimization of the set of the procedure's functions and coordination-optimization of the set of procedures' relations. These linkage-matching relations include aspects like the matter amount, mass flux, concentration, temperature, energy, time, space, metal structure, property, quality, etc. It is a series of "generalized loop engineering" (buffer engineering) practically, whose reliability and flexibility may be presented for appraisal in its entirety of manufacturing process. Generally, abatement of the buffer value is the developing trend. For example, under the condition of normal production and operation, the buffer value of process route: blast furnace—mixer—open hearth—teeming—ingot storage—soaking pit—blooming—intermediate billet stocking—reheating—hot rolling mill is very large. On the other hand, the buffer value of the route: blast furnace — torpedo — hot metal pretreatment — converter — secondary metallurgy—thin slab casting—strip rolling is obviously smaller. The technological significance and economical value are self-evident.

The relationships among various procedures in manufacturing process may be characterized by the mathematical concept of "set".

Let X represents the set of procedures X_i in the BF-BOF process steel plant. The relationships involve relations of "capacity", "intensity" and "time-characteristic", meanwhile, these relations even include the collection of engineering relationships as heredity, variation, pregnancy (especially at long range) among procedures and transportation in process system at the same time. According to system theory, if one procedure $X_i \in X$ has interacted with the other procedure $X_o \in X$ of the system, the interaction relationship is expressed by r, then:

$$X_i r X_o, \quad X_o r X_i$$

or

$$X_o = r(X_i),\ X_i = r(X_o)$$

where X is the set of procedures in the process; i, o is index number of procedure; r is the interaction relationship among procedures.

In fact, the process running is supported by the mutual coordination of various generalized buffer among unit procedures, so the set of procedures' relations must contain the generalized buffer relations among processing procedures. Its expression is the relationships of collection of buffers among the procedures.

As the production process system of different types of BF-BOF steel plants is the integration of much more procedures with specific relationships among each other, and then the set of procedures' relations in whole process system has the expression formula as follows:

$$R = \{r \mid r = \langle X_i, X_o \rangle\} \quad i,o = 1,\dots,n$$

where R is the set of procedures' relations; r is the interaction relationship among procedures; i,o is index number of procedure, $1,\dots,n$.

If the above-mentioned set of procedures' relations are expressed by matrix, then:

$$R = |r_{ij}| = \begin{vmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{vmatrix}$$

The set of unit procedures' relations are mainly embodied with the collection of relations among neighboring procedures, sometimes those of longer range, then:

$$R = \{r_{ij}|_{i=1\sim m,\, j=1\sim n}\}$$

As the connotation and formulation of unit procedures' relations are very complicated, it seems that it is convenient for description of the set of unit procedures' relations with the basic parameters (W, T, and t) of the steel manufacturing process, then:

$$r_{ij} = \varphi(W(\Sigma w_k), T(\Sigma T_k), g(t))$$

4.4.4 *Reconstruction-optimization of set of procedures in steel manufacturing process*

In the past 150 years, the tech-progresses of the steel industry can be summed up to the following indications:

1. A series of new technologies and facilities developed with innovation, such as oxygen converter, continuous caster, hot metal pretreatment, secondary refining, controlled rolling and controlled cooling (TMCP), thinslab casting-

rolling, strip casting, ore direct reduction, smelting reduction and so on.

2. A series of technologies and facilities were improved in the evolution, such as ultra-large blast furnace, UHP-EAF, large sintering machine, tandem hot rolling mill, seamless tube mill and so on.

3. A series of technologies and facilities disappeared and were replaced in the couse of competition, such as ore sintering pot, air blown converter, open hearth, hot metal mixer, ingot casting, blooming mill, three-high reversing mill, pack-rolling mill, small electric arc furnace with reduction period, and so on.

The above mentioned tech-progresses affected the structure of the steel manufacturing process and embodied the thought on the analysis-optimization of the set of procedure's functions, the coordination-optimization of set of procedures' relations, and consequently the reconstruction-optimization of set of procedures. In general, the basic parameters of the steel manufacturing process are converged into the optimum critical-value gradually, that results some technologies to be eliminated from production line or some functions to be replaced. Finally, the structure change entirely of the steel manufacturing process is brought about, i.e. the restructuring-optimization of set of procedures has arisen.

Reconstruction-optimization of procedures in the steel manufacturing process may be characterized by mathematical concept of set also. Presuming process system X is collected with some recognizable and independent procedures X_i with special functions, then:

$$X=\{X_i \in X \mid _{i=1\sim m}\}$$

Due to process system consists of the procedures of "rigid component" and "flexible component", so it could be expressed as,

$$X=\{(X_{\mathrm{Fl}}, X_{\mathrm{Ri}}) \mid _{X_{\mathrm{Fl}} \in X,\ X_{\mathrm{Ri}} \in X}\}$$

The above discussions on the set of procedure's functions, the set of procedures' relations and the set of processing procedures intend to get statement of physical-mathematical model of system function and system structure of steel manufacturing process. Modeling of system is effective to understand the system function, system structure and cross-relevance among different functions furtherly.

The evolution and development of steel industry tell us that the operation modes of complex manufacturing process are usually with the competitive nature. The results of competition show that only one mode, or several modes existed stably under certain external conditions. As a method to describe process system characterized by dissipative structure, the conception of modality has great advantages. Compared with description of micro-structure, we need not to know about nemerous coordinates for degree of freedom of all particles (atoms or molecules), just only several parameters is needed for mode configuration. We should search step by step to describe the macroscopic orderly state with several parameters (or degree of freedom) in the steel manufacturing process.

4.4.5 *Combination of process science and information technology*

Steel industry is a kind of process manufacturing. Application of information technology in the steel manufacturing process is mainly embodied with the formulation or reflection on process, the control of process and devices and feed back from them, as well as the evaluation and optimization of process system. A control strategy of process system will be gotten through improvement gradually.

The control strategy of process system is mainly used for regulation and optimization of the most important parameters of the manufacturing process. Through that the specific functions of various procedures are realized steadily. Along with the multi-factor mass flow runs among procedures orderly under the direction of objective state, the control strategy will present requirements like heredity, conjunction, variation, transmission, feedback, etc.. Certainly, the control strategy of the process system should both run through every procedure and make a series of optimum objectives realized at respective procedure.

Steel manufacturing processes are characterized by operation in series connection, and integrated production. The information is the linkup to dynamically regulate functional factors of manufacturing process, as well as one of important basis of integration-optimization of the process. By analysis of the information flow of steel manufacturing process, the input set (*I*) of each procedure in the process becomes related output set (*O*) after the interaction in various procedure (X_i). The transformation from input set to output set is controlled by the set of procedure's functions (*F*) and procedures' relations (*R*). The corresponding information subsystem will turn up in every level of this process under the regulation of the set of control strategy (*C*), and then it is integrated to the decision-making center to form the corresponding information system of manufacturing process(Fig. 4.5).

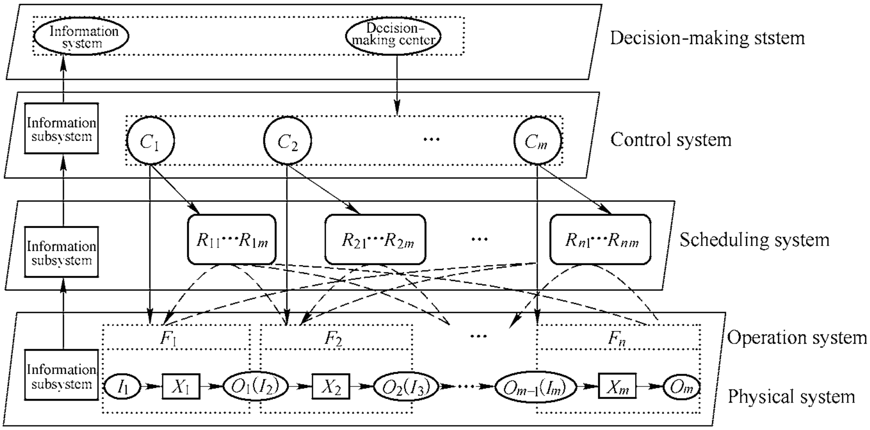


Fig. 4.5 Schematic of the relationship between steel manufacturing process structure and information system

In sum, combination of process science with information technology will be helpful to describe physical model of process system excellently, furthermore contributing to the effectiveness and the reliability of mathematical model.

References

Kavanagh L, Carson C, Dasgupta B, et al (1998) Steel industry technology roadmap. AIME、 Han Jingtao, Wang Fuming et al tromstred, Science Press, Beijing

National Research Council U.S.A, (1990) Translated by Beijing Institute of Aeronautical Materials et al. Materials Science and Engineering for the 1990 s. Aviation Industrial Press, Beijing, (in Chinese)

Shen X F, Hu G, Jiang L (1987) Dissipative structure. Shanghai People's Publishing House, Shanghai, 90-97 (in Chinese)

Xu G Z (2000) Systems science. Shanghai Scientific & Technological Education Publishing House, Shanghai, 26, 185-192 (in Chinese)

Yin R Y (1997) The multi-dimensional mass-flow control system of steel plant process, Acta Metallurgica Sinica 33(1): 29-38 (in Chinese)

Yin R Y (2000) Analysis and integration of steel manufacturing process. Acta Metallurgica Sinica 36(10):1077-1084 (in Chinese)

Chapter 5
Multi-Factor Mass Flow Control for Metallurgical Manufacturing Process

The basic elements of dynamic–orderly manufacturing processes are "flow," "process network" and "program." "Flow" is the principal material entity of the manufacturing process's operations. "Process network" consists of nodes and connectors and constitutes the carrier and the time/space limits of flow operations. And "program" may be seen as the reflection, in the form of information, of the operational characteristics of the "flow."

For comprehensive regulation and control of the steel manufacturing process it requires that we thoroughly understand the operational features of the "flow," extract physical models that reflect the essence of its operations and form a body of information that is effective and useful for conducting dynamic and effective regulation and control of that process.

The process of old steel plants consisted of many batch operations. So the manufacturing process was frequently intermittent with more semi-product stock and high energy consumption. It induced the product mix be universally and made the general layout complex and jumbled. Due to some traditional concept fettering and some technical condition restricting, these batch operations have blocked production efficiency and also have occupied plenty capital. It increased cost, consumed resource and worsen environment, and became "technical bottleneck" which blocks total rationalization of process. Meantime, the connection and coordination among main processes with batch operation's mode has put forward complex requirements which are not clearly rational. As the above problems that the batch operation of ingot casting and breakdown in steel plant process related to limitations and uneconomic, many important improvements of metallurgical technology developed to increase continuation and compactness of process worldwide in recent 30 years.

Based on "entirety" topic of continuation/quasi-continuation and compactness

R. Yin, *Metallurgical Process Engineering*

in steel plant process, some technologies for different unit procedures and unit devices have been developed, for example, caster equipment and 100% continuous casting regime, campaign elongation of BF, BOF, reheating furnace, ladle, etc. And the further studies on the concept and the theory of matter state transformation, matter property control and related multi-factor mass flow control for effectively connecting, matching, coordinating and running through in whole steel plant process had carried out. A new technical system of optimization in entirety, continuation/quasi-continuation and compactness has been established. This is a topic of a very complicated problem of advance manufacturing technology——metallurgical process engineering which also intersected with mechano-electronic engineering, thermal power engineering and information technique.

5.1 Some Fundamentals of Multi-Factor Mass Flow Control

A series of characteristics which are on aspect of the physical essence for metallurgical manufacturing process were discussed in Chapter 4. It is indicated that, on viewpoint of physics, metallurgical manufacturing process is a multi-factor *flow*. The flow is dynamically and orderly operated according to some *program*, completes every physical and chemical conversion/transformation and realizes muti-objective optimization within a complex *process network* which is consisted of procedures with different functions and linkers among procedures.

5.1.1 *Concept and elements of manufacturing process*

As described above on physical manufacturing process, it may deduce that process operation has three elements, which are *process network*, *flow* and *program*. Their definitions in metallurgical manufacturing process are as following:

1. Process network. *Process network* is a matter-energy, time-space structure to integrate "flow of resource", "node" and "connector" in the opening process system. This structure requires static rationalization for the space structure (e.g. the general layout of plant etc.). And especially the dynamic ordering, continuity and compactness should be represented in the flow of resource operating.

The "flow of resource" contains raw material flow, energy flow, and related information flow at inlet, also mass flow, energy flow and related information flow in process running, as well as product flow, by-product flow, any other emission flow with information flow out (Fig. 5.1).

These "nodes" mean procedures and devices with different functions in the process network, such as BF, BOF, etc. These "connector" are the connecting measure, mode and facilities among nodes, such as pipe, roll conveyer, railway, crane, vehicle, steel ladle, iron ladle, etc. Therefore, process network also may be regarded as the optimized configuration and the space-time boundary among the nodes and the connectors.

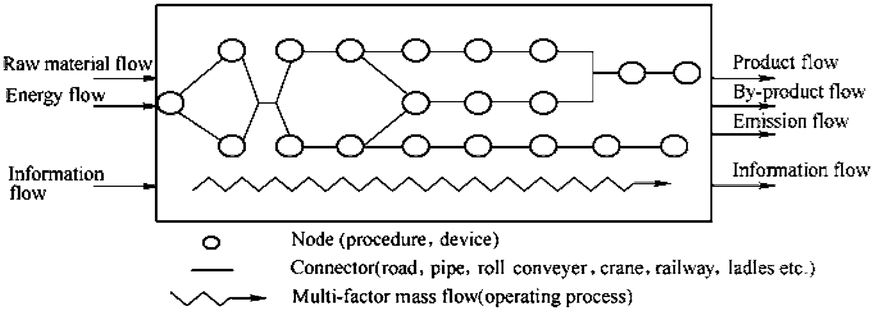


Fig. 5.1 Sketch of conceptions and elements in manufacturing process

If the process network becomes irrational, the behavior of flow should operate as disorder of the time-characteristic factors or present chaos state always, moreover, it brings the information of operating and controlling program of process passively and confusedly. In this way, it should increase the dissipation of mass flow and energy flow.

As a whole, dynamic order for the metallurgical manufacturing process not only depends on each factor, such as the procedure/device, respectively operating orderly and relative steady, but also is influenced, restricted or promoted by the process network, such as flowchart, layout, etc.

2. Flow. *Flow* is generally refer to running characteristics of operated different *resources* including matter, energy and information in the opening process system, i.e. the variation of its quantity, phase state and performance with time. As regard as the metallurgical process, the physical essence of the *flow* for multi-factors, i.e. chemical composition factor, physical phase state factor, energy and temperature factor, geometry factor, surface feature factor, space-location factor, time-sequence factor, has been described in Chapter 4. This multi-factor flow would be shown as multi-factor character exists in running and controlling of the process. The *multi-factor* character appears that the matter state transforming, matter property controlling and related mass flow controlling are compounded by *mass flow, energy flow and information flow* in the operating process. The *mulli-facler* character also is embodied in the process control over basic parameters(matter quantitt index, temperature, time)and derivative parameters(gield, performance, cost erc.)of manufacturing process.

3. Program. In short, *program* in the operation of manufacturing process may regard as collections of orders, rules, strategies, paths in many forms. *Order* includes array of order or disorder and also of succession by someone factor. The order pattern includes function order, space order, time-characteristic order and spatio-temporal order in addition. *Rule* hails from the different demands, the dif-

ferent external conditions and the entire function of process, for example, the continuation and compactness of process running, which are main response of the rule. The combination of *order* and *rule* reflects the whole controlling strategies and the detailed operating paths of multi-factor mass flow in manufacturing process.

5.1.2 *Dynamically and orderly operating of process*

A. Conditions of dynamic order operation

The steel manufacturing process belongs to dynamic orderly structure of macro-scale. Dynamic orderly structure is dissipative, coming of process dissipation.

The static order character on aspect of space, time and functions in metallurgical manufacturing process is obvious. Since the process is always arranged by the spatio-temporal order of raw material yard—sinter/coking—ironmaking—hot metal pretreatment—steelmaking—secondary metallurgy—solidification—reheating—hot rolling, success is primarily owed to the design, specially the layout. The extent of ordering depends on the ideas of entirety while designing. Another key problem is how to operate the process dynamically and orderly in manufacturing, namely, to realize linking and coupling by optimization of procedure functions and interaction (coordination or restriction) among procedures. The continuation/quasi-continuation and compactness of process will come of synergetic and rhythmizable ways of process in multi-factor mass flow running.

As known in dissipative structure theory, the condition of formation of the dynamic orderly structure, at first, is the open system. That is different from prerequisite to isolated system in the classic thermodynamics. In fact, all the manufacturing processes in process industry are open systems, which exchange matter and energy with surroundings including input and output flows. Another condition of dissipative structure is the process system to be irreversible and far away from equilibrium. I. Prigogine(1977) indicated that the open system of nonequilibrium may construct a stable orderly structure by the fluctuations with nonlinear interaction in the system under some controlling conditions. Therefore, on the view of the state and process of system, steel manufacturing process is the same as most manufacturing processes which have the conditions of dynamic orderly structure.

B Driving power of dynamic orderly operation

Above conditions being over, the driving power should be found to form dynamic orderly structure. For steel manufacturing process, the driving power will be:

- Fluctuations of component (procedure or device) behavior. For an instance, tap-to-tap time of one converter heat is defined as 30 min, but it is possible within 28~32 min with different probability in practice. This is the fluctuations on procedure or device scale. Certainly, the fluctuations are also appeared on tapping temperature and composition etc.

- Nonlinear coupling of component interaction with each other. Due to the functions of each component's self in process are different, meantime, behaviors of component (procedure/device) are fluctuating, therefore, the basic parameters as quantity index of matter, temperature, and time are uneven in process. It induces that relations of components with each other must be nonlinear. For an instance, linking temperature between caster and reheating furnace may be ⩾200℃, or ⩾600℃, even ⩾1000℃, so the state of linkage and relation of processes under different temperature between caster and reheating furnace are nonlinear.
- Component (procedure/devices) being far from equilibrium. This is certainly the result of opening and irreversibility of process system.

Therefore, the desirable state of dynamic orderey operation is just dissipation deduced by self-coupling of fluctuations, irreversibility, nonequilibrium and opening of procedures or devices on time axis through nonlinear coupling among them. Dissipative structure itself possesses the inherent "self-organization" function. The running state of dynamic order process, on some meaning, is evolution of complexity and time-characteristic factor in the process.

The problem of order parameters in process must be analyzed on synergetic view for further improvement of process structure and operation state.

Synergism figures out, a great number of variables, which affect system behaviors, always force the system return to initial stationary state when the system is disturbed and then fluctuated. These variables act as one damping effect and attenuate very rapidly, so they have less influence on the process of structure conversion of system. They are named variable of quick relaxation. But other few variables, when system is disturbed and then fluctuated, can make the system far away stationary state and get nonequilibrium or grow into a new stationary state. They always determine the procession of system evolution, and decide structures and functions of system evolution. They are variables of slow relaxation. H. Haken defined that these variables of slow relaxation were order parameters of system (Xu, 2000).

Synergism theory points out, the variable of quick relaxation relies on the variable of slow relaxation, and order parameters control behaviors of subsystems. This viewpoint also is called "*servo principle*" (Xu, 2000b).

Therefore, would the structure and the operation function of the process system be farther adjusted or optimized, study on order parameters of process is the cut-in point of importance, and the keynote to know and cognize the process system. We must analyze and study in detail on:

- Number, situation and stimulus-response mechanism of order parameters in process;
- Time sequence of order parameter appearance in the process, meantime, the earlier or later of their appearance for one more order parameters;

- Possibility of synergetic effect and new structure emergence excited by some order parameters.

C Generation and modality of self-organization function in process operation

Steel manufacturing process belongs to system of dissipation. Formation and improvement of an order state in dissipative system by its self during running may apparently intitule them as *self-organization*. The function of *self-organization* in manufacturing process is described as above, but reasons and methods to excite the forming and improving *self-organization* function should be much more studied.

Firstly, steel manufacturing process acts as a dissipative structure, itself has inherent *self-organization* nature in dynamic operating, as each process's component (subsystem like procedure) has the tendency to fluctuations, and then related nonlinear interaction among components in the process running. These fluctuating tendency and nonlinear interaction under such attractive factors as dynamicorder and process continuation have made inherent *self-organization* performance of system evolution by its own.

Secondly, after recognization of the inherent self-organization nature of the process's own, people understand that the new manufacturing process may be established by researching its order parameters, such as analyzsis-optimization of set of procedure 's functions, coordination-optimization of set of procedures' relations and reconstruction-optimization of set of procedures. That is the new dissipation operation with more advantages. The extent of fluctuations of each component (procedure, device) and the nonlinear coupling relation among them are further optimized and more stable in the new process operation. So dynamic-ordering and process continuation running are much more realized that strengthen the inherent *self-organization* of process system.

Then, any information in process will be received and described to formulate the physical-mathematical models and to calculate and control the process running with computer. On some meaning, this is man-made construction on some functions of *self-organization*.

According to above discussions, *self-organization* of process system is to form certain functions and structures of process by the attractive requirements (dynamicorder and continuation/quasi-continuation), with effect of interactions among components of the process system under some conditions. The most important research is the characteristic analysis of the process system constructed from *self-organization*, being more ordered and more continuous steady than before. Certainly, this is mainly analysis on order degree, especially the comparision of process mode on aspects of function, time and space as well as on the state steadiness before and after *self-organization*. The steady state of space ordering, time ordering, time-space ordering, function ordering in process system may be shown through comparision. *Self-organization* may be analyzed and compared by order degree, and the type of process system may be distinguished by kind of ordered states, and so on. *Self-organization* in process operation is a dynamic process, the dynamic characteristics are not only represented in state variation during *self-organization*, but also in feature of steadiness self organized process system.

Self-organization is rich and colorful, has many modalities: mainly *self-generation*, *self-reproduce*, *self-growth*, and *self-adaptation* (Xu, 2000c).

1. Self-generation. *Self-generation* is an explanation on *self-organized* state by comparing new forming state with old intrinsic state in *self-organization*. *Self-organization* is analogous to phase transformation in the process evolvement. In some outside conditions, process system will spontaneously generate new structure and function from intrinsic unstable and disorder state by interaction among components (procedures, devices) of the process, and become a new state, which didn't exist before. This *self-organization* mode is *self-generation*.

The characteristics of *self-generation* are that the process system produces new state, new structure and new function which are not in original phase. These new state, new structure and new function with respect to original system state before *self-generation* can not analyzed by some organization theory. For example, continuous casting instead of ingot casting-blooming in steelmaking process leads the relations between solidification and smelting or rolling to an obvious change. The new high temperature linking and process structure of relatively high continuity and the new operation function of ordered mass flow have appeared. Vast variation of the fully continuous casting in steel manufacturing process was not forecasted by the organization theory of system engineering.

Comparing the new state after *self-organization* with original state, if order degree is increased, the *self-organization* is mean as *self-generation*, contrariwise, if order degree is decreased, the *self-organization* is mean as *self-collapse*. Some *self-collapse* had appeared in steel technical reconstruction, for example, the new devices were added random disregarding rationality of layout, or the workshop was laid confusedly, as well as universality of product mix were taken for production expansion temporarily. When *self-collapse* appeared in technical reconstruction of steel manufacturing process, which always brings negatives that the loss overweighs the gain with long-term and whole situation.

2. Self-reproduce. *Self-reproduce* is depiction of state characteristics from *self-organization*, in case of which components how interact each other to ensure the process system being ordered and stable. Time structure, such as tap-to-tap time induced by *self-organization* in process system is the simplest aspect of *self-reproduce*. *Self-reproduce* analyzed relations and features among process states each other through time procession of *self-organization*. Evolution of process system shows ordered state in *self-organization*. On ana-

lyzing with time progressing, the new pattern which appears after a time period is same as the original pattern, this kind of evolution is named as *self-reproduce*. For a process system consists of many components (many subsystems), state of process system in whole is changeless, namely, keep original operation on viewpoint of entire process system. But from viewpoint of subsystem level, the state varies and every component (subsystem) is all varying. So we easily observe *self-reproduce* of components (procedures, devices) of process system in majority instance. The function of *self-reproduce* of components just keeps the ordered state through *self-organization* in process system. *Self-reproduce* is ground for stable existence of state made from *self-organization*. The time scheduling—operation chart for producing some products in the steel plant belongs to a kind of *self-reproduce*. This *self-reproduce* on subsystem level shows repeatedly appeared time-order on each component (procedure, device).

3. Self-growth. *Self-growth* is depiction of state evolution with time on process integral scale, and is analysis for state of process in entirety. Structure and functions of process keep invariable in *self-growth*. *Self-growth* relies on a certain environment, such as input of matter, energy and information, to become averagely the power of process system, and to enlarge the integrity by *self-organization* of the process system and/or interaction among components. In major instances, *self-reproduce* of components (subsystems) is the reason of *self-growth* of the process system. For example, periodic operation of converters and rolling mills shows *self-reproduce* of components, but the manufacturing process of steel plant is incessantly running under quasi-continuation. The raw materials, energy and information are imported, products and by-products are delivered, and some wastes are recycled, so the operation more and more goes along with time. Hence shows the evolution of *self-growth*.

4. Self-adaptation. *Self-adaptation* is depiction of process system concerned in its relation with outside environment. *Self-adaptation* announces that process system responds to environment and appears new structure, new state or new function to adapt outside by *self-organization* in certain conditions.

Self-adaptation is seemed as *self-generation* that both of them want to analyze the whole *self-organization* and to study the differences of states before and after *self-organization* of process system. But they are different, *self-generation* is analysis on characteristics of *self-organization* in process system, and on new structure and new functions which are appeared in process system after *self-organization*. It is description on process's own states and discussion on internal behavior mechanism in process system. *Self-adaptation* in system is *response* by *stimulus* due to outside environment change, is analysis and research on characteristics of *self-organization* from view of relation between process system and surroundings. Therefore, in same one instance, issue of internal interaction in system is *self-generation*, issue of relation between system and surroundings is *self-adaption*.

On discussion of a certain practical problem, if process system was non-structure and disorder before *self-organization*, there appears new structure which emerged from internal interactions, is referred to *self-generation*. If a certain structure state existed in original process system and it is changed by stimulus from outside environment changing, this phenomenon is named *self-adaptation*. *Self-adaptation* emphasizes that the ordered state in process system will be changed by variation of the environment, even if the structure of process system had been ordered. That is embodiment of the ability on environment adapting.

The above classification on *self-organization* is described and analyzed on different views, levels and scales. In practice, *self-organization* is complex that many hybrid patterns appear with different degree in most case. So that, when practical problem of *self-organization* is analyzed, it must be observed and analyzed on many positions.

5.1.3 ***Targets, contents and methodology of study on multi-factor mass flow control***

General target of study on multi-factor mass flow control in steel plant is study on feature, state and outside conditions from beginning of process dynamic-orderly running, that is study on self-organization in itself of process and on order parameters in process operation through the dissipative structure to develop into continuation/quasi-continuation and compactness of the steel production process. The further purposes are to improve market competitiveness, to promote sustainable development and to join in circular economy of society.

Main contents of research on multi-factor mass flow are:

- Structures and behaviors of manufacturing process;
- Interrelations between correlating/adjacent levels in process;
- Functions, structure and efficiency of each component in process;
- Interactions among components in process etc.

Main methods for research multi-factor mass flow of steel plant are:

- The fluctuations and their probability of each component running in process;
- Nonlinear relation on interactions of each components' operation in process;
- Function of self-organization existing in dissipation—process operation;
- Order parameters of process running and their contribution to new structure emerging;
- Influences on process structure and its operation state from outside condition and their adaptation with each other.

5.2 Multi-factor Mass Flow System Control of Steel Manufacturing Process

The process features of steel manufacturing process, concept of operation in steel manufacturing process and analysis on stimulus-response of manufacturing process system are described in this part as follows.

5.2.1 *Process features of steel manufacturing process*

A. Abrief review

Evolution of steel manufacturing process has induced variation of steel plant pattern generation by generation, but the essential characteristics of matter state transformation and matter property control are not significant change in metallurgical process. Production process of steel plant contains chemical metallurgy and metallurgical physical process usually. Chemical metallurgical process is mainly interested in embodying relations among composition, temperature and time. The metallurgical physical process does interest in relations among deformation, microstructure, temperature and time mainly. The connection region between chemical metallurgy and metallurgical physical process——solidification of steel had taken invaluable change from 1970s. This provided variation is key of the most active factors to promoting modern steel production development, it is the order parameter of entire operation of process practically. After steel continuous casting technology is adopted, the duration of steel casting procedure shortens, the process efficiency improves, and the temperature undulation of metals decreases. It has induced some procedures such as ingot casting and blooming, which belongs to slow relaxation variables, to be eliminated. Then the bottleneck of mass flow in operation process is opened in some degree. These have driven process to integrated optimization. So a great change in plant pattern, mill scale, product mix, investment and market competitiveness of steel plant has arisen.

B. Combination of matter state transformation, matter property control and mass flow control in production process—multi-factor mass flow control system

In the view of engineering, the essence of steel production process is the technology of matter state transformation and matter property control, such as phase transition and state control, steel grade and quality control, metal shape-size and surface feature control, as well as product performance control etc. On the other hand, the essence is control on multi-factor mass flow of manufacturing process, this mass flow control is not only material transport, but also optimized connection and matching of main parameters, such as reasonable linking for flowrate, temperature and time-point of mass flow, matching for inlet and outlet flowrate between adjacent procedures, buffer and coordination of time rhythm, optimization on transport direction, distance and ways of mass flow, compactness of mass flow etc. These parameters are very important to influence plant pattern, investment, input-output benefit and even environment burden of steel plants. So that, in viewpoint of engineering science, characteristics of steel manufacture are coordination-optimization for the matter state transforming, the matter property controlling and the mass flow controlling in process. Through improvement and soundness on functions of a series of techniques and devices, and with comprehensive application of automation technology in process, the guidance to development pattern, investment direction, investment sequence, and specific investment of steel plant may be gained in time and effectively. Matter state transformation, matter property control and mass flow control are always undergone simultaneously and/or respectively reqarding ferruginous mass flow in steel production process. The present case of mass flow in steel manufacturing process is quasi-continuous and/or batch running in general. It obviously differs from the logistic systems of railway transportation, postal mail distribution, logistic system for chain stores, also from mass flow in automobile assembly line or machinery cold processing line. The mode of mass flow in steel production results in a multi-factor mass flow control as shown in Fig. 5.2.

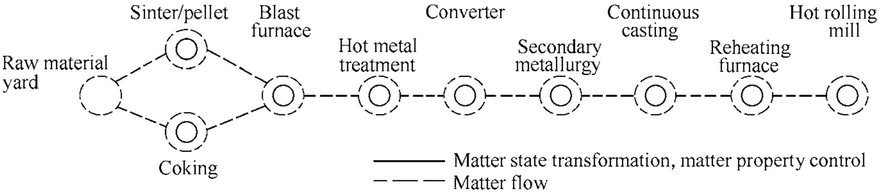


Fig. 5.2 Schematic diagram of matter state-matter property-mass flow in steel production process

The multi-factor mass flow in the steel plant has been discussed briefly in Chapter 4.3. As cybernetic engineering of multi-factor mass flow in steel production process, the connection, matching, continuation and steadiness of the following parameters must be considered:

- Transformation, transfer, connection and matching of state, composition and quantity of mass flow;
- Coordination, buffer and acceleration on time rhythm of mass flow;
- Solidification of liquid metal into slab/billet with ordinary shape and size, and

then the deformation and coordination of shape and size of slab/billet in mass flow process;

- Conversing, transferring, coordinating and saving of energy in mass flow process;
- Variation, heredity and control of metal surface quality, macrostructure, microstructure and steel performance in mass flow process;
- Adjustment, coordination and optimization of materials transport route and way.

To realize the coordinating and matching on above parameters, it not only must improve functions' optimization of procedures, equipment reliability and controllability of each procedure, but also pay more attention to the flexible adjustment on adjacent procedures each other. Based on the optimum and match of abilities of capacity and function of procedures/devices in the process system, the flexible buffer engineering, playing role of combining, linking up and adjusting between relevant procedures, i.e. the self-organization function is formed. In fact, flexible buffer engineering has incessantly been developed since the middle of 20th century with evolution of procedure's functions and coordination-optimization of procedures' relations. The relations of relative *flexibility* or relative *rigidity* are often presented on some functions between neighbor procedures and even more, therefore, the flexible buffers for different function parameters are composed, and then the structure optimization of the whole process or process section is realized at a higher level.

5.2.2 *Concept of operation in steel manufacturing process*

To abstract the character of the steel manufacturing process system and to extract some essential concepts, the correlation among different functions in process must be fully understood, the nature of functions about existence value of procedure and their relations in process system must be known and confirmed, then the modeling is abstracted on the base of these concepts.

A. Abstract-analogy—stimulus-response

The steel production process system is a manufacturing process with optimum combine of matter state, matter property and mass flow. The process system is very huge, its processing parameters are numerous, and many parameters are quickly changed simultaneously or successively in short time. This type of change often faces difficulty on directly measuring these parameters. So, it is very difficult to describe this complex process system. Therefore, it is necessary to study the process system through abstract-analogy.

In fluid mechanics, analyzed on fluid stress and strain, the partial differential equations of four dimension system are gone out by tensor method. However, the fluid is continuum medium. Analysis of continuum is rather simpler than of dispersed system or quasi-continuous/batch process. If the partial differential method is directly applied on describing a manufacture process, great difficulty must take place. But on the engineering methodology, stress-strain analysis is the same kind as outside stimulus-inside response in essence. The essences of continuum system and the essences of process manufacturing system have commonness. But obvious difference between the both sides exists. This difference is: the outside stimulus to every volume-element in continuum system has uniform even simultaneous inside response, but the outside stimulus factors, such as variances of market, investment, resource, energy, price etc., call response of many components (procedures, devices) in manufacturing process being heterogeneous, anisotropic and with an extent of delay lag.

B. Coherent system and unequal delay

Steel manufacturing process may be abstracted into a coherent processing which is analogous to viscous fluid flow. For functions of each procedure in process are different, performances of every device take some fluctuations, but they have strongly coherency in quite great degree——a certain skill of self-organization. It is seemly as non-uniform continuous process or quasi-continuous process. When stimulus generates outside, the responses of different components in the coherent system show different time delay, and have different fluctuations on capacity parameters displaying, and thus functional parameters have differently selecting or fluctuating. So that, this coherent system is stimulated, each component of system always has different kinds and delays of responses. These process characteristics need treating by different method of self-organization for flexibility-coordination.

One of the advantages for this system analysis is that dissipation has source of system's own characters (like viscous dissipation of fluid), instead of artificial characters. However, process manufacturing system not only has coherency of manufacturing system's own, but also takes certain artificially influenced, named as artificial coherency. Therefore, control of process optimization does not be detached from management fully.

It is very difficult that steel manufacturing process system takes full flexibility and becomes real continuation. It is not necessary over pursuing on-site. Since, the system of quasi-continuation or definite setting flexibility must be sought now.

C. Description on quasi-continuation and/or batch operation

The basic condition of system description with differential equations is that the continuously differentiable independent variable is contained in the system. There are three continuously differentiable independent variables as the quantity index of matter, the temperature and the time in both chemical metallurgy and metallurgical physical process of steel manufacturing system. The three variables are the basic parameters of system. Other parameters such as product quality and steel grades etc. consequently depend on the variation of above independent variables, which belongs to derivative parameters in system process.

For the major independent variables being continuously differentiable in the procedures of steel manufacturing processing, the quasi-continuation and/or batch operation system is trend to evolve as coherent continuous system consisting of rigid and flexible components. The modern steel plant is seen as coordinating system composed by rigid and flexible components, namely,

$$\Sigma v = f(\Sigma Fl, \Sigma Ri, \Sigma R)$$

where Σv means coherent system; ΣFl is set of flexible components; ΣRi is set of rigid components; ΣR is set of relations among components.

It would be mentioned that these rigid components and flexible components are shown in relative meaning and not absolute meaning.

These rigid components and flexible components in steel production separately are:

1. rigid components: sinter machine, coke oven, blast furnace, BOF(or EAF), continuous caster, hot rolling mill etc.
2. flexible components: raw materials yard, transport facilities, iron ladle or torpedo car, steel ladle, secondary refining devices, tundish, reheating furnace with slab/billet store, other storage vessels etc.

Certainly, rigid components of steel manufacturing process don't appear absolutely rigid. They have definite elasticity on many parameters, namely, many parameters have a certain fluctuations. The flexible components have only larger scale of fluctuations than nearby rigid components, but do not become unlimited flexible. The flexible component will fail its function beyond this fluctuating limit, thus becoms nonflexible.

The elasticity of rigid components and the limit of flexible components as well as their composition relations to form these functions in manufacturing process, characterize the coherency of whole manufacture process.

Variation of these coherent characteristics would lead to change viscous dissipation in system, namely, coherent dissipation of entire process system would be influenced by variation of set of components and set of components' relations. The coherent dissipation will be reflected on the product cost, quality, labor productivity as well as the environment burden and investment. Finally, it will influence the market competitiveness and the sustainable development of the enterprise.

The coherent dissipation is mainly subject to the structure of process system, namely, is influenced by flowchart design, investment, operation rate and management plan etc. It may be named as mechanical coherent dissipation. In fact, coherent dissipation of process system also is influenced by human artificial factor (such as management philosophy, human quality, organization etc.). It is artificial coherent dissipation.

$$\Phi=f(\Phi_{\mathrm{m}},\Phi_{\mathrm{p}})$$

where Φ is coherent dissipation of process system; Φ_{m} is mechanical coherent dissipation; Φ_{p} is artificial coherent dissipation.

In addition, the coherent dissipation of process system possesses functional relation with steel plant structure, set of components (procedures), and composition among procedures. Namely, under some social and natural environments:

$$\Phi=f(S)=f(\Sigma E,\Sigma R)$$

where S is structure of steel plant; ΣE is set of components (procedures); ΣR is set of procedures' relations.

D. Analysis of elements in multi-factor mass flow control system

Either chemical metallurgy or metallurgical physical process in the multi-factor mass flow control system of a steel plant, three independent variables, i.e. matter quantity index (weight, composition, flowrate), temperature and time, are characterized as continuously differentiable in whole process. They are three basic parameters. The characteristics of these basic parameters are penetrated through the whole steel manufacturing process from beginning to end with same appearance and same unit. They often directly relate to the important techn-economic indexes such as productive efficiency, product quality, operating cost etc. (Yin, 1997).

There are other parameters which are also very important to production and administration for steel plant, but don't penetrate from beginning to end with same appearance and same unit. They are product quality, product grades, steel specification, mass state transforming, transport ways etc.

1. Expressions of quality, grades, specification in ferruginous mass flow are different in chemical metallurgy, solidification, metallurgical physical process, and do not be continuously differentiable. They are shown as:

In chemical metallurgical process, quality and grades are expressed as: steel composition, chemical accuracy, cleanliness, homogeneity, preparation condition (such as grain control, inclusions morphology) for next metallurgical physical process.

In solidification, quality and grades are expressed as: macro-structure, segregation, surface quality, accuracy of section size, flatness along longitudinal direction and so on.

In metallurgical physical process, quality and grades are expressed as: metal structure (macroscopic, microscopic), accuracy of shape and size, surface feature, mechanical and physical properties etc.

2. Variations of aggregate state of ferruginous mass flow also are not continuously differentiable, their presentations are:

In chemical metallurgical process, variations of aggregate state are: oxides-metals, solid—liquid, oxidized melt-deoxidized, alloying etc.

In solidification, variations of the state are: molten steel—cast metal, different cast structures, different segregations, different surface qualities, different shape sizes (section, length) etc.

In metallurgical physical process, variations of the state are: casting texture-rolling (forging) texture, high temperature structure—room temperature structure, equilibrium structure—nonequilibrium metastable structure, original surface-treated surface, different product sizes, different package states etc.

3. Transport ways of materials and semi-products also are not continuously differentiable, their presentations are:

In chemical metallurgical process, transport mode includes belt conveying, automobile transport, railway transport, crane transport etc., transport direction may be horizontal, vertical, titling, even curved etc.

In solidification process, transport mode includes crane transport, roller conveying, railway transport etc., its direction may be horizontal, vertical, curved, or titling etc.

In metallurgical physical process, transport mode includes crane transport, special equipment transport, roll table transport, automobile transport etc., its direction may be horizontal, vertical, titling or curved etc.

So far as the nature of elements is concerned, these variables or parameters like steel quality, grades specifications, state change, transport ways, are dependent on the basic para meters as matter quantity index, temperature and time. So they have property of derivative parameters.

The fundamental relations between independent variables and derivative parameters of mass flow in the steel manufacturing process are discussed in Chapter 4.3.1.

The running trajectory of manufacturing process both of BF—BOF process for flat product and EAF process for long product is drawn on Fig. 5.3. It shows the route and direction in space with three dimensions—three independent variables (matter quantity index Q, temperature T, time t). Mass flow paths for all kinds of steel plant manufacturing process are on Fig. 5.3 and only have difference on route and position. However, just multi-factor mass flow of different steel plants takes different route and direction along axes of three independent variables, series of derivative parameters will be influenced by the independent variables, the characteristics and advantage or disadvantage of different manufacturing system will simultaneously be presented. Certainly, the mass flow trajectory in system will influence the important input—output index, such as investment account, product cost, capital turnover rate and its efficiency, production scale and its efficiency, environment burden etc.

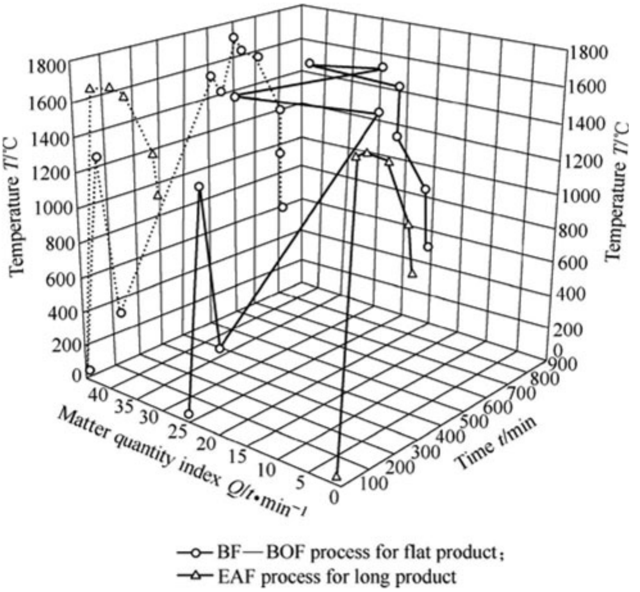


Fig. 5.3 Schematic diagram of multi—factor mass flow trajectory in different steel plants

E. Operation pattern for quasi-continuation/batch process—elastic chain/semielastic chain syntonization

Since above discussions, steel manufacturing process system has been schematized as quasi-continuous/batch operation process with rigid component set and flexible component set and theirs relations on connecting, matching, buffering and coordination. In practice, due to different elastic values of rigid components, different limits of flexible components, and different connecting and matching relations among procedures, the running pattern of steel production system shows different kinds of syntony of elastic chain/semielastic chain. In general, syntonic state of elastic chain/semielastic chain in process includes two classes, namely steady syntony and unsteady syntony.

1. Steady syntonic state. It contains designed common state, normal flexible control state, maximum flexible control state. They are shown as in Fig. 5.4.

The designed common state is the desired regular running pattern regarding investment, design and manufacture.

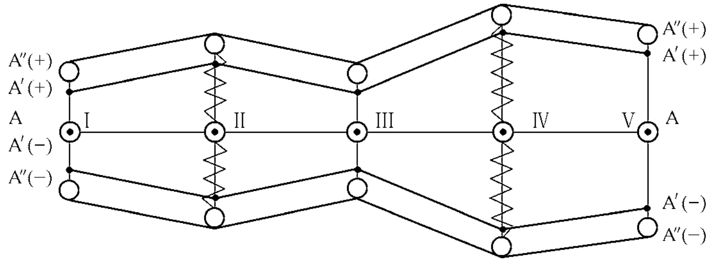


Fig. 5.4 EAF process route, steady syntonic state of elastic chain/semielastic chain and its different types

A-A—Designed common state; A'(+)-A' (−)—Normal flexible control range;
A"(+)-A"(−)—Maximum flexible control range;
I —Electric arc furnace; II —Ladle furnace; III—Continuous caster;
IV—Reheating furnace with store; V —Hot rolling mill

When the process system is disturbed by some factors, the process running is deviant from designed common state, but still be normal operation. This state names normal flexible control state.

The maximum flexible control state is the process running under extreme function range of a certain procedures/devices or their nonlinear relations. If the extreme value will be exceeded, process system does become fault and pause, and departs from syntonic state of elastic chain/semielastic chain.

2. Syntony fault state. While the process system is disturbed by outside or treated itself improperly, the rigid components exceed their elasticity and flexible components exceed their extreme value, or procedures' relations can not be linking up and adaptive each other, then the process system become syntony fault state and leave from elastic chain syntonization. It also means the out of control of self-organization. When the syntony fault state appears, some effective measures must be applied to make the extensive property and functional abilities of each relevant component recovery and to reorganize the relations among them (self-adaptation). Certainly, when the syntony fault of elastic chain/semielastic chain happened, it often pays cost on economy.

F. Critical phenomenon and engineering effectiveness in process

From physical terminology, *critical phenomenon* means a second order phase change. The critical point is a singular point, which can not be described by the state equation of any analytical expression. To research the phenomenon, we can not apply commonly approach method for average field, but must apply strict field theory considering order parameter fluctuations. Correlation length is divergent and approaches infinite at the critical point. In general, correlation length of liquid is very short, with molecular scale magnitude. It belongs to short range correlation. The very weak fluctuations in short range correlation may be described by mean field theory. When the correlation length approaches infinite and the fluctuations become significant, the mean field theory, ignoring the fluctuations, is not available. During this case only the strict field theory to consider the fluctuations of order parameters may be applied for research. Moreover, for the correlation length approaches infinite, coarse-grained method may be applied without restraint, this is the concept of theory of re-normalization group (Guo, Hu, Wang, et al, 2002a).

Theory of re-normalization group, not only is an academic breakthrough, but also is beginning of research on *critical* in engineering, especially, research on the breakthrough from non-critical area (including subcritical and supercritical) to critical.

There were a series of critical which influenced the structure, performance and efficiency of metallurgical process in historic meaning. Different macroscopic structure, performance and efficiency are related to the microscopic/mesoscopic ordering in metallurgical process. For example, if the casting speed, which influences single strand output and annual output of a caster, reaches an optimized critical value, it is possible to realize fully continuous casting production and at the same time attains a rational economy of the whole steel plant. As a result, some of the original main operations such as ingot casting-blooming mill/breakdown mill can be eliminated. Furthermore, oxygen converter replaces open hearth furnace, thin slab casting-rolling has arisen, strip casting appears, all these evolutions have induced the fluctuations of order parameters in steel manufacturing process and lead to re-integration and reconstruction of macroscopic process structure, so the engineering effectiveness has happened.

The engineering effectiveness in steel manufacturing process means that the macrostructure, performance and efficiency of process have been greatly enhanced due to appearance of new technology and new equipment to reach the critical value of order parameters of whole or sectional process (Yin, 2000).

The engineering effectiveness is colorful, such as *critical-optimization*, *critical-compactness-continuation* and *critical-simplification* are inspired due to one or some order parameters attaching its critical values in steel manufacturing process. Especially in casting-rolling process it shows clearly (Fig. 5.5).

If ingot casting was applied, the steel product would be produced through blooming mill or breakdown mill, then rough rolling mill and finish rolling mill. In casting-shaping procedure, the thickness of the cast slab would reach in to 220~300 mm for replacement of blooming mill of 3 Mt/a,. This is the critical value of slab thickness, but also there is another critical value as critical casting speed. If one blooming mill will be replaced by two casters with four streams, the critical casting speed can be computed. Therefore, the critical metal flowrate based on critical casting speed and critical thickness is the critical order parameter for replacement of blooming mill by fully continuous casting. The structure, performance and efficiency of steel plant will be greatly changed once ingot casting-blooming is replaced by fully continuous casting. It shows that the solidification technology is very close in correlative degree between steelmaking and rolling for quite a long time.

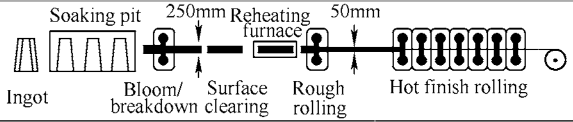
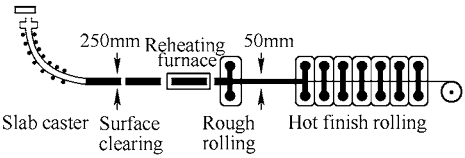
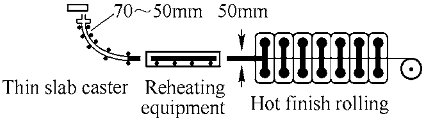
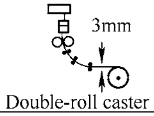
Ingot(slab) thickness/mm	Process patern	Process operations
About500 (Ingot)	Ingot casting	
250 (Cast slab)	Slab casting	
70~50 (Thin slab)	Thin slab casting-rolling	
3 (Strip)	Strip casting	

Fig. 5.5 Evolution of the manufacturing process and critical-compactness-continuation effect

However, even though the slab thickness decreases from the range of 220~250 mm to 150~180 mm, roughing mill is still necessary for hot strip mill. But once thin slab casting technology is applied to decrease the slab thickness of 50~70 mm, not only rough rolling mill will be eliminated, but also super long slab reheating-rolling with tunnel furnace will be carried out, and even semi-endless rolling will be applied to process structure in more compactness and continuation.

The slab thickness for strip casting becomes about 3 mm, in principle, the strip products can be obtained without rolling. But the strip with 1 or 2 pass rolling is much better to ensure grain density and surface of coil. Thus, strip manufacture would be more compact-continuous and simplified.

The critical phenomenon of relation between strip coil thickness and stand numbers of hot rolling mill exists at different thin slab thickness as shown in Fig. 5.6. If thickness of products is 1.5 mm, seven rolling stands is needed for the thickness of thin slab being 70 mm, and six rolling stands is needed for the thickness of thin slab being 50 mm, and so on.

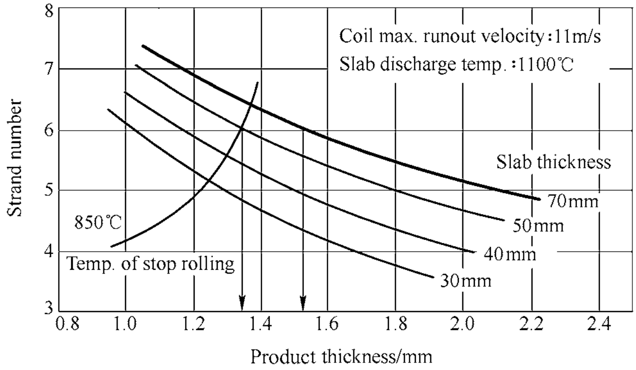


Fig. 5.6 Relation between critical value of slab thicknesses and number of rolling stands (Flick , Schwaha, 1993)

5.2.3 *Analysis on "stimulus-response" of manufacturing process system*

When steel manufacturing processes as a coherent system being stimulated by outside, the response of each component/procedure will be different type or different lagging degree. Various response types have different time-delay, and even same response has also different time-delay.

In general, the major outside stimulating factors or environmental factors for steel manufacturing system are as following:

- Variation of overall market capacity, or requirement of some product grades and specifications;
- Global market integration and international competition with it;
- Variation of supply, transport and price on resources and energy;
- Collection and effective circulating of enterprise capital and the funds market;
- Progress of technology and development situation of social economy;
- Variation of staff organization and employment, and labor cost ratio to total cost;
- Environmental requirements and sustainable development, and so on.

Generally, under above different outside stimulating factors, there are different types of responses as *reflection*, *absorption*, *conduction*, *conversion* for the steel manufacturing process (coherent system).

1. Reflection type response. It means that the direct and rapid responses in the coherent system quickly appear under outside stimulating factors. For example, when shortage of a product in market occurs and price ascends, the production plan and the sales plan on increasing output of this product will be made, and

even proper investment will be carried out.

2. Absorption type response. When the functions of the coherent system have enough capacity or less influence by outside stimulating factor, the response can be ignored and the coherent system still runs under initial way. For example, when price of one spare part or additional material ascends, the ascending factors on influences to product cost and funds-turnover are also not obvious, since their spent account is very little. The response is not probably occurred.

3. Conduction type response. When the coherent system was seriously influenced by the outside stimulating factor, it not only stimulates someone component (procedure/device), but also further influences the connecting procedures and even the whole system. The response on the coherent system at this case has obvious conduction (diffusion) feature. For example, when new product replaces old one or rather products standard and engineering specification take greatly modification, production system and management system in some procedures or even whole steel plant will be changed successively.

4. Conversion type response. When the steel plant as a coherent system was affected by the outside strong stimulating factor, the response on great structural variation to resist and subside the stimulus' influences should happen. Other words, the system will be led to a conversion at the core to adapt the environment, and to take surviving and developing opportunity. For example, the world oil crisis had inspired a series of great energy-saving measures to adapt the energy price rising at that time, therefore, universal type of steel plant characterized by ingot casting-blooming was gradually changed into specialized steel plant with fully continuous casting technology. This is a structural conversion being induced by very strong stimulation and deeply effective in further ages.

The above different types of outside stimulus-process response, actually are mode in structural optimization of different types and levels in steel production process. The major goal of structural optimization in steel plant is to obtain more economic benefit. The optimum integration of steel process on maximum economic benefit is realized by proper response mechanism on the coherent system and the limitation of environmental factors.

5.3 Dynamic-Orderly Structure and Information Flux in Process

The multi-scale and multi-level do exist in the steel manufacturing process. Multi-level structure and their coupling would effect self-organization of manufacturing process and its information flow. It will be described as follows.

5.3.1 *Multi-scale, multi-level and self-organization*

1. Multi-scale, multi-level——explanation of complexity of manufacturing process. In physical world, each element or system consisted of multi-elements all has conception of scale and level. Both scale and level are individual concepts but correlate each other (Guo, Hu, Wang, et al, 2002b). The level mainly discusses structure level and its relevant function level. Such as, matter structure levels are separated from fundamental particle to atom, to molecule, and to molecular aggregate (lattice, grain, crystal, etc.), each structure level is expressed itself level of functions. The scale contains space scale and time scale in general. The scale size of elements on same level is very different. Certainly, the scale size of element for high level is not always larger than for low level. Beside the size of space scale, the dimension is also for time scale. The dimension of time scale reflects conversion speed and duration time and so on.

The structure of steel manufacturing process is also of multi-scale and of multi-level. The operations of process system have unit operation (decarbonization, deoxidation, etc.), monomeric running of procedure or device (blast furnace, converter, reheating furnace, etc.), sectional running (multi-procedures' combined running within steelmaking and rolling mill), entirely operation of steel plant (integrated BF—BOF route, EAF mini-mill route). These dynamic running structures directly reflect the multi-scale and multi-level features of steel manufacturing system. The multi-scale and multi-level of system structure practically are a presentation on complexity of process. The complexity principally characterizes the multi-scale and multi-level both of space and time in system structure, process running state and evolution. It can be concluded as follows:

- The advance structure of the process system is of multi-level and of multi-scale;
- Conversion and operation of multi-factor mass flow in process system is orderly, sometimes is multi-event and multi-factor coupling process through long time period. Therefore, when the conversion and operation of process will be investigated, its variation must be comprehensively assessed on different scale and different level in most case;
- State variation, stability and control of system are multi-level in multi-event process of the multi-factor mass flow.

The relation among above three aspects always shows a complex integration, named as upper to against lower level relation. On the constructing of structure, the upper level structure commands the constructing of lower level structure, and the lower level structure also affects (even decides) to construct the upper level structure. On dynamic variation of structure, variation of the lower level structure influences development and evolution of the upper level structure, but the upper level structure controls and guides the development, even elimination or generation of the lower level structure.

2. Scale-level coupling and the division of steel manufacturing process. The process system can be divided and recombined by means of separated procedures and procedures' interrelation. As applied with conception of directed graph, the principles of division and recombination should be determined:

(1) The process system is divided into some procedures, each can realize its major function which have being in one procedure, but in some case, to share properly by other procedure is not rejected.

(2) Subgraph of divided procedures must obey the relation of time order of process system.

(3) Connection of some functions has arisen among a certain divided procedures. If some functions are contradictory each other, the functions would be separated into several adjustable parts, and assigned to proper procedures, the new procedure's division can be formed, it meets the non-antagonistic of functions.

(4) If the probability of some function relations between divided procedures is very little, these relations would be removed, and procedures would be divided again, new relation between procedures could not form as closed circuit between the adjacent procedures, that means the relation between two procedures not being circuit.

(5) The relation among inner systems in divided procedure and its implementation must be meet constraints and objectives of the divided procedure, i.e. the divided procedures take their own constraints and objectives, and can be realize with optimization.

So that, the multi-level structure of process system and the optimized division of procedure in process system can be built up. The process of steel manufacturing system also is expressed by directed graph as $D=\{F,r\}$, where F is all variables for set of functions of process system, including the common function variables and also the special function variables in special process; but r is directed boundary of relations between functions set variables. The r can express the time-sequence of relations, and also the acting direction of relations. The multi-level structure of the steel manufacturing process system can be shown in Fig. 5.7 by using of the above expression on multi-level structure, realizing method and applied principle. Where the lines and its directions are relations among nodes and acting directions respectively, the black points are nodes.

The first level structure shows function variables for child nodes of each subsystem in each procedure of process system, and being divided level-by-level constructs the (k-1) level structure by the above five principles (1)~(5). The (k-1) level structure contains seven procedures, which is subsystems of minimum strong connection. Where, $z_1^{(k-1)}$, $z_2^{(k-1)}$, $z_3^{(k-1)}$, $z_4^{(k-1)}$, $z_5^{(k-1)}$, $z_6^{(k-1)}$ and

$z_7^{(k-1)}$ represent the procedures of raw material preparation, blast furnace ironmaking, BOF steelmaking, secondary refining, continuous casting, hot rolling and deep finishing respectively. The k'th level structure consists of three subsystems of minimum strong connection, where $z_1^{(k-1)}$, $z_2^{(k-1)}$ and $z_3^{(k-1)}$ are subsystem for raw material supply and preparation, chemical metallurgy including solidification, as well as metallurgical physical process respectively. Finally, only the system $z_1^{(k+1)}$ is on (k+1) level of structure, that is the steel manufacturing process system.

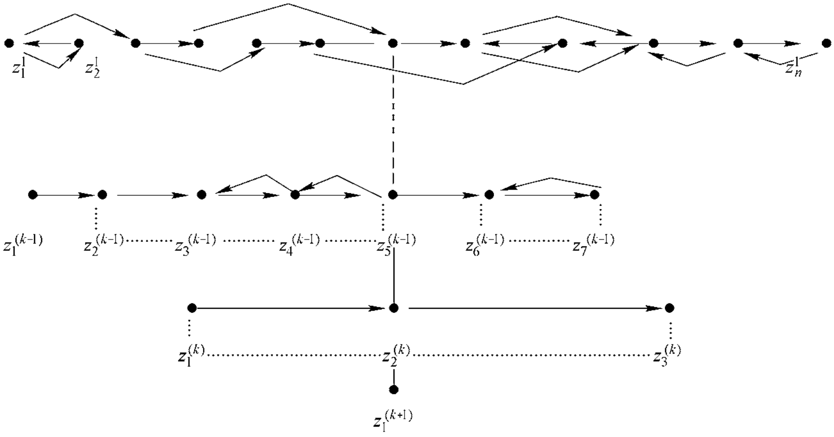


Fig. 5.7 Multi-level structure in the steel manufacturing process system

Being understanding of the relations of level-scale in process as well as optimizing division and recombination of procedures, it is very important to dynamic-order running of process by further research on the scale-level coupling in process. Some issues on formation and modalities of self-organization in process system, such as self-reproduce, self-growth and so on, have been discussed in 5.1.2C The time structure of self-organization, e.g. periodic time of processing is the simplest case of self-reproduce in process system. Evolution of process system shows order state in self-organization of process running. According to the analysis on variation with time, the appeared graph is same as the original graph after a period. This pattern can be called as self-reproduce. Researching on process system with several components (procedures/devices), the state of process system is unchanged on the process level, i.e. is kept initial operating state; but the state of component is changed on the lower level. Each component changes periodically, i.e. the process state is on self-reproduce (Fig. 5.8). The stable state of self-organization in process system is just due to the self-reproduce of components.

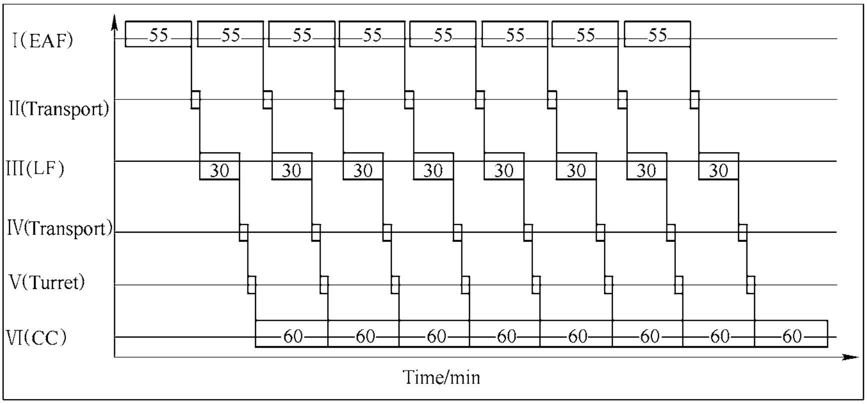


Fig. 5.8 Self-reproduce for main procedure running in steel manufacturing process (Electric furnace steelmaking)

Self-growth describes evolution with time for self-organization of process system on level of whole process. The process keeps unchanged structure and functions in self-growth, and then the input materials, energy and information will be connected throughout and be constantly converted into products, by-products and any emission by means of *self-reproduce* and interaction of components. Thus it can be seen that the openings of process, incessant receiving set of inputs, self-reproduce of component and nonlinear relations of components' interactions are the powers of *self-growth* in process system.

Therefore, the evolution of multi-factor mass flow can be regarded as the different level-scale coupling in the steel manufacturing process, that is:

- Multi-factor mass flow respectively realizes converting-coupling of many factors on level (or scale) of each procedure/device along time axis;
- Multi-factor mass flow does self-reproduce on functions of these procedures/devices, and then operates periodically along time axis, and realizes coordinating-coupling of many factors on level (or scale) of components;
- Multi-factor mass flow is connected with time and space by self-reproduce and interaction of procedures/devices, and then forms the flows of product, by-product and emission, namely it realizes self-growth on process level. This is evolving-coupling on level-scale of whole process (Fig. 5.9).

5.3.2 *Information flow and model building*

The concept and essentials of manufacturing process have been discussed on physical view and emphasized that the basic essentials in their operation are as *process network*, *flow* and *program*, also these meanings are described respectively in chapter 5.1.1. The flow is the material subject in the process, the process network includes node and connector, and is carrier of flow running and its time-space boundary (framework), also the program is set of orders, rules, strategies and paths, and mostly is reflected by information of characteristics in mass flow.

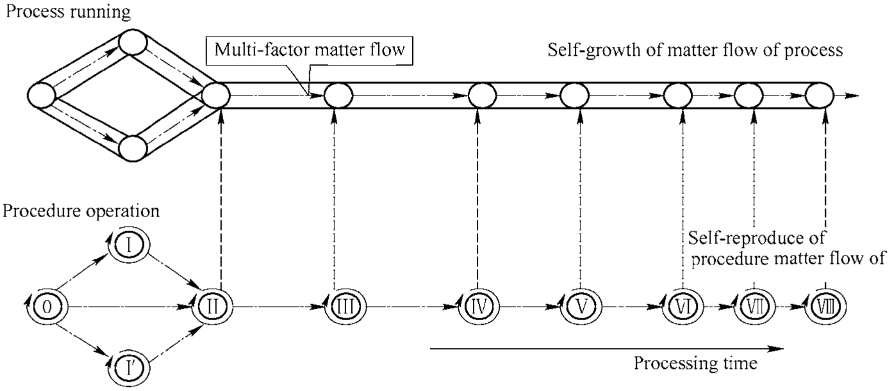


Fig. 5.9 Self-reproduce and self-growth (evolving-coupling on level or scale) in steel manufacturing process (BF-BOF route)

0—Raw material yard; I—Sinter(pellet); I′—Coke oven; II—Blast furnace;
III—Hot metal pretreatment; IV—BOF; V—Secondary metallurgy;
VI—Continuous casting; VII—Reheating furnace; VIII—Hot-rolling mill

About definition of information, N.Wiener (1948) said: "information is information, not matter or energy". But in modern science it was proved that information fundamentally is a property of matter, and can not exist individually apart from the matter. No any separated information aside from matter existed in objective world or to our mind. Information is closely to matter and information is obtained, transferred, treated and utilized without energy consumption. Any information must be carried, represented and fixed by a certain material form, and the material form is information carrier. Certainly, it can be known that the information is a very special property of matter, and can not be recognized completely by natural science until now. Functions of information characterize the matter's composition, structure, state, nature, behavior, performance, evolution trend and so on (Xu, 2000d).

Therefore, if multi-factor mass flow does not run smoothly (includes the related process network unfavorable), information consequently confuses, and it is difficult to make the information flow to collect, to treat and to utilize easily. If model of information flow is not stable and dynamic-orderly, information technology could not be applied in complex manufacturing process to effectively control the system. Even information technology is constrainedly applied in some partial processes and regions, it always gets half the result with twice the effort or is titular.

On the whole, in order to make an effective and valuable information flow in manufacturing process, the operation behavior and the characteristics of *flow* must be understood firstly, and then the reliable process network (static structure of enterprise) should be re-constructed. Establishing physical model of the process operation, the effective mathematical model can be formulated by information technology with effective and valuable information flow, and then the dynamic-order process can be controlled effectively. Fig. 5.10 shows the relationship between physical-mathematical model and integrated model.

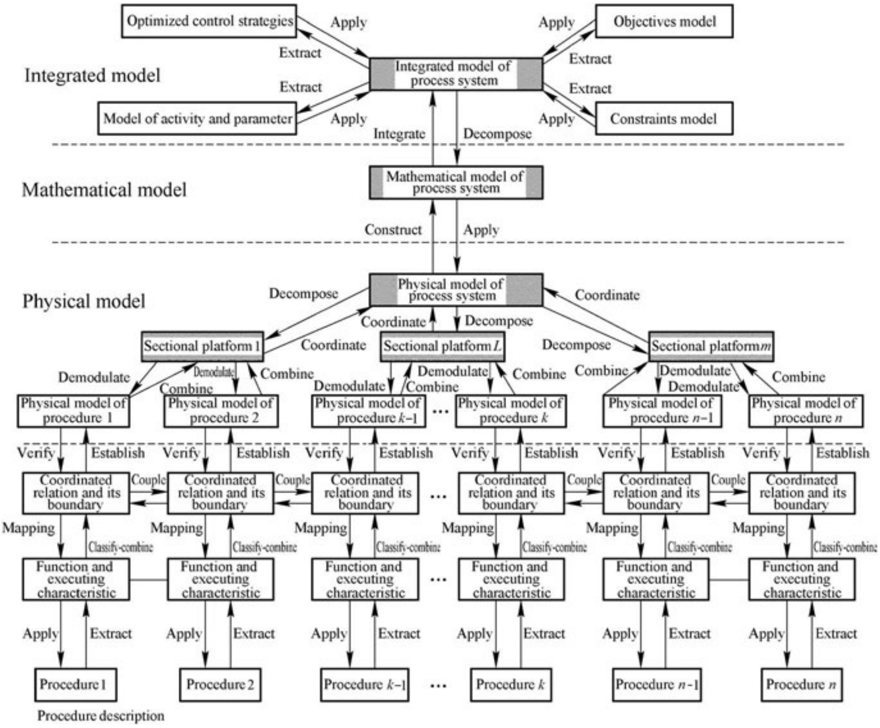


Fig. 5.10 Relationship between physical-mathematical model and integrated model

The physical model of process system means the entire physical statement based on understanding of operational essence of multi-factor mass flow and rational process network. The statement can be made with conceptual words, and also made by formulation. Here, modeling can be adopted mainly with formulated dynamic description.

The dynamic theory can provide the model to describe dynamic behavior and evolution regularity, and provide the language for system analysis. Therefore, it is suitable for describing integrity, stability, adaptability and evolution in complex manufacturing process system. The characteristics of modeling are as follows:

1. Research on the lower levels (some subsystems as procedure, device, workshop) in process system, relating a great number of its components;

2. Analysis and study on the partial connection among components (search for the rules of partial connection);

3. Describing the relation between entire and partial process system qualitatively by attractor (general objective of process system);

4. Embodying the emergence of entire structure and function of manufacturing process with interaction among components (subsystems as procedure, device, workshop).

The steps of physical modeling of steel manufacturing process system are as follows:

1. Dividing optimally the process system to form set of procedures;

2. Defining set of inputs, set of results, set of control and set of procedures' relations;

3. Constructing compact set and its influencing matrix by variables of set of functions and set of inputs;

4. Optimum select variables and values of compact set of procedures (include cost matrix);

5. Combined the optimal compact set and set of procedures' relations to obtain, the whole optimization on process system;

6. Rescinding the circuit between procedures during feedback arising in process, namely circuit existence.

The schematic diagram of control in steel manufacturing process is shown in Fig. 5.11.

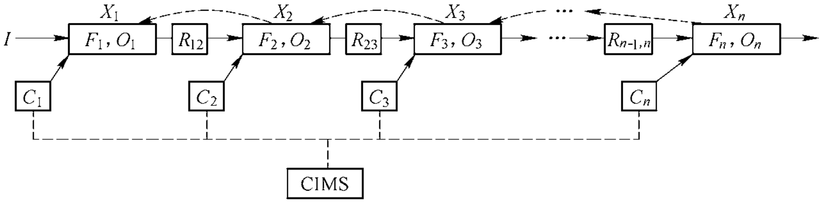


Fig. 5.11 Schematic diagram of control in steel manufacturing process

X—Set of procedures, the collection of procedures with different functions constructing the process; F—set of functions, the collection of procedure functions realized under some constraints; R—Set of procedures' relations, the collection of relations between adjacent procedures or among interacted procedures; I—Set of inputs, the collection of any inputting resources (incl. material, energy, information) into process or procedure; C—Set of control, the collection of control strategies under a certain rule and constraint condition to realize the procedure functions or optimal procedures' relations; O—Set of outputs, the collection of conversion situations and performances realized by set of functions in someone procedure or even entire process under control set C

The combination of process engineering with information technology will have more fit description of the physical model of macro-scale process system, and then improves the effectiveness and reliability of integrity control.

The mathematical model of process can be established on the base of physical model by mathematical analysis, its analysis method may be mechanism analysis or measured data analysis in general.

The integrated model of process can be established by framework language characterizing organization and behavior or by method of strategy, and made on the base of physical and mathematical model under certain rules satisfying the integrity, concept and reference of system.

5.4 Case Study of Multi-factor Mass Flow Control in Steel Manufacturing Process

The essential target of multi-factor mass flow operation in steel manufacturing process is minimum process dissipation. The minimum process dissipation means few or none mass flow decay, smallest energy loss, least emission, brief process time, shortest space route etc. Therefore, the evolution of steel manufacturing process is trend to:

1. Continuation or quasi-continuation;
2. Integration(on time and space);
3. Dynamic-order and controllable.

Research or analysis on multi-factor mass flow in steel manufacturing process could be made by the following steps.

1. The undulation in real running for procedures or devices in process system is investigated, determined and analyzed. For example, in electric arc furnace (EAF)-thin slab casting-rolling process the distribution graph of following parameters can be determined respectively.

- Distribution of tap-to-tap time of EAF (Fig. 5.12);

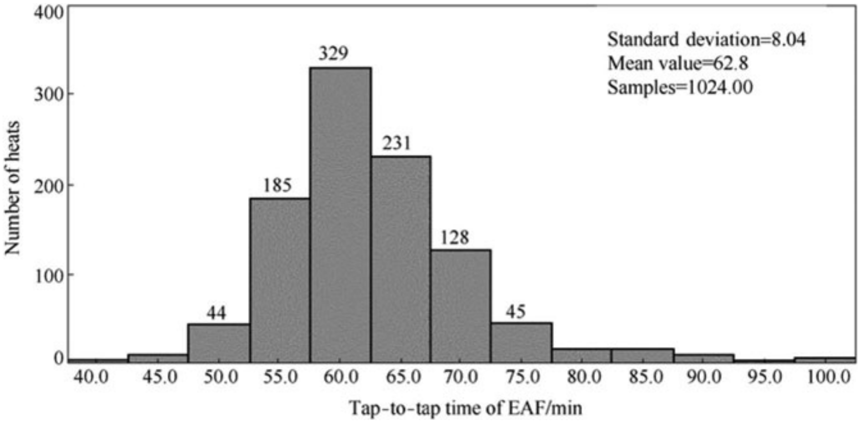


Fig. 5.12 Distribution of tap-to-tap time of EAF

- Distribution of tapping temperature in EAF (Fig. 5.13);

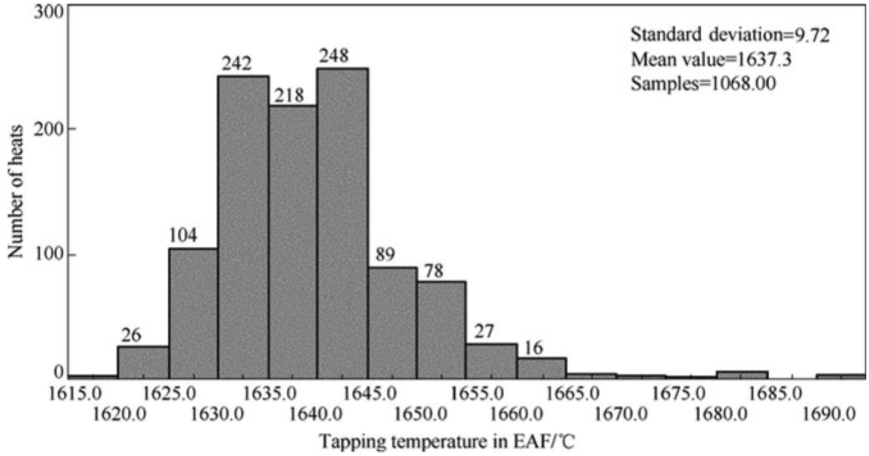


Fig. 5.13 Distribution of tapping temperature in EAF

- Distribution of time-interval from EAF tapping to LF arrival (Fig. 5.14);

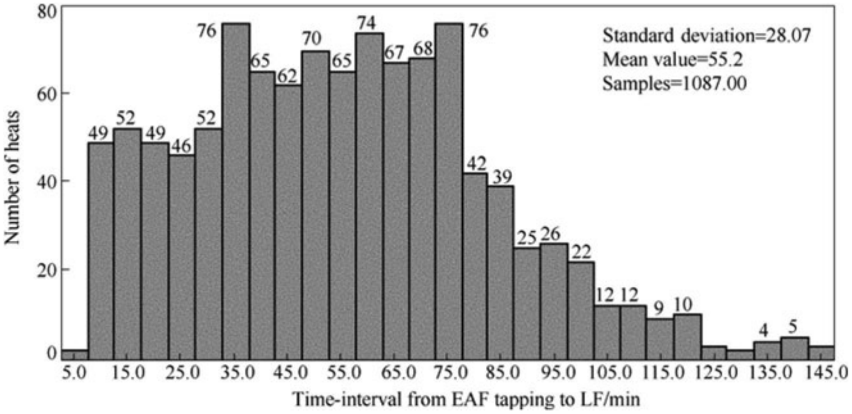


Fig. 5.14 Distribution of time-interval from EAF tapping to LF arrival

- Distribution of temperature drop value from EAF tapping to LF arrival (Fig. 5.15);
- Distribution of refining time in LF (Fig. 5.16);
- Distribution of temperature variation in LF refining (Fig. 5.17);
- Distribution of casting time of one heat of steel on thin slab caster (Fig. 5.18).
- Distribution of slab surface temperature change from entering to exiting tunnel reheating furnace (Fig. 5.19);
- Distribution of time from slab exiting tunnel furnace to biting by rolling mill (always about 8~20 minutes);
- Distribution of time from slab entering stand F1 to leaving stand F6 of rolling mill (Fig. 5.20);

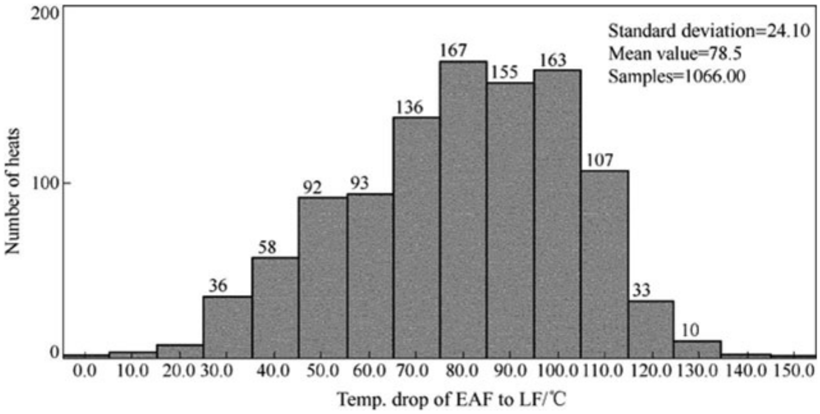


Fig. 5.15 Distribution of temperature drop value from EAF tapping to LF arrival

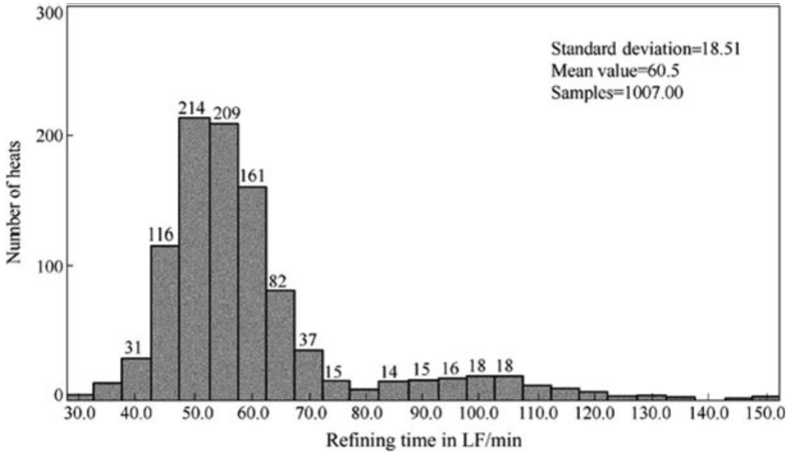


Fig. 5.16 Distribution of refining time in LF

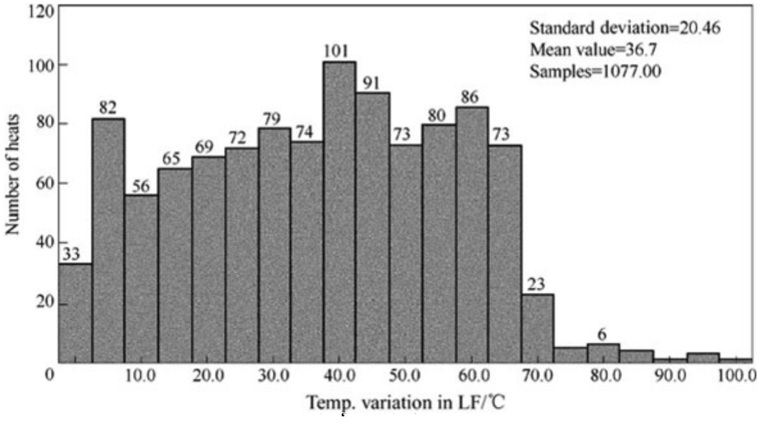


Fig. 5.17 Distribution of temperature variation in LF refining

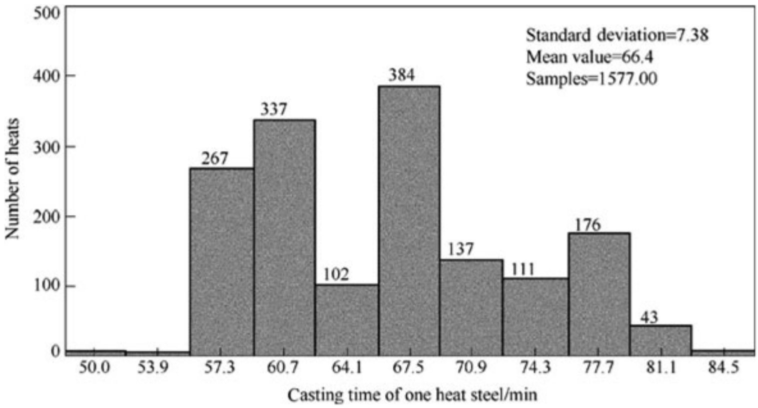


Fig. 5.18 Distribution of casting time of one heat steel on thin slab caster

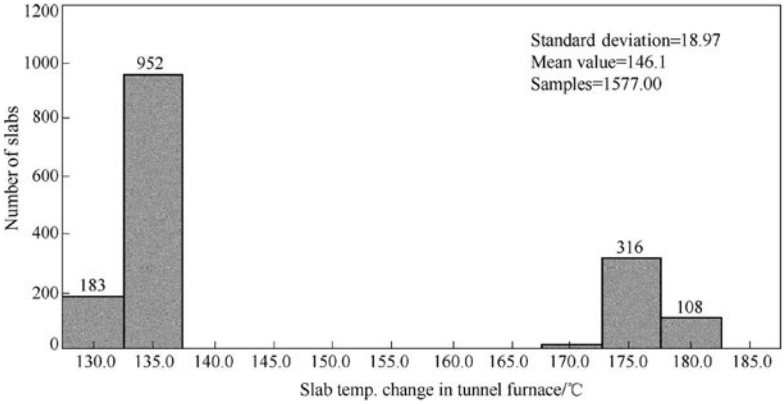


Fig. 5.19 Distribution of slab surface temperature change from entering to exiting tunnel furnace (as few grade in statistical samples only on low carbon steel and middle carbon steel, so deviation is more obvious)

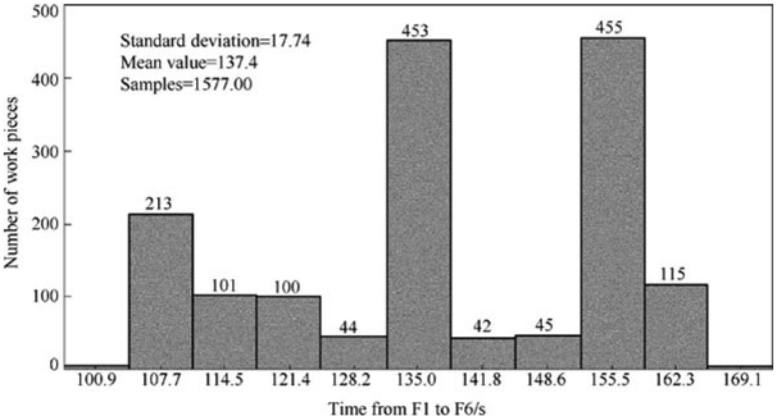


Fig. 5.20 Distribution of time from slab entering stand F1 to leaving stand F6 of rolling mill

- Distribution of time from strip leaving last stand to closing coiling (Fig. 5.21).

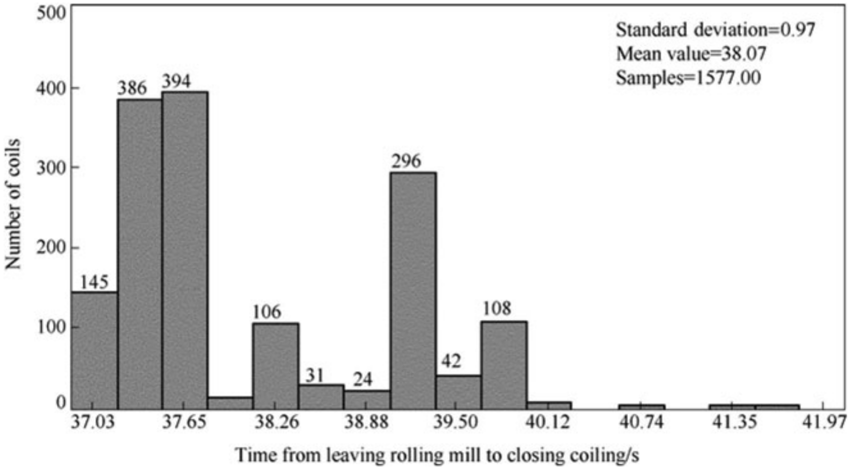


Fig. 5.21 Distribution of time from leaving last stand to closing coiling

2. The nonlinear relations among procedures/devices in process is investigated and analyzed, such as major relationship of basic variables on time, temperature and mass flow.

Fig. 5.12 shows that tap-to-tap time of EAF is mainly 55~70 min, the statistical mean value is 62.5 min.

Fig. 5.18 shows that casting time of one heat steel on thin slab caster is mainly 57~77 min, the statistical mean value is 66.4 min.

Fig 5.16 shows that LF refining time is mainly 45~60 min, the statistical mean value is 60.5 min.

The control rule of procedures' time is meet that the process operates continuously under the key procedure of thin slab caster, namely as following formula:

$$t_{\mathrm{EF}} \leqslant t_{\mathrm{CC}}$$

$$t_{\mathrm{LF}} \ll t_{\mathrm{EF}} \leqslant t_{\mathrm{CC}}$$

where t_{EF} is tap-to-tape time of EAF, min; t_{CC} is casting time of one heat steel in caster, min; t_{LF} is refining operation cycle in ladle furnace, min.

However, Fig. 5.14 shows that time-interval from EAF tapping to LF arrival is 10~70 min, and is almost more than 55 min, the time-interval (incl. transport time, waiting time and so on) is not desirable, and can be shorten to 10~25 min by enhancing the coordination on time-rhythm among procedures, and then improved the continuation and integration of process.

In Fig. 5.12 to Fig. 5.21, it shows that the relation among procedures/devices in steel manufacturing process is nonlinear. In practice, this nonlinearity is expressed as the nonlinear coupling of running time of unit procedures on time axis, and the nonlinear coupling of temperature as well as the matching of mass flowrate for processing time.

3. Analyzing the "pull-buffer-push" in process operation dynamics (chapter 7) coordinating nonlinear relations among procedures/devices, the elastic limiting value of rigid components and the extreme flexibility value of flexible components in process would be determined. Then after certain constraints the proper flexible buffers, including time factor buffer, flowrate buffer, temperature buffer, composition buffer and so on, can be constructed.

4. Many important factors in multi-factor mass flow, especially matter quantity index (as flowrate, composition) and temperature in sectional platform (e.g. steelmaking workshop, rolling mill, etc.), can be coupled on time axis, then the time scheduling plan of process operation in sections can be integrated.

5. The above steps over other sections to construct more sectional platforms are spreaded, and then integrated platform of entire process can be integrated.

6. In real operation on integrated platform of entire process, some order parameters to optimize the process can be found, feeding back on the existing process structure. By means of redistribution of procedure's functions, re-coordination on procedures' relations, reconstruction of procedure constitution and so on, the evolution (optimization) can be improved in steel manufacturing process.

7. The principles for engineering design of entire process are as followings:

- Equivalent principle of mass flow (in minute scale) between upstream and downstream procedures or among devices;
- Convergent and steady principle of temperature with time;
- Continuous/quasi-continuous principle of mass flow;
- Compacted principle of time and space;
- Compacted and simplified principle of process structure.

References

Flick A,Schwaha K L (1993) Das Conroll-Verfahren zur Flexiblen und Qualitts Orientierten WarmbanderZeugung.Stahl und Eisen, 113(9):66

Guo M S, Hu Y, Wang K, Li J H (2002) Multi-scale effect of substance transformations. Heilongjiang Education Press, Harbin, 21-23(in Chinese)

Guo M S, Hu Y, Wang K, Li J H(2002a) Multi-scale effect of substance transformations. Heilongjiang Education House, Harbin, 44-45(in Chinese)

Nicolis G , Prigogine I (1977) Self-organization in nonequilibrium systems. John Wiley & Sons, Inc. NewYork

Wiener N (1948) Cybernetics. Hao Jiren translated (1963). Science Press, Beijing, 133(in Chinese)

Xu G Z (2000a) Systems science. Shanghai Scientific & Technological Education Publishing House. Shanghai, 192-194(in Chinese)

Xu G Z (2000b) Systems science. Shanghai Scientific & Technological Education Publishing House, Shanghai, 194-196(in Chinese)

Xu G Z (2000c) System Science. Shanghai Scientific & Technological Education Publishing House, Shanghai, 196-202(in Chinese)

Xu G Z (2000d) System Science. Shanghai Scientific and Technological Education Publishing House, Shanghai, 342(in Chinese)

Yin R Y (1997) The multi-dimensional mass-flow control system of steel plant process. Acta Metallrugica Sinica, 33(1): 32-38(in Chinese)

Yin R Y (2000) Structural analysis on steel manufacturing process and some problems of engineering effectiveness. Iron and Steel, 35(10): 1-7(in Chinese)

Chapter 6
Time Factor in Manufacturing Process

Time has a decisive effect on the compactness and continuity of multi-factor mass flow operations in manufacturing processes. In the steel manufacturing process, coordination in terms of time is crucial in the operations of all its procedures and devices. The time factor in manufacturing process operations has assumed a wealth of manifestations and forms, as for example time-points, time-positions, time-rhythms, time-cycles, and so forth. Analysis of these forms is of major significance for setting up an effective information regulation and control system at steel plants. Time has a dual role as both an independent variable and an objective function in the dynamic-orderly operation of the manufacturing process at steel plants.

Time factor is the important foundation for studying Metallurgical Process Engineering(MPE). An event has got beginning and end, and an affair has been all along. All the variation and the process evolution always progressed on the time coordinate. The movement and variation cannot be discussed without time sense, let along the processes and manufacturing process yet. The velocity and change rate are shown out through time.

In many cases of fundamental research, the ways of sorting are often used for researching movement or variation under single level-scale relationship, and analyse of time factor is relatively simple. But in the operation course of production of process manufacturing industry involved are complex, so the pattern of expression of time parameter is quite complicated. The time character is multi-level, multi-scale and coupled. The course in manufacturing process includes substantive sub-courses with different distinct, in which some go in parallel, some go in series, some go by coordination, some go by rhythm, some go continuously, some go in batch with intermission etc. Especially, in the production operation of plant, time is treated as a very important objective function, in order to ensure stable, high-efficiency and safe production. So, the colorful time-characteristic factors are special problem which should be researched in process engineering.

R. Yin, *Metallurgical Process Engineering*

6.1 Function of Time in the Manufacturing Process

The basic forms of any substance's existence and movement are space and time. Space embodies the extensive property of substance's existence and movement. Time expresses the pattern of substance's existence and process length of movement, it also expresses the periodic rule and cycle of motion and change of objective events. (Lin, 2002). Time is vital factor to study on processes and manufacturing process, because all the processes develop along time dimension.

6.1.1 *Connotation of time*

Time has two aspects of meaning:

Firstly, time is a measure of movement. This is the time conception in category of physics. Time is quantity of length of events and processes. It shows being longer or shorter about event occurrence or physical/chemical processes. Time factor characterizes the correlations between state and state, event and event, state (or event) and process, process and process.

Secondly, time is the abstraction of all cosmological changes. This is the time conception in category of philosophy. Time is the reflection of all observable objective events, movements and variations in subjective consciousness. It is the absolute regularly lapsed time in subjective mind with idealization, standardization and schematization, and also the theoretically unified time.

6.1.2 *Character of time*

Time has different meaning of science in different conditions. In description of classic mechanics, time t is only an exterior parameter, which is symmetric under reversal, that is, when t is substituted by $-t$, no difference in sight appears. For example, in Newton's equation

$$F = m\frac{d^2x}{dt^2}$$

where variable t expresses time reversible and symmetric. The arrow of time would be no sense for described course. For many physical laws from Newtonian mechanics to quantum mechanics, the elementary equations of motion are symmetric under time reversal.

It is worthy to note that, for thermodynamics, statistical physics and self-organization theory etc, time t possesses vector character in motion system of numerous things. It is asymmetric under time reversal. For example, in Fourier's equation of heat conduction

$$\frac{\partial T(x,t)}{\partial t} = -\rho \frac{\partial^2 T(x,t)}{\partial x^2}$$

where $T(x, t)$ represents temperature at position x and time t, $\rho(>0)$ is coefficient of thermal conductivity. The direction of thermal motion in the equation should be reversed when t is substituted by $-t$. That means, the behavior of described system takes asymmetric under time reversal. Variable t has direction sense. The arrow of time is of crucial importance for studying evolution of system, because system (e.g. process) is with direction. The arrow of time points to the direction of evolution (Xu, 2000). Time, as is well known, is remarkably different from space. In space, it could be realized that something can move from one point to another, but never occurs time reversal. Even if time reversal occurred, an infinitive entropy barrier would be overcome, that is impossible yet (Prigogine and Stengers , 1984).

In realistic course, process and system, time possesses the features of irreversibility and continuity, and it is shown as monotropic reference axis extending towards infinitive. Time is idealization and standardization of a series of process cycles including movement, circulation and variation.

In nature, there are periodic motion and aperiodic motion. Further more, the periodic motion is repeatable in some kinds of forms or features, but not repeatable absolutely and fully. Its general trend does not simply return to original, but develops upward in screw pattern, toward the advanced and newer movement course.

Abstractly, in most occasions, the generation and development of events get periodic feature. The movement course in periodic rule is isotonic continuous process divided by its time-cycle with isochronism, constancy and universality. However, the opinion about periodicity of motion seems idealized and abstracted for much more real systems. In actual production process and daily life, the pure periodic motion occurs only in special conditions, in limited range of certain phase and shows relative periodicity in certain form and certain degree. It would be out of reality of events, if the specificity could not be recognized, or the repeating and re-circulation were emphasized and exaggerated, and the difference and variety of motion were noticed.

In modern condition of science and technology, periodic phenomena in microscopic and mesoscopic view are relatively easy to be observed and studied, but the macroscopic, complicated and gradual evolutions are hard to be observed and are even ignored. Therefore, attention to the significance of corresponding time scale must be paid for researching problems of processes with different scales and levels. Furthermore, details in confusion of micro-processes must be avoided while researching entire macro-process; otherwise, it might be concerned only as tree instead of forest in the time scale. So the corresponding time scale must be well dealt with when we study macroscopic large scale or complicated high level process system.

6.1.3 *Time, clock and time scheduling*

Time, time-cycle and frequency possess identity, which is oriented from periodic motion and its course length.

Clock is periodical counting system, and it is also regarded as the standard frequency generator. Time—the length of an objective movement course can be measured by the size of a cycle of steady recirculating change, i.e. by time-cycle and its multiple. Conventionally, the standard time-cycle of object's recirculating change is the scale for counting time, and its stability and harmoniousness decide the accuracy of time counting.

Frequency and cycle are reciprocal each other. Frequency is the ratio of a circulating motion length to clock showing motion length. Conversely, cycle, i.e. the time length of each cycle, is the ratio of clock showing motion length time to circulating motion length.

In terms of time factor, object's movement course is continuous and countable. So, time is a quantified moving course and also a standard course with measure scale. Actually, in different field the time value of process reference system is decided by running time value of clock in the corresponding reference system. Time scheduling is an important plan for production process and daily life. Time scheduling is always established for describing, forecasting or controlling object's development and progressing. As moving steadiness and stability of development are relative, and the instability and variance are absolute, so time scheduling should always be monitored, controlled and adjusted in movement course.

6.1.4 *Time—a basic and essential parameter*

The object's movement course follows the law of causation. There is no effect without cause. The asymmetry of cause-effect order means that the object always develops forwards and never reverses with time. Time has monotropic character and always goes ahead, i.e. one way direction without return. So the description and control of object's movement course could be just performed with the description and control of time scheduling, but impossible with re-adjustment again in a course of time reversal.

Time is one of the most easily measured parameters in a complex system such as steel plant in process manufacturing industry and social life course. At the same time, it is one of the most easily continuously monitored parameters at everywhere and any moment. It is also a parameter of being most easily measured and controlled in different procedures, different devices, different courses, different objects and different sites. It is noteworthy that time is often a basic and essential parameter to all processes.

6.2 Time Factors in Metallurgical Manufacturing Process

Time is a basic parameter as well as an objective function in metallurgical manufacturing process, however, the knowledge of time is insufficient and the research on time factor is inadequate.

When studying behavior of object's development course or control of production process, time factor is just regarded as a random independent variable with uncertainty. It is believed that time studying is difficult and worthless. Meanwhile, time, as an important target value in metallurgical process, is also ignored. Oftentimes people think that time is chaos even disordered in manufacturing process; look that the coordinator just controls the production process through experience of handling random problems; even consider that time factor is unnecessary to study in metallurgical engineering.

In fact, in metallurgical process engineering, if observing or studying time factors in terms of different scales and levels, some new concept and knowledge would be gotten. The time value of some phenomena or events looks like random or disordered at lower level or smaller scale, but it is ordered and valuable at higher level or larger scale. In many cases, it is found that time is the technical bottleneck in a production procedure or a production process. In other words, there is a critical value of time. For example, when the tap-to-tap time of secondary metallurgy is longer than that of steelmaking furnace and caster, it is very difficult to realize the sequence casting, and the operation continuation of steel workshop would be interrupted.

Obviously, in metallurgical production process, especially in modern manufacturing process, the orderliness and continuity of time parameter are the guarantee for realizing the orderly operation in different scale and continuity of multi-factor mass flow in larger scale. Because any substance changes and develops with time, quasi-continuation/continuation of steel manufacturing process can be expressed as mass flow and energy flow coordinately coupling on time axis through structure optimization of network in steel plant and its functions in different levels (Fig. 6.1). Time factor plays the role of the principal axis for continuation/quasi-continuation of dynamic operation in the metallurgical process. To ensure the continuation of metallurgical devices, procedures and process operations, many crucial parameters such as target values of chemical composition, of deformation, of phase state change, of solidification, of process temperature and of mass flowrate, etc. should be coupled on time axis synergically. Therefore, time is the principal axis on which other crucial parameters are coupled (Fig. 6.2). In other words, only when factors such as chemical composition, physical phase state, energy and temperature, surface feature, and geometry are harmonized with some optimized time-points on time axis, thus the metallurgical process is regarded as optimized or perfect. Here, the chemical composition factor includes the chemical change in metallurgical process, chemical segregation in solidification and composition precipitation under certain temperature in phase change. The physical phase state factor includes the characteristics of aggregate state such as solid or liquid phase in chemical metallurgy and the phase structure and dispersion in rolling process. The geometry factor includes material lumpiness, porosity and fluid flow boundary conditions in chemical metallurgy, the geometric feature of casting mold and its material, as well as the shape of solid and liquid metal in solidification. The geometric deformation of pieces in rolling is also included. The surface feature factor includes surface conditions, phase boundary characteristics, steel cleanliness and defects in chemical metallurgy as well as surface fineness and profile etc. in steel rolling. The energy and temperature factor includes transfer rate, efficiency, and quantity of all temperature or energy parameters in the process of chemical metallurgy, casting, rolling, transportation, stopping and stocking etc. (Table 6.1). The space-location factor includes point locating and plane locating of procedures/devices, such as the number and site of procedures/devices, the correlations and linkage among procedures/devices, the layout of workshops and general layout of plant. This factor would determine the static structure of steel plant directly. The time factor is the principal axis of other factors being coupled, which would be discussed with colorful meaning later.

Table 6.1 The important factors in metallurgical process

Factor classification	Contents of factors			
	Raw materials preparation	Chemical metallurgy	Solidification	Hot rolling
Chemical composition factor	Chemical composition of raw materials or semi-products	Chemical composition of reactants and reaction products	Composition change and distribution in segregation	Composition precipitation at different temperature in phase change
Physical phase state factor	Gaseous, liquid or solid state of raw materials or semi-products	Aggregation state of reactants and reaction products	Change, distribution and state of liquid-solid phases	Phase structure and dispersion degree at different temperature
energy and Temperature factor	Temperature, transfer rate, efficiency, quantity of energy and heat transfer of raw materials or semi-products	Temperature, transfer rate, efficiency, quantity of energy and heat transfer of reactants and reaction products	Temperature, transfer rate, efficiency, quantity of energy and heat transfer of matter	Temperature, transfer rate, efficiency, quantity of energy and heat transfer of matter
Geometry factor	Lumpiness and porosity of raw materials or semi-products , geometric characteristics of reactor flow field	Lumpiness and porosity of reactants and reaction products, property and state of interface, geometric characteristics of reactor flow field	Geometric characteristics of mold, casting pieces and solid-liquid phase	Geometric deformation, dispersion of matter at different temperature
Surface-feature factor	Surface porosity, roughness of raw materials or semi-products	Surface characteristics, property and state of interface of reactants and reaction products	Surface cleanliness, surface defect characteristics of casting pieces	Characteristics of surface smooth state, surface defect and property at different temperature
Space location factor	As the static framework and spatio-temporal boundary of process operation			
Time factor	As the quasi-continuation/continuation cooperative coupled principal axis for other factors			

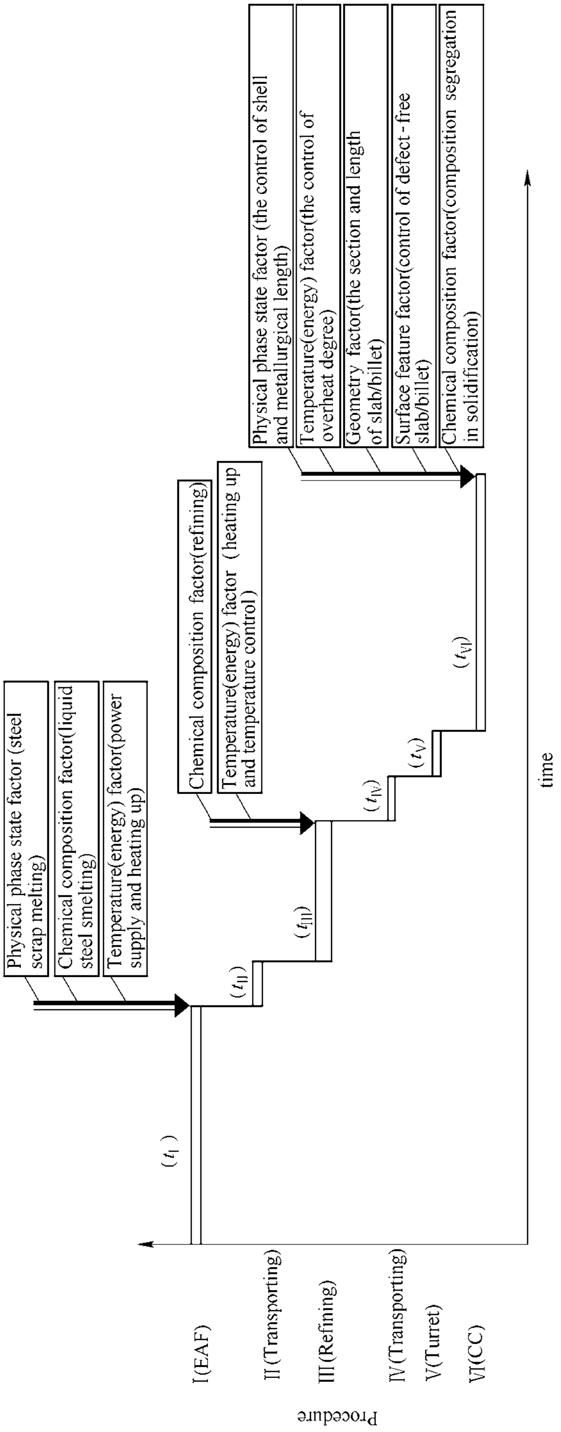


Fig. 6.1 The coupling-running course of multi-factor mass flow at time axis in electric arc furnace steel plant with fully continuous casting

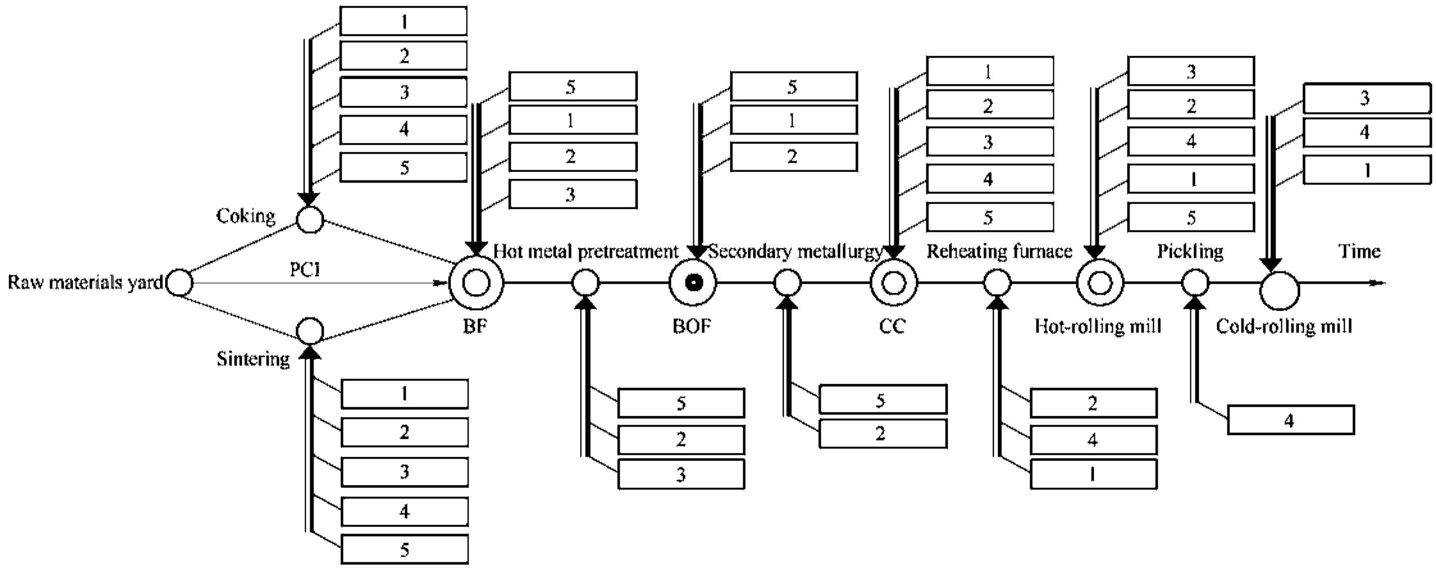


Fig. 6.2 The sketch of important factors of different procedures coupled with time axis in integrated steel manufacturing process

1—Physical phase state factor; 2—Temperature(energy) factor; 3—Geometry factor; 4—Surface feature factor;

5—Chemical composition factor (The space-location factor is not involved because the process dynamic runs in a determined static structure)

During the modernization of metallurgical production process, information passing through is very important. In modernized compact steel manufacturing process, such as thin slab casting-rolling, the research on time scheduling of mass flow in manufacture process should be crucial and frontier issues, which must be studied as a basic research subject for automation and intelligence of the new generation steel manufacturing process.

In terms of the history of the ferrous metallurgy, the time factor has critical and subversive impact on survival, development or elimination of some techniques, devices and procedures because of the comprehensive influence of time factors on energy consumption, material consumption, quality and product costs, and environmental burden. It seems as if the open hearth furnace has advantages of multi-function and integration, so the open hearth furnace had been regarded as the best or most flexible technology and a substitute for air bottom blown converter, even some electric arc furnace. However, the open hearth furnace could not match with sequence continuous casting and was finally eliminated, because the tap-to-tap time is to long (over 5 hours at least). So the importance of time factor is obvious.

The reason of the large-scale UHP-EAF development is the plentiful of cheap scrap and electricity. However, in terms of process engineering science, the main achievements of modern electric arc furnace technology are utilization of UHP and application of physical energy, chemical energy and oxygen blowing, so the melting time, heating-up time, oxidizing time are shortened and reduction period is eliminated. On the basis of integration and application of some technologies, the tap-to-tap time of electric arc furnace has been shortened from 4 hours to 90min or 60min even less. It makes that EAF(Electric Arc Furnace) smelting can coordinately running with continuous casting. In this case, the oxygen consumption of about $30\text{Nm}^3/\text{t}$ steel is needed to reach the tap-to-tap time of less than 60min. Correspondingly, the tap-to-tap time of ladle furnace should also fit the time-rhythm.

In steel manufacturing process, time factor is becoming more and more important because of the application of continuous casting, continuous rolling, semi-endless rolling, especially thin slab casting-rolling technology. Therefore, it is more indispensable to research and design time factors for the continuation, compactness, orderliness and harmonization in steel manufacturing process.

In metallurgical production process, the continuity of process can be expressed by the continuation/quasi-continuation of mass flow on time axis, the compactness by more and more shortening of time-cycle in whole process, the orderliness by the sequence, rhythm and stability of each unit, each procedure/device in manufacturing process, the coordination of function and efficiency by adjacent procedures/devices in mass flow coupling and coupling speed on time axis. The coordination of process can also be regarded as the restoring ability of procedures/devices coupling, if the coupling be broken down. Therefore the continuation can fit the varying and complicated environment.

Therefore, it is observed that time factor takes extremely obvious comprehensive influence on existence and development of steel plant. Moreover, time factor must be studied entirely and deeply for the process information passing through.

The study on time factor is a cut-in point that promotes the fundamental research of metallurgy from simplicity to complexity. And it is also one of the keys to do research on different scales and levels. Because time factor can not only be abstracted from issues at different levels and scales but also be proposed from a critical target at a higher levels and reduced to lower levels and scales for analyze-optimizing, a series of R&D subjects would be put forward.

6.3 Time Factors in the Production of Steel Plant

It can be found from above discussion that time is a parameter especially worthy to be discussed in steel manufacturing process. The time factors influence many aspects on different spatio-temporal scale, such as continuatiou or batch operation in manufacturing process, character of the conversion and its mechanism, business opportunity and market competition, recycle of social waste, energy etc. All the technological meaning and economical value of them are necessary to research.

6.3.1 *The importance of time factors*

The time is a key parameter in production system of steel plant and is also a basic variable in the production and management (Yin, 1998). The operation time of steel manufacturing process has become shorter and shorter, because most steel plants involved to fully continuous casting system and faced with plant restructuring, especially since 1990s, thin slab casting-rolling had been successfully put into use widely and the compact steel plant had been rapidly developed and operation time of steel plants has become shorter and shorter. The control of time factors in steel plant becomes more and more important.

For the management of steel plant, the delivery term characterizes the importance of time and influences competition of steel plant. During the whole course of order receiving, raw materials and fuels purchasing, production preparing and organizing and products delivering as well as fund circulating, the operation program and time-cycle must be arranged reasonably.

For the manufacture in steel plant, the importance of time embodies in series of time factors, such as the time scheduling of raw materials and energy transportation and different procedures operation as well as the harmonization of time-points in the process. At the same time, it is necessary to regulate time scheduling when production condition is changed.

6.3.2 *Forms and connotation of time in steel manufacturing process*

In production process of steel plant, especially in compact steel plant, the coordination of time factors among procedures/devices is very important. So the expression forms of time in production process are becoming more and more plentiful. In order to make the process to be coordinated and controlled easily, the time is expressed not only as the time length of some processes, but also as the time-point, time-interval, time-position, time-order, time-rhythm and time-cycle etc. It is significant to analyze the expression forms of time factors for establishing effective information controlling system in steel plant. For realizing the continuation/quasi-continuation operation of manufacturing process, time factors must be studied as the objective function. The meaning of time in coordination or integration of unit procedures in steel manufacturing process should be analyzed. In fact, steel manufacturing process is incessantly developing forwards to continuation. The continuation of manufacturing process is more complicated than that of a simple continuous reactor. For example, when studying on intelligent scheduling and control of steel production, all kinds of influence factors and the mechanisms must be researched. The shortest time of process and the highest continuation degree, including high temperature linkage, compatibility and production efficiency should be reached in the case of all requirements and boundary conditions. Here, time is regarded as an objective function. Obviously, with a view to the regularity of temperature change, processing time and transportation time among procedures have great influence on temperature change in ferruginous mass flow (hot metal, molten steel, slabs and rolled pieces). In these moments, time of processing, transporting and waiting is treated as an independent variable. Thus, it is clear that time in steel production plays the both roles of independent variable and dependent variable (objective function).

For a procedure/device, the time value is composed of all kinds of main operation time, supplement operation time, transporting time, loading/unloading time and waiting/buffering time. The concrete expression forms are the scheduling and controlling of time point of procedure (starting time or leaving time), time-interval of process (time length and start-end period) and time-rhythm (frequency of procedure operation time and process cycle).

For the relationship between upstream and downstream procedure, time factors behave as the arrangement of time-order, the control of time-position, the linkage, buffering and coordination of time-interval in long and/or short range. The short range control exists between two procedures and the long range control exists among three or more procedures. It also behaves as the arrangement of transportation, length of waiting time and scheduling between transporting and waiting time.

6.3.3 *Statement of expression of time factors*

1. Time-point. The start-end time of operation *k* in procedure *o* corresponded by ferruginous mass flow, such as ore, scrap, hot metal, molten steel, slab, rolled piece etc, is defined as time-point, which is expressed as $[t^o_{\mathrm{ks}}, t^o_{\mathrm{ke}}]$(Fig. 6.3(a)). The meaning of time-point is reflected not only in procedure, but also in the entire manufacturing process (Fig. 6.3(b)). However, there is difference between scheduled time-point and real time-point in production process.

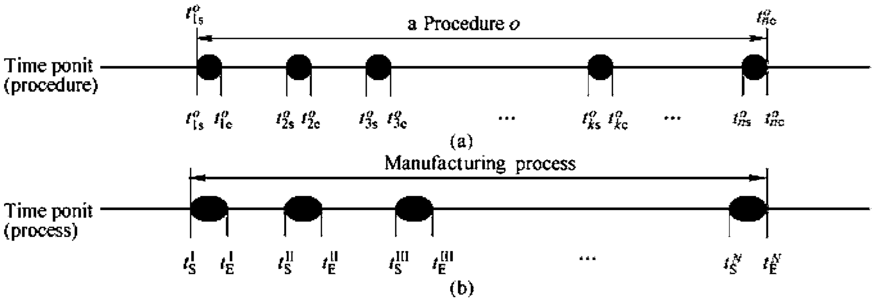


Fig. 6.3 The schematic diagram of time-point

(a) Procedure; (b) Manufacturing process

In Fig. 6.3, $t^o_{1\mathrm{s}}, t^o_{2\mathrm{s}}, t^o_{3\mathrm{s}}, \cdots, t^o_{k\mathrm{s}}, \cdots, t^o_{n\mathrm{s}}$ are the start time-points of the operations 1, 2, 3,···, *k*,···, *n* in procedure *o*;

$t^o_{1\mathrm{e}}, t^o_{2\mathrm{e}}, t^o_{3\mathrm{e}}, \cdots, t^o_{k\mathrm{e}}, \cdots, t^o_{n\mathrm{e}}$ are the end time-points of the operations 1, 2, 3, ···, *k*, ···, *n* in procedure *o*;

$t_{\mathrm{S}}^{\mathrm{I}}, t_{\mathrm{S}}^{\mathrm{II}}, t_{\mathrm{S}}^{\mathrm{III}}, \cdots, t_{\mathrm{S}}^{N}$ are the start time-points of procedures I, II, III,···, *N* in manufacturing process;

$t_{\mathrm{E}}^{\mathrm{I}}, t_{\mathrm{E}}^{\mathrm{II}}, t_{\mathrm{E}}^{\mathrm{III}}, \cdots, t_{\mathrm{E}}^{N}$ are the end time-points of procedures I, II, III,···, *N* in manufacturing process.

2. Time-order. For improving the technical and economic indexes such as cost and productivity etc., the time of every procedure in mass flow should be arranged in series and scheduled coordinately according to the sequence of technological process. So the time-order of manufacturing process integrated running would be formed. Time-order contains two concepts, i.e. time scheduling order of some operations in procedure *o* and the array order of some procedures in manufacturing process (Fig. 6.4). It can be described as follows:

In Fig.6.4, $t^o_1, t^o_2, t^o_3, \cdots, t^o_k, \cdots, t^o_n$ are the time scheduling order of the operations 1,2,3,···,*k*,···,*n* in procedure *o*;

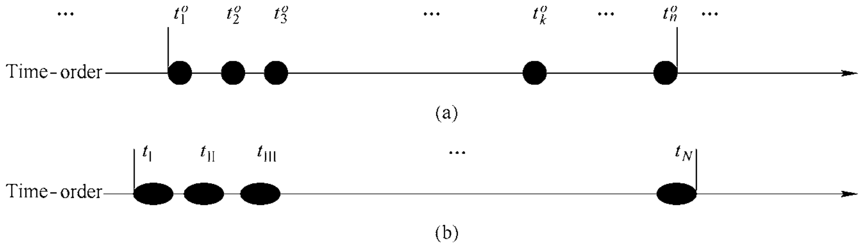
$t_{\mathrm{I}}, t_{\mathrm{II}}, \mathrm{t}_{\mathrm{III}}, \cdots, t_N$ are the time array order of the procedures 1,2,3,···,*N*.

3. Time-interval. Generally, the time length of mass flow located in procedure *o* is composed of time as for main operating, supplementary operating, transporting, waiting and buffering etc. Time-interval contains the total time of all above and the start and end time-points. It can be expressed as follows:

$$t_{\mathrm{SE}}^{o} = \sum t_{\mathrm{se}}^{\mathrm{r}} + \sum t_{\mathrm{se}}^{\mathrm{a}} + \sum t_{\mathrm{se}}^{\mathrm{w}} + \sum t_{\mathrm{se}}^{\mathrm{buf}} + \sum t_{\mathrm{se}}^{\mathrm{t}}$$

$$[t_{\mathrm{S}}^{o}, t_{\mathrm{E}}^{o}]$$

where t_{SE}^{o} is the total operation time of procedure *o*, min; $\sum t_{\mathrm{se}}^{\mathrm{r}}$ is the main operation time of procedure *o*, min; $\sum t_{\mathrm{se}}^{\mathrm{a}}$ is the supplement operation time of procedure *o*, min; $\sum t_{\mathrm{se}}^{\mathrm{w}}$ is the waiting time of procedure *o*, min; $\sum t_{\mathrm{se}}^{\mathrm{buf}}$ is the buffering time of procedure *o*, min; $\sum t_{\mathrm{se}}^{\mathrm{t}}$ is the transporting time of procedure *o*, min; t_{S}^{o} is the start point of procedure *o*, min, t_{E}^{o} is the end point of procedure *o*, min.



(a)

(b)

Fig. 6.4 The schematic diagram of time-order

(a) Time-order of different operations in a procedure$\{t_1^o, t_2^o, t_3^o, \cdots, t_k^o, \cdots, t_n^o,\}$;

(b) Time-order of different procedures in manufacturing process$\{t_{\mathrm{I}}, t_{\mathrm{II}}, t_{\mathrm{III}}, \cdots, t_N\}$

The time-interval of procedure characterizes not only the start time-point and end time-point but also the time length of different procedure (Fig.6.5). In addition, the concept of time-interval could be extended to series of procedures or even more.

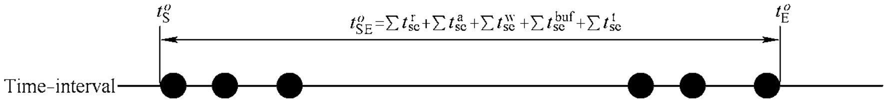


Fig. 6.5 The schematic diagram of time-interval in procedure

4. Time-position. Due to the supplementary operation time, waiting time and buffering time, it is observed from the definition of time-interval that the main operating time should locate at a rational position in the corresponding time-interval, which would directly influence the scheduling, controlling and optimizing of the entire manufacturing process. Therefore, time-position means the position of certain time-interval. Time-position is described by following expressions mathematically:

$$t^o_{SE}=\{\Delta t_{BE}, t^r_{SE}, \Delta t_{AF}\}$$

$$t^r_{SE}=t^r_E-t^r_S$$

$$t^r_{SE}=\Sigma t^r_{se}$$

$$[t^r_S, t^r_E]$$

where t^r_{SE} is the main operation time-interval in procedure, min; t^o_{SE} is the time-interval of procedure, min; t^r_S is the start time-point of main operation, min; t^r_E is the end time-point of main operation, min; t^r_{se} is the operation time-interval in procedure, min; Δt_{BE} is the supplementary operating, transporting, waiting and buffering time before main operation, min; Δt_{AF} is the supplementary operating, transporting, waiting and buffering time after main operation, min.

The relative values of Δt_{BE}, Δt_{AF} and t^r_{SE} have direct influence on the position of t^r_{SE} in certain t^o_{SE} (Fig. 6.6). The time-position characterizes the time length of mass flow through the procedure, rational time position of operation and its start-end time-point.

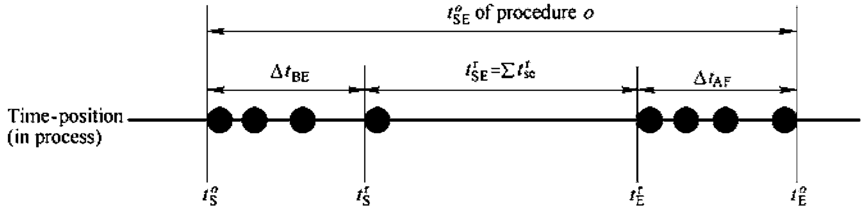


Fig. 6.6 The scheme of time-position

5. The time-cycle and time-rhythm of production. The time-cycle is the total time length, while mass flow passes through all procedures in manufacturing process. It contains main operation time, supplementary operation time, transporting time, waiting time and buffering time (Fig.6.7). It can be expressed as following:

$$t_c=t^{I}_{SE}+t^{II}_{SE}+t^{III}_{SE}+\cdots+t^{N}_{SE}$$

where, t_c is time-cycle, min; t^{I}_{SE}, t^{II}_{SE}, t^{III}_{SE},⋯, t^{N}_{SE} is the time-interval of the procedure I, II, III,⋯,*N* respectively, min.

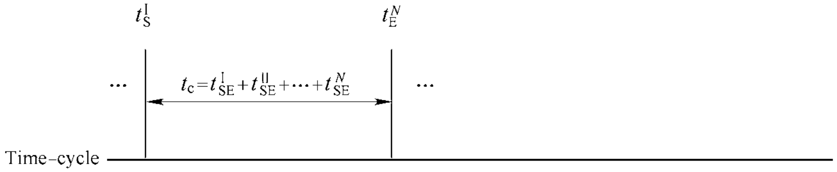


Fig. 6.7 The composition of time-cycle

When a number of production time-cycles proceed continuously and the time-cycle approximately equals with each other, the time-rhythm is established as following:

$$t_c^{i} \approx t_c^{ii} \approx t_c^{iii} \approx \cdots \approx t_c^{N}$$

A regular and ordering time-rhythm would be formed in this way (Fig.6.8).

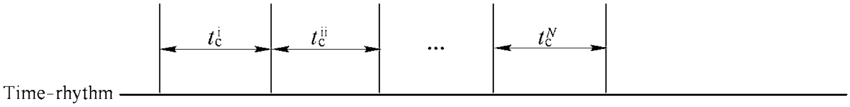


Fig. 6.8 Scheme of time- rhythm

Of course, this type of manifestation of time-cycle and time-rhythm of production expresses not only in operation running of whole manufacturing process but also in running of procedures and workshops.

6.4 Continuation Degree of Steel Manufacturing Process

In process industry as metallurgical and chemical industry, the continuation degree of manufacturing process reflects the technological progress, marketing competition and sustainable development potential of enterprises. It also becomes one of the targets of research, design and production.

The operation of manufacturing process is the course of time consumption. As the whole production process, time consumption value and its composition are the important mark of continuation degree.

6.4.1 *Theoretic continuation degree*

For a kind of product producing, there should be a theoretic time of processing, if the manufacturing process has been designed correctly and perfectly. Moreover, the procedure, device and technology have also been optimized. The theoretic time of processing can also be regarded as the minimum process time t_0 when product producing under ideal boundary conditions and be expressed as

$$t_0 = \Sigma t_1 + \Sigma t_2 + \Sigma t_3 + \Sigma t_4$$

where t_0 is the theoretic time of processing of mass flow in steel manufacturing process to produce a kind of product, min, Σt_1 is the sum of theoretic operation time of mass flow passing through all procedures or devices, min, Σt_2 is the sum of designed transporting time in process network of mass flow, min, Σt_3 is the sum of designed buffering and waiting time in process network of mass flow, min, Σt_4 is the sum of designed maintenance time which influences the whole process operation, min.

Obviously, the theoretic continuation degree C of the manufacturing process is

$$C = \frac{\Sigma t_1}{t_0} \qquad 0 < C < 1$$

In process design, it should be pointed out that t_0 should be shortened and Σt_1 could not be increased for improving the continuation degree C.

6.4.2 *Actual continuation degree*

In production process, the actual processing time of mass flow is different from the design under ideal boundary conditions, because there are time fluctuations in operations, procedures or devices.As it is impossible that production process runs under ideal boundary conditions, generally, the actual processing time of mass flow is longer than theoretic time and can be expressed by

$$t_0^r=\sum t_1^r+\sum t_2^r+\sum t_3^r+\sum t_4^r+\sum t_5^r$$

where t_0^r is the actual time of processing of mass flow in steel manufacturing process for producing a kind of product, min; $\sum t_1^r$ is the sum of actual operation time of mass flow passing through all procedures or devices, min; $\sum t_2^r$ is the sum of actual transporting time in process network of mass flow, min; $\sum t_3^r$ is the sum of actual buffering and waiting time in process network of mass flow, min; $\sum t_4^r$ is the sum of actual maintenance time which influences the whole process operation, min; $\sum t_5^r$ is the sum of time of breakdown which influences the whole process operation, min.

The actual continuation degree C^r of the manufacturing process is

$$C^r=\frac{\sum t_1^r}{t_0^r} \qquad 0<C^r<1$$

In production process, it is possible to shorten t_0^r obviously by adopting a series of advanced technology and management measures. When the near-net-shape casting replaces the traditional continuous casting and the tunnel reheating furnace replaces the walking bean furnace, the $\sum t_1^r$ is shortened obviously. The $\sum t_2^r$ and $\sum t_3^r$ are also shortened accordingly, and then a new manufacturing process with higher continuation degree would appear.

The continuation degrees C^r of different steel manufacturing processes are compared in Table 6.2.

Table 6.2 The continuation degree of some steel manufacturing processes

Manufacturing process	t_0^r/min	Σt_1^r/min	C^r/%
BF—BOF—ingot teeming—hot charging—hot rolling	4900	857	17.5
BF—hot metal pretreatment —BOF—secondary metallurgy—continuous casting — cold charging — hot rolling	2456	653	26.6
BF—hot metal pretreatment—BOF—secondary metallurgy—continuous casting — hot charging — hot rolling	1506	653	43.4
BF—hot metal pretreatment —BOF—secondary metallurgy—thin slab casting-rolling	917	603	65.8

The processing time and temperature of different steel manufacturing processes are shown in Table 6.3 ~ 6.6.

Table 6.3 Processing time, temperature in BF—BOF—ingot teeming—hot charging—hot rolling process

Procedure	Actual time consumption /min	Cumulative time consumption /min	Temperature /℃
Taking out of raw material yard		10	
Raw material transportation	30	40	
Sintering	32	72	1400
Sinter transportation	15	87	800
Stocking in bin	393	480	
Charging and smelting in blast furnace	390	870	
Blast furnace tapping	30	900	1450
Hot metal transportation—mixer—pouring from mixer	120	1020	
Waiting and preparing for charging hot metal to converter	10	1030	1350
Converter blowing	40	1070	1650
Ladle delivering and waiting	15	1085	1560
Ingot teeming	60	1145	1550
Waiting	60	1205	
Entering in soaking pit	60	1265	750
Reheating in soaking pit	150	1415	1250
Blooming	50	1465	400
Slab/bloom transportation, entering storehouse and cooling	360	1825	40
Slab/bloom stocking	2880	4705	40
Slab/bloom transportation	60	4765	
Reheating	60	4825	1180
Hot rolling and coiling	15	4840	700
Product transportation to storehouse	60	4900	100

Table 6.4 Process time, temperature in blast furnace—hot metal pretreatment—converter—secondary metallurgy—continuous casting—cold charging—hot rolling process

Procedure	Actual time consumption /min	Cumulative time consumption /min	Temperature/℃
Taking out of raw material yard		10	
Raw material transportation	30	40	
Sintering	32	72	1400
Sinter transportation and stocking	120	192	350
Charging and smelting in blast furnace	390	582	
Blast furnace tapping	30	612	1450

Continued Table 6.4

Procedure	Actual time consumption /min	Cumulative time consumption /min	Temperature/℃
Hot metal transportation	15	627	
Hot metal pretreatment	40	667	
Deslagging and hot metal transportation	30	697	1300
Converter blowing	36	733	1650
Ladle delivering and waiting	8	741	
Secondary metallurgy	25	766	1580
Ladle delivering and waiting	10	776	1570
Continuous casting	60	836	1550
Slab transportation	10	846	500
Slab stocking	1440	2286	60
Slab transportation and reheating	100	2386	1180
Hot rolling and coiling	10	2396	700
Products transportation to storehouse	60	2456	100

Table 6.5 Processing time, temperature in blast furnace—hot metal pretreatment—converter—secondary metallurgy—continuous casting—hot charging—hot rolling process

Procedure	Actual time consumption /min	Cumulative time consumption /min	Temperature /℃
Taking out of raw material		10	
Raw material transportation	30	40	
Sintering	32	72	1400
Sinter transportation and stocking	120	192	350
Charging and smelting in blast furnace	390	582	
Blast furnace tapping	30	612	1450
Hot metal transportation	15	627	
Hot metal pretreatment	40	667	
Deslagging and hot metal transportation	30	697	1300
Converter blowing	36	733	1650
Ladle delivering and waiting	8	741	
Secondary metallurgy	25	766	1580
Ladle delivering and waiting	10	776	1570
Continuous casting	60	836	1550
Slab transportation and waiting	540	1376	650
Reheating	60	1436	1180
Hot rolling and coiling	10	1446	700
Products transportation to storehouse	60	1506	100

Table 6.6 Processing time, temperature in blast furnace—pretreatment of hot metal—converter—secondary metallurgy—thin slab casting - rolling process

Procedure	Actual time consumption /min	Cumulative time consumption /min	Temperature /℃
Taking out of raw material		10	
Raw material transportation	30	40	
Sintering	32	72	1400
Sinter transportation and stocking	120	192	350
Charging and smelting in blast furnace	390	582	
Blast furnace tapping	30	612	1450
Hot metal transportation	15	627	
Hot metal pretreatment	40	667	
Deslagging and hot metal transportation	30	697	1300
Converter blowing	36	733	1650
Ladle delivering and waiting	8	741	
Secondary metallurgy	25	766	1580
Ladle delivering and waiting	10	776	1570
Continuous casting	50	826	1550
Thin slab transportation and waiting	1	827	950
Reheating	20	847	1100
Hot rolling and coiling	10	857	700
Products transportation to storehouse	60	917	100

6.5 The Analysis for Time Factor of Thin Slab Casting-Rolling Process

The thin slab casting as an advanced technology is also called near-net-shape casting which developed at the end years of the 20th century. The compact steel plant was formed from it. Here, the meaning of compactness is the compact of space and shorten of time.

The characteristics of the compact steel manufacturing process are as follows:

- By selecting critical slab thickness for reasonable rolling mill, the slab can be filled into hot strip mill directly without roughing mill.
- By rapidly regulating temperature of slabs with ultra cut-length in tunnel reheating or holding furnace to get further spatio-temporal compactness and much lower consumption of material and energy.
- By the self-organization function among steelmaking furnace-refining furnace-thin slab caster–tunnel furnace-hot strip mill-coiler, including control measure of information integration, the online operation coordination with time among procedures and devices in manufacturing process would be realized, then the continuation degree would be improved.

Obviously, thin slab casting-rolling process is a sort of compact-coordinating-continuous production process. From the view point of continuous-coordination running, the manufacturing process can be regarded as an elastic syntony chain constituted of rigid components and flexible. components. The rigid components contain steelmaking furnace, caster, hot rolling mill. The flexible components contain secondary metallurgy, reheating furnace, ladle and tundish. For the sake of continuation-coordination running among these components, the principles should be considered as following:

- Optimization of operation time of procedures and devices as well as optimization of time scheduling of the whole manufacturing process;
- Coordination optimization and minimization of transporting time, waiting time and buffering time among procedures and devices;
- Optimization of overheat degree of molten steel in tundish and estimation of tapping temperatures of secondary metallurgy and steelmaking;
- Determination of casting speed and surface temperature of slab according to overheat degree of molten steel in tundish, and calculation of minimum time through reheating furnace or holding furnace correspondingly;
- Rational temperature range of molten steel in procedures/devices, and the corresponding successive convergence of temperature range in each procedure/device(Fig.6.9);
- Time scheduling of mass flowrate - temperature - time among procedures;
- Combination of static optimization at designed condition (convergence) and dynamic control under practical operating condition (divergence-convergence).

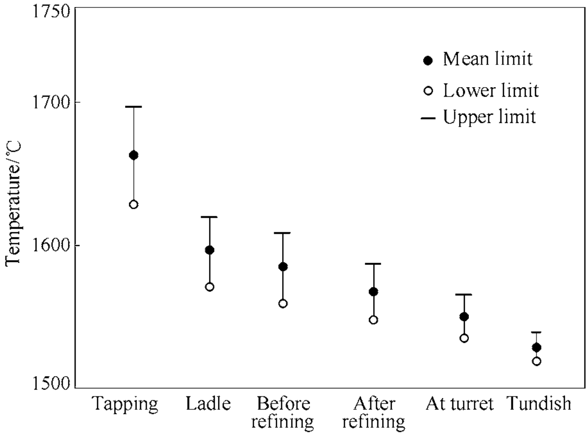


Fig. 6.9 Convergence analysis of temperature in steelmaking process (Yin,1998)

In regulation and control of the thin slab casting-rolling, the mass flowrate and process temperature should be coupled on time axis for continuation and coordination of whole process. So, the processing time in steel manufacturing process can be analyzed and integrated briefly by using concepts such as time-point, time-order, time-position, time-interval and time-cycle under designed layout (Fig.6.10).

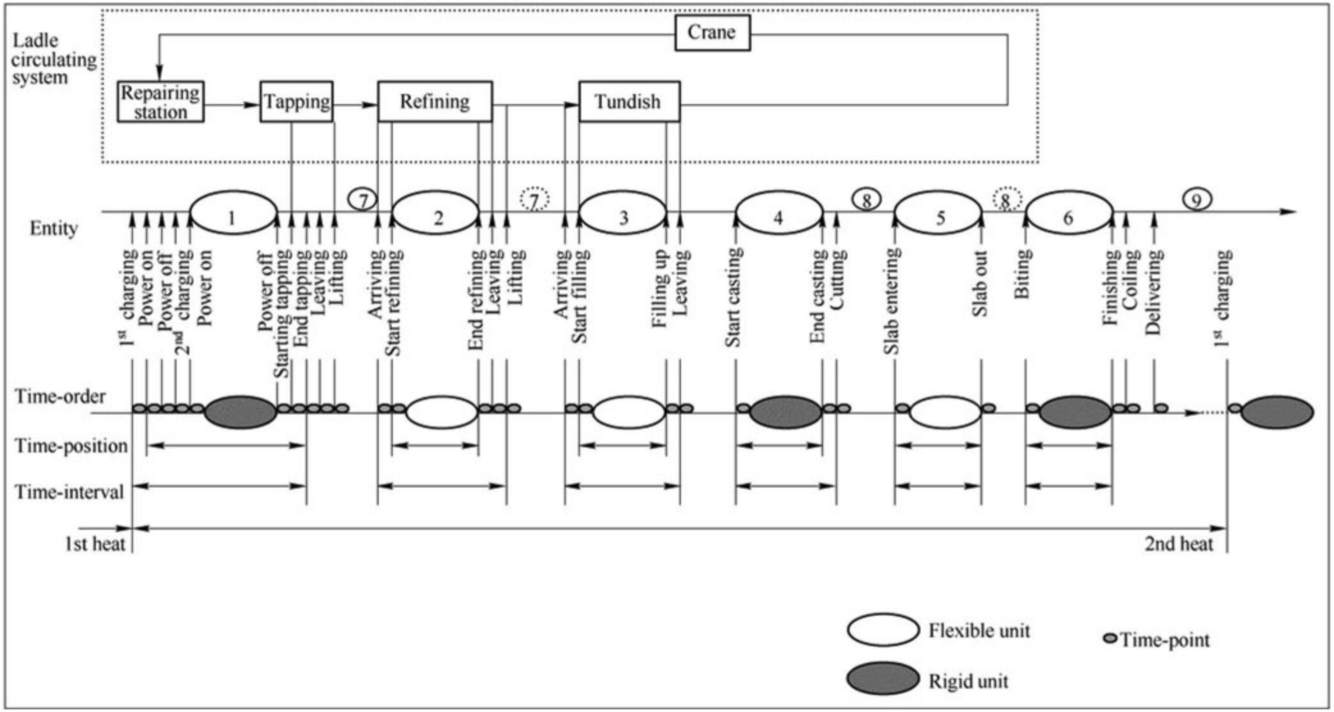


Fig. 6.10 Time analysis and integration in thin slab casting-rolling process（Yin, 1998）

1—EAF; 2—Refining furnace;3—Tundish; 4—Caster;5—Reheating furnace;

6—Rolling mill; 7—Molten steel; 8—Slab ; 9—Products

It can be seen from Fig. 6.10 that time-order in process is decided by function order in process firstly. Taking the electric arc furnace—thin slab casting-rolling process as an example, the functions of melting-temperature control-time scheduling are realized by electric arc furnace, the functions of refining-temperature control-time scheduling by refining furnace, the functions of casting-shaping-temperature control-time scheduling by caster, the functions of heating or holding-time scheduling by reheating furnace and the functions of deforming-phase transforming-temperature control-time scheduling by hot rolling mill. Similarly, the time-charocteristic order of a series of unit operations is also arranged by corresponding function order for a certain procedure.

The time-interval of a procedure/device consists of main operation, supplementary operation, transportation, loading/unloading, buffering and waiting time for realizing the specific functions such as steelmaking, refining, casting and rolling in the corresponding procedure/device. Because of the difference of the time-interval values in every procedure/device, one or more key procedures, their time-intervals and running rhythms should be found, and then the time-intervals and time-positions of other procedures/devices would be determined for continuation/quasi-continuation and compactness. So the thin slab caster is the key procedure in electric arc furnace workshop. For continuous and compact running, the rule of key parameters of time-interval control among procedures should be

$$t_{\mathrm{EF}} \leqslant t_{\mathrm{CC}}$$

$$t_{\mathrm{LF}} << t_{\mathrm{EF}} \leqslant t_{\mathrm{CC}}$$

where t_{EF} is tap-to-tap time of EAF, min; t_{CC} is casting time of one heat steel in caster, min; t_{LF} is refining operation cycle of ladle furnace, min.

In normal conditions, the reasonable range of operation time fluctuations should be

$$\Delta t_{\mathrm{CC}}^{o} \leqslant \Delta t_{\mathrm{EF}}^{o} < \Delta t_{\mathrm{LF}}^{o}$$

where, $\Delta t_{\mathrm{CC}}^{o}$ is the rea sonable range of operation time fluctuations of caster, min; $\Delta t_{\mathrm{EF}}^{o}$ is the reasonable range of operation time fluctuations of electric arc furnace, min; $\Delta t_{\mathrm{LF}}^{o}$ is the reasonable range of operation time fluctuations of ladle furnace, min.That means the operation time of thin slab caster should be stabilized and optimized.

The range of waiting time fluctuations of each procedures should be

$$\Delta t_{\mathrm{CC}}^{\mathrm{w}} \leqslant \Delta t_{\mathrm{EF}}^{\mathrm{w}} < \Delta t_{\mathrm{LF}}^{\mathrm{w}}$$

where, $\Delta t_{\mathrm{CC}}^{\mathrm{w}}$ is allowed range of time fluctuations of caster, min; $\Delta t_{\mathrm{EF}}^{\mathrm{w}}$ is allowed range of time fluctuations of electric arc furnace, min; $\Delta t_{\mathrm{LF}}^{\mathrm{w}}$ is allowed range of time fluctuations of ladle furnace, min.

That means the waiting time of thin slab caster should be minimized as much as possible. At the same time, the total waiting time of all procedures should be stabilized and minimized.

The overheat degree of molten steel in tundish should be controlled within 10~20℃ above liquidus.The objective temperature fluctuations ranges of molten steel leaving EAF and LF should be restricted within ±20℃ and ±10℃ respectively.

The objective temperature fluctuations ranges of molten steel in EAF, LF and CC should be

$$\Delta T_{\mathrm{CC}} < \Delta T_{\mathrm{LF}}^{\mathrm{off}} < \Delta T_{\mathrm{EF}}^{\mathrm{off}}$$

where $\Delta T_{\mathrm{LF}}^{\mathrm{off}}$ is the objective temperature ranges leaving LF, ℃, $\Delta T_{\mathrm{EF}}^{\mathrm{off}}$ is the objective temperature ranges leaving EAF, ℃, ΔT_{CC} is the objective temperature ranges of tundish metal for CC, ℃.

That means by coordination of procedures, the overheat degree of molten steel in tundish could be controlled within 10~20℃ above liquidus.

The coordinative rule of mass flowrate of procedures is

$$Q_{\mathrm{EF}}=Q_{\mathrm{LF}}=Q_{\mathrm{CC}}$$

where Q_{EF} is the average output per minute from EAF, t/min; Q_{LF} is the average output per minute from LF (ladle furnace), t/min; Q_{CC} is the average slab output per minute from caster, t/min.

It means that stable sequence casting had been realized and slab output optimized by coordination of mass flowrate from EAF(electric arc furnace) and LF(ladle furnace).

The relationship between temperature drop and waiting time in thin slab casting-rolling process can be expressed as

$$\Delta T=f(\Delta t^{\mathrm{w}}, G, R)$$

$$\Delta t=f(\Delta T, R)$$

where ΔT is the temperature drop of molten steel between procedures,℃; Δt^{w} is the waiting time between procedures, min; Δt is the transporting and loading time, min; G is molten steel capacity of ladle or tundish, t; R is other correlation factors.

That means the molten steel temperature drop is related with capacity of ladle or tundish, and also with waiting time, transporting time, etc.

To maintain continuation and compactness of manufacturing process, the rules of operation time minimization, mass flowrate coordination and energy consumption minimization must be abided by from thin slab caster to hot rolling mill.

The mass flowrate coordination takes

$$nQ_{\mathrm{CC}}=nQ_{\mathrm{rh}}=Q_{\mathrm{ro}}$$

where Q_{CC} is the average output per minute from thin slab caster, t/min; n=2 or 1; Q_{rh} is the average output per minute from reheating furnace or holding furnace, t/min; n=2 or1; Q_{ro} is the average output per minute from hot rolling mill, t/min.

Actually, the mass flowrate of reheating/holding furnace and rolling mill are decided according to the mass flowrate of thin slab caster. If there is accident of rolling mill and intermittent time is too long, the mass flowrate of thin slab caster would be influenced. For example, if intermittent time of rolling mill exceeds 20min, casing speed should be reduced; if exceeds 40min, the thin slab casting would be interrupted. For compact steel plant, the accident feed back of rolling mill to thin slab caster should be paid attention to. The total time of t_{CC}^{rh}, t_{rh}, t_{rh}^{ro} and t_{ro} should be minimized. Here t_{CC}^{rh} is the transportation time from cutting machine to reheating/holding furnace, min; t_{rh} is the operation time of slab in reheating/holding furnace, min; t_{rh}^{ro} is the transportation time from reheating/holding furnace to rolling mill, min; t_{ro} is the operation time of rolling mill, min.

Reduction of slab processing time from thin slab caster to rolling mill would benefit the energy consumption, production efficiency and cost saving.

The total temperature loss ΔT_{cc}^{rh}, ΔT_{rh} and ΔT_{rh}^{ro} should be minimized to save energy. Here ΔT_{cc}^{rh} is the slab temperature drop from cutting machine to reheating/holding furnace, ℃; ΔT_{rh} is the slab temperature increase in reheating/holding furnace, ℃; ΔT_{rh}^{ro} is the slab temperature drop from reheating/holding furnace to rolling mill, ℃.

The waiting time between rolling mill and reheating furnace should be

$$\Delta t_{ro}^{w} < \Delta t_{rh}^{w}$$

where Δt_{ro}^{w} is the range of waiting time of rolling mill, min; Δt_{rh}^{w} is the range of waiting time of reheating/holding furnace, min.

In order to coordinate the time-intervals of every procedures, the flexible components, such as secondary metallurgy, reheating furnace or holding furnace, are necessary not only for controlling the time-interval lengths but also for coordinating the time-positions. For example, if the time-intervals t_{EF}, t_{CC}, and t_{LF} are 60 min,60 min and 40 min respectively, there are some time-interval lengths used for transporting, buffering as well as waiting before and after t_{LF}. time-position designing of ladle furnace is how to set start and end time-points of t_{LF}. The selection of time-position has a critical influence on parameters time and temperature of the corresponding procedure and device operation. It also influences whole process continuity and stability as well as the techneconomic indexes such as energy consumption etc.

The time-point in process running is often take as a target value to be controlled. It means the clock measured start and end time of a procedure or an operation in the procedure and characterizes the clock measured time-cycle or rhythm running. It is also the objective function for arranging, regulating and controlling of time scheduling.

Generally speaking, the dissipation value, consisting of decay of mass flowrate, temperature undulation, and time-space interval of mass flow in manufacturing process, will be minimum because of the high continuation degree and spatio-temporal compactness of thin slab casting-rolling process.

References

Prigogine I, Stengers I (1984) Order Out of Chaos. Zeng Qinghong and Shen Xiaofeng translated.(1987), shanghai Trauslation Pub.Shanghai: 29, (In Chinese)

Lin J F (2002)What does the time be. Studies in Dialectics of Nature.18(2)：75-76 (in Chinese)

Xu G Z (2000) System Science. Shanghai Scientific & Technological Education Publishing House, Shanghai:30 (in Chinese)

Yin R Y (1998) The Engineering analysis of thin slab casting and rolling process, Iron and Steel, 33（1)：2-6 (in Chinese)

Chapter 7

Operating Dynamics in the Production Process of Steel Plant

From the viewpoint of the time operations of mass flow in steel plant manufacturing processes, the diverse procedures and devices in the steel manufacturing process should function as ***pushing forces****,* ***buffers****, and* ***pulling forces*** *respectively in order to ensure continuous and smooth implementation of production operations and schedules. Analysis of the operating dynamics of the upstream and downstream sections of steel plant manufacturing processes shows that blast furnace acts as a* ***pushing force*** *in the entire operation; continuous caster plays a dual role, i.e. as a* ***pulling force*** *in the upstream section and as a* ***pushing force*** *in the downstream section; whereas downstream hot rolling mill acts as a* ***pulling force****. To ensure continuous and coordinated operations between the* ***pulling forces*** *and* ***pulling forces****, it is necessary to set up a number of procedures and devices that serve as* ***buffers*** *or* ***flexible loops*** *between the two forces, so as to coordinate these two forces and bring about a continuous or quasi-continuous operation of mass flow in the manufacturing process.*

In general, process dynamics is a science of the mechanism and the regularity about the state of matters or objects with time. Dynamic process characteristics at different scales and levels may be general or different. The difference shows in dimension, scale and space-time.

Process dynamics at the micro and meso scopic levels in the iron and steel manufacture is easy to be observed, estimated and simulated. This type of dynamic process can easily be modeled for its short cycle and on small scale.

It is difficult to estimate the dynamics of evolutionary process at the macroscopic level for its large space scale, long time cycle and the complexity. This large scale complex process system is often considered as to be disordered and is hard to study for many influencing factors and instable interference sources. It is difficult to model the macro process operation dynamics such as the production

R. Yin, *Metallurgical Process Engineering*

process in entirety of steel plants. Sometimes, the model can be obtained based on the understanding the micro and mesoscopic kinetics analysis-optimization of the set of procedure's functions and further integration-optimization of the set of procedures in steel manufacturing process.

On studying dynamic processes at different scales and levels, it should be noticed that the significance of the magnitude and the spatio-temporal scale of the matter or energy. It couldn't be neglected. Space factors are rather steady because the layout was fixed. Time-characteristic factor should be considered much more. Time-coordinate axis is mostly to be as the backbone. Many factors such as production efficiency, product quality, product specification, process emission,and process recycle, should match the time scheduling of manufacturing process. In other words, these factors should harmonize on the time-coordinate axis of production. Meanwhile, details in the kinetics of micro or mesoscopic processes may be ignored, emphasis should be laid upon the continuity, compactness and synergism of the production flow in entirety of the whole steel mill, as well as the coupling and efficiency on the function—structure of procedures and devices. Otherwise, many problems as disorientation, conceptual chaos and unmerited method would happen. The production process of the steel manufacture from the storage of raw materials and energy sources, coking, sintering, ironmaking, hot metal pretreatment, steelmaking, secondary refining, continuous casting, reheating to hot rolling could be regarded as a typical multi-scale and long-route complex process system. The research topics on the operating dynamics in the manufacture process of steel plant are as follows:

1. Manifestation and essence of operation;
2. Operating dynamic characteristics of production process;
3. Operating mode and rhythm of different procedures / devices in production process;
4. Relationship between the pushing and pulling force of different procedures /devices and the ability of matching, buffering and coordinating in manufacture process;
5. Evolution and optimization of interface techniques in production process such as ironmaking-steelmaking interface, steelmaking-continuous casting interface, continuous casting-hot rolling interface;
6. Engineering synergistic effect of operations in the production process of steel plant.

7.1 Evolution of Production Operation in Steel Enterprises since 1990s

Guiding idea and its trendency for production operation in steel enterprises will be discussed in these sections.

7.1.1 *Guiding idea for production operation in steel enterprises in the first half of the 20th century*

In the first half of the 20th century, the production operation in steel plants took the steadiness of the system as its target; the dominant trend of operation was stability. At that time, the main bottleneck was the long operation time with great undulations about the open hearth steelmaking, ingot teeming and blooming. The equipment durableness couldn't be desired and the production failures often appeared. Therefore, the structure of the process system pursued the stationary improvement. Those were reflected in the technical measures taken by the iron and steel enterprises:

1. Direct repetition. Many of the major technological equipment sometimes set up spare devices, the results were more and more blast furnaces and open hearth furnaces, ingot teeming and rolling lines.So it became more complicated.

2. Increasing the intermediate buffer devices, or the storage quantity. For example, the rhythm of time between blast furnace and open hearth furnace was not coordinated. The flow of liquid metals between the ironmaking and the steelmaking could not be matched because the long time of the open hearth heat. Therefore, bulky mixer for hot metal was introduced between blast furnace and steelmaking. It seems to make coordination of liquid metal flow, but a long intermittence of the ferruginous mass flow existed and the energy consumption and the environment load were also increased. Similarly, ingot bay and numerous soaking pits had been installed between ingot teeming and blooming. Between blooming plant (including breakdown mill) and the finishing mill section there were large stock of semi-finished products....Certainly, these measures kept steady production of iron and steel enterprises, but there were a series of issues in terms of per capita output efficiency, products delivery, logistic transport, energy depletion, material consumption, emissions and environmental load.

3. Universal product mix. As the system ingot casting-breakdown rolling was easy to get blooms with various sizes and various shapes, so the iron and steel enterprises always made many diverse products of plates, tubes, pipes, sectional bars, bars and wire rods. Even more than 8 hot rolling production lines were located in one factory. This further led to the frequently reciprocating transportation and the piecemeal workshop distribution. The final result was the total confusion in the layout and the frequently reciprocating traffic.

In the first half of the 20th century, the production process structure was featured as simple repetition and overlap because of the lower technology and simple facilities in ironmaking and steelmaking. The operation was characterized by frequent intermittence. The goal was stability under conditions of heavy ingot and thick bloom with multiple reheating and rolling. This is actually a negative feedback strategy.

7.1.2 *Guiding idea for production operation in steel enterprises in the second half of the 20th century*

Down to the later half of the 20th century as the end of world war the global reconstruction led to the increasing market demand for steel products. Moreover, due to the implementation and the improvement of basic oxygen converter, large volume blast furnace, tandem rolling mill and particularly continuous casting technology, the manufacturing process became itself to the quest for development. This is the development based on the steadiness of the process system. Since development of the fully continuous casting technology the "bottleneck" of the ingot teeming—breakdown rolling route had been eliminated. It coupled with the replacement of OHF by efficient BOF, the continuous/ quasi-continuous and ordered operation of the steelmaking section was founded. The high productive steel works with fully continuous casting appeared in the 1970s. Fully continuous casting in the iron and steel enterprises made the steelmaking section not only to be continuous/quasi-continuous operation but also to increase a substantial productivity. This, in turn, promoted development of the facilities and functions in the up-stream and the down-stream processes. Large blast furnace with the volume over 4000m^3, hot rolling strip mill with the productivity over 3.5 million t/a had developed well. These three items had formed the back-bone of continuous/quasi-continuous operation of the steel manufacturing production process of whole steel works. The iron and steel enterprises' structure were undergone an important revolution. Due to the simplication and coordination of production process and also equipment, a substantial increase in production capacity, production efficiency and energy efficiency has been improved, the process emission reduced, and the product quality improved.

After middle age of 20th century, the mode of steel mill has changed basically through three stages:

1. Since basic oxygen converter process appeared in 1952, the capacity of the iron and steel production has been expanded step by step. Appearance and maturity of mammoth converter's promoted the large blast furnace and the various rolling mills to be enlarged, continuous, automatic and high-speed. The hot rolling strip mill was representative of which. Until the oil crisis, all the steel works kept the core procedure of ingot teeming-breakdown mill, and usually being a universal steel factory which could produce all types of products, such as coils sheets, plates, pipes, sections, bars, rods and wires. Even one plant for ultra-large-scale of

10 million t/a of products was targeted.

2. From 1973 to 1989, as the oil crisis and energy insufficiency the system of ingot teeming-blooming as well as the OH steelmaking were eliminated because of the rapid development of continuous casting, particularly the fully continuous casting system. The process system had been changed thoroughly accompanied with development of UHP-EAF, slab hot conveying and charging into reheating furnace etc. Mode of the steel mills developed to energy saving, specialized product competitory and with rational capacity.

3. Since 1989, the thin slab casting-rolling technology has been put into production in Nucor. Steel production processes became "compactness and continuous", the new "compact" steel plant mode has been applied in industrial production. Meantime clean steelmaking, semi-endless rolling, ferrite rolling, substituting cold strip with hot strip etc. began practising to a certain extent.

Generally speaking, the guiding idea of the steel plants was development on the base of the steady operation in the second half of the 20th century. It is a positive feedback strategy.

7.1.3 *Tendency of guiding idea for production operation of modern steel plants beyond the 20th century*

Since the end of the 20th century, steel plants tend to sustainable development and products' competitiveness with reasonable capacity for the following factors: oversupply of steel products in the global market, problems of the resource limitation and the earth environment pollution. Due to restriction from market space, price, cost and offering radius, the process operation in iron and steel production is designed considering not only the rationality of the operation inside the plant but also the friendliness between mankind and nature. The unity of development and environment, the adaptability for industrial ecology and the circular economic society must be pursued. The premise of development depends on how to position the iron and steel enterprises' social/economic functions. And the functions which adapt and coordinate to neighbor urban, surrounding industrial zone and social consumption are needed.

In the view of technological progress, the production process of steel plant develops from simplicity to complexity and then returns to simplifying. In the process, matching, coordination, compactness, energy-saving, resources utilization, cleaner production and eco-industrial chain should be attracted much attention. Steel plant with the capabilities to consume a large amount of municipal wastes by the way of resource recycling is interested.

Since the end of 20th century, the development strategy of steel plant would not only limit to the inner issues but also extend to the society. So it becomes an open, cooperative and comprehensive engineering system.

Through the reasonable process system, rational sale region and production capacity, then by means of organization, the steel group corporation even an enterprise strategic alliance would realize the competition, cooperation and win-win. Furthermore, the steel enterprise should be harmonized into the circular economy based on the ideas of LCA and inter-process linkage, becoming an important sector in the eco-industrial zone. This is a more intensive development strategy.

7.2 Dynamic Features of Production Process Running of Steel Plants——Operation Form and Essence

From the history of the production process development of the iron and steel manufacture, it can be seen that the production process went on the way from batch running to continuous/ quasi-continuous. The compactness, quasi-continuation /continuation and product specialization of manufacturing process are still the main adjustment direction of the process structure. The variation of the production process resulted in not only the evolution of steel modes generation by generation, but also the product mix composition, the capacity rationality, the gross domestic investment and the market competitiveness. In the view of the operation dynamics the character of the steel production process running feature is developed from a series of batch operations structure to the integral continuous/quasi-continuous operation.

The production process in steel plants which mainly use iron ore and coal as raw materials is a complicated system consisting of the chemical metallurgy (reduction, oxidation, refining etc.), the solidification and the physical metallurgy (rolling, forging, phase control, surface treatment etc.). In the engineering essence, the steel production process is a combination of the matter state transformation, the matter property control and the mass flow control. The matter state transformation means course from oxides to metal; from liquid metal to solid; from casting structure to rolling/forging structure; from high temperature structure to room temperature structure etc. The matter property control means the control of metal/slag behaviors, the control of steel cleanliness, the control of the shape and size of rolled steels, the control of metal structure, the control of product properties & surface feature etc. The mass flow control means the procedure's arrangement and route of manufacturing process, transportation of materials and energy, logistic transportation etc. (Fig.7.1, Yin, 1997a).

Taking a view of structure of plants, the steel production only considered the combination of the matter state transformation and the matter property control until the 1970s. The mass flow control was separated before the fully continuous casting plant arising. This was manifested as the fact that there are many ingot pits & yards, bloom or billet storing bay and bulky mixers. As the fully

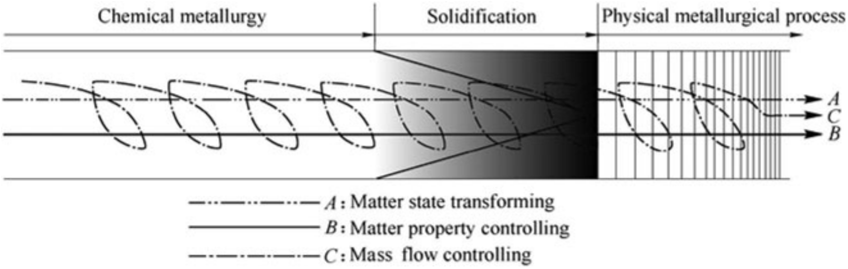
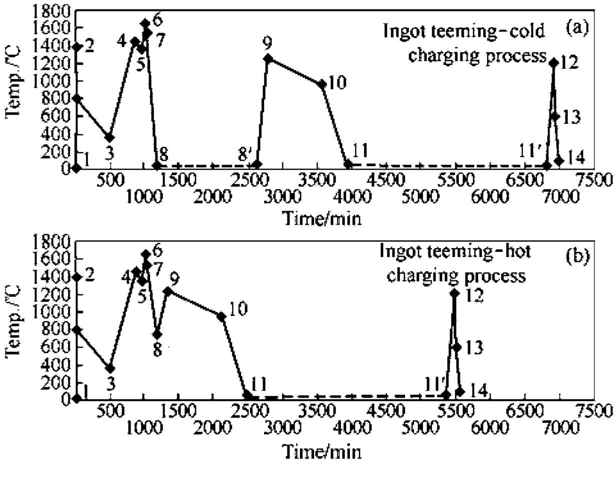


Fig. 7.1 Combination of the matter state transforming, the matter property controlling and the mass flow controlling in the production process

continuous casting steel plant setting up, the ingot teeming—blooming disappeared, finish rolled metal was made with only one reheating operation. The hot connection of steelmaking—refining—casting—reheating—hot rolling began realizing. Since that the matter state transformation, the matter property control and the mass flow control are tightly combined in the production process. With the near-net-shape casting as the core technology, a new generation of compact steel plants is appeared. In such steel plants, the combination of the matter state transformation, the matter property control and the mass flow control is much more tighter. Moreover, the features of coordination and rhythmic became more obvious. Differences about the tight degree of the combination of matter state transformation, matter property control and mass flow control will lead the process to various temperature undulations and unlike operation cycles as shown in Fig.7.2(Yin, 1998).



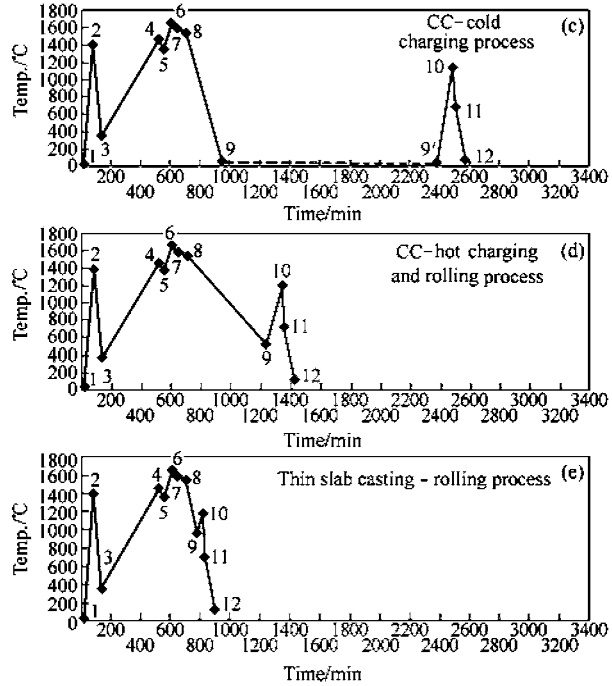


Fig. 7.2 Scheme of compactness, continuation and intermittence in the steel production process

Ingot teeming process(a,b):

1—Raw materials; 2—Sintering; 3—Ore chute; 4—Blast furnace tapping; 5—Hot metal charging; 6—Converter tapping; 7—Teeming; 8(8') —Ingots; 9—Soaking pit; 10—Breakdown mill; 11(11')—Slab yard; 12—Reheating furnace; 13—Finishing-coiling; 14—Products warehouse;

Continuoas casting process(c,d):

1—Raw materials; 2—Sintering; 3—Ore chute; 4—Blast furnace tapping; 5—Hot metal charging; 6—Converter tapping; 7—Refining; 8—Casting; 9(9') —Slab yard; 10—Reheating furnace; 11—Hot rolling-coiling; 12—Products warehouse;

Thin slab casting-rolling process(e):

1—Raw materials; 2—Sintering; 3—Ore chute; 4—Blast furnace tapping; 5—Hot metal charging; 6—Converter tapping 7—Refining 8—Casting 9—Slab transport 10—Reheating furnace; 11—Rolling-coiling; 12—Products warehouse

The variation in the structure of three generations of steel plants characterizes sustained continuation of the manufacturing process. The gradual process continuation led to the minimum attenuation of mass flow of metals (high yield, low cost of manufacture); the minimum undulations of metal temperature during the process (energy saving, environmental protection, low cost, etc.); the minimum processing time and inventory (productivity, cost, delivery time, etc.) as well as the satisfaction on quality of products optimized (qualified metals and exact performance).

Above all, the operating dynamics of the production running in steel plants in form of a series of batch operations of procedures or devices is cooperative to continuous/quasi-continuous process by means of synergy and integration.

The continuation/quasi-continuation of the production process in the steel plants takes the following features:

- The continuous / quasi-continuous mass flow;
- The continuous energy flow;
- The compact link of the material flow and energy flow in the space scale (layout, transport route etc.);
- The exact coupling of the mass flow, energy flow and information flow on the time axis.

7.3 Operating Mode of Different Procedures and Devices in Steel Production Process

Through a great deal of long term practice in R&D and production, it is noted that the steel manufacture process is very complex and is made up of many procedures. On purpose to pursue continuation of the steel production process, we can not just change the batch operation of each device into continuous, nor also the whole process direct into straight-way continuation at one go. Instead, the continuity of steel production process should be obtained by the technical ways of the optimization of the procedure functions, the joint among the short or long procedures with rhythmic, compact and coordinative relationships via interface technique. Moreover, the continuation and quasi-continuation of the steel production process had begun with some key procedures, such as blast furnace, continuous casting and continuous rolling and then extended to the whole production process by effective combination.

In other words, the character of the steel production process should be described with the physical model at first by the process engineering research. Then, the Management Information System (MIS) in every section will be established on the support of the management science and the information technology, ultimately the Computer Integrated Manufacturing System (CIMS) for the whole process. It is obvious that the continuation can be realized depending on the integration of process engineering, information technology and management science.

From the process engineering point of view, the running features of main production procedures in the steel plant are as follows(Yin, 1997):

1. Blast Furnace. The running essence is the continuous reduction-carbonization with heat transfer in a counter current moving bed of the shaft furnace. But the iron tapping is with intermittence. So the blast furnace has a continuous operation process with batch iron tapping.

2. Converter. The running essence is the rapid reaction and heating-up of the bath with high rate but not continuous. The steel tapping is batch operation also. So the converter steelmaking belongs to the speedy, high frequent, periodic batch

processes.

3. Secondary metallurgy. The running essence is the bath reaction- temperature-control and time-control process with flexible and frequent intermittence. The way of tapping is also flexible and intermittent with a coordinating function. Its flexibility is expressed in parameters as mass flowrate, temperature, time, and just metal quality etc.

4. Continuous Casting The running essence is the continuous/quasi-continuous heat exchange-solidifying-cooling process. But the output way of slabs, blooms or billets is quasi-continuous operation.

5. Reheating furnace. The running essence is heating-up temperature control and time control process with continuous heat transfer. The output of slabs or billets is batch operating.

6. Hot Rolling Mill. Continuous operation is the essence of its plastic deformation and phase transformationat high temperature, but the way of input-output of rolled pieces is with intermittence. The endless/semi-endless rolling promotes the continuation of input-output of metals.

According to the above-mentioned analysis about the running essence and the output operation of the major procedures, as well as the structure evolution of the three generations of steel plant, we can see that the progress of steel production processes is based on the coordination of the batch or continuous operations in various procedures and the output with intermittence. By the way of "*generalized loop engineering*" for short and long processes, i.e. developing the interface techniques among procedures or devices, the quasi-continuous / continuous production process in entirety of steel plant can be gradually realized.

7.4 Running Strategy for Steel Production Process

From the analysis about the operation features of different procedures / devices in the steel production process, it is obvious that different procedures and devices have different running essences and operation modes. With a generalized observation on the coordinative running of the steel production process, different procedures and devices play different roles in the operation dynamics of the entire coordinative running of steel manufacture. From the view of the running time of material flow, different procedures and devices play different roles such as of pushing, buffering or pulling in the material flow of production in order to advance the time scheduling fluently, coordinatively and continuously.

7.4.1 *Section division of running strategy for production process of steel plant*

The steel production process can be divided into two sections: the upstream section from Blast Furnace to Continuous Casting and the downstream section from Continuous Casting output to Hot Rolling finish-up. The upstream section is mainly of chemical metallurgical process and solidification. The downstream section is the physical change control of the slab/billet transportation, reheating and rolling, plastic working, deformation and transformation. The process flow in steelworks could be resolved into two stage: upsteam which is from ironmaking to continuous casting,and downstream which is from runout of continuous casting to the end of hot rolling.

So the analysis-integration about the operation dynamics of steel production process can begin with the three key procedures: ***Blast Furnace***, ***Continuous Casting*** and ***Hot Rolling***. The characteristics of upstream and downstream sections in running strategy for steel production process are shown in Fig. 7.3.

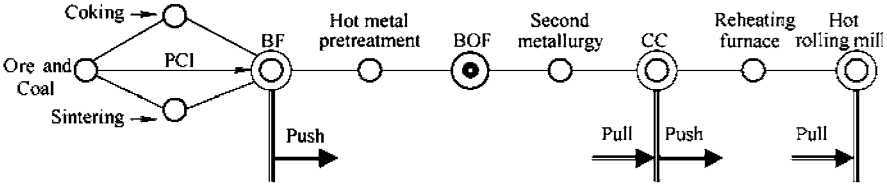


Fig. 7.3 The scheme of the running dynamics of steel production process

7.4.2 *Pushing force and pulling force in up-stream of steel manufacturing process*

1. Blast furnace. The running essence of blast furnace is a continuous moving bed operation, which requires a fluent continuous and steady operation without intermission even some undulations. As the hearth of blast furnace has a limited volume (the general design of the hearth volume is about 14% of the volume of the blast furnace), hot metal should be tapped in time. So a pushing force for the mass flow was originated with the tapping necessity for uninterrupted BF running. The pushing force can be expressed as

$$F_{\mathrm{BF}}^{\mathrm{push}} = \int_{t_0}^{t_1} \frac{V\eta}{1440 t_{\mathrm{SE}}^{\mathrm{BF}}} \mathrm{d}t$$

where $F_{\mathrm{BF}}^{\mathrm{push}}$ is the pushing force from blast furnace production on the mass flow , t/min; V is the volume of blast furnace, m^3; η is the utilization coefficient of blast furnace, $\mathrm{t/(d{\cdot}m^3)}$; $t_{\mathrm{SE}}^{\mathrm{BF}}$ is the time-interval of blast furnace operation, $t_{\mathrm{SE}}^{\mathrm{BF}} = (t_1 - t_0)$, min; t_0 is the time-point of last iron tapping, min; t_1 is the time-point of current iron tapping, min.

This pushing force has the significance of not only the mass flow rate but also the energy flow and the time-rhythm.

In practice, the pushing force has many forms. For hot metal pretreatment, converter and such following procedures, the pushing force can be expressed as the weight of hot metal in torpedo or ladle and the needed time-rhythm. In addition, the pushing force is related with the number of blast furnace, the transportation way of hot metal, the capacity of railroad transport and especially the layout.

2. Continuous casting. The running essence of continuous casting is the continuous process of cooling, heat-exchange and solidification. The efficiency of continuous casting is represented by the time length of sequence casting and the operation ratio of caster. From the view of the material flow of steel production process, the continuous running of continuous casting is the source of pulling force for blast furnace, hot metal pretreatment, converter and secondary metallurgy. The pulling force has the significance of not only the mass flowrate but also the temperature and metal quality in mass flow. Continuous casting requires supply molten steel from uptream procedure in time, in temperature and in quality, so these pulling forces should be coupling and coordinating on the time-coordinate axis. In other words, continuous casting pulls the procedures such as blast furnace, hot metal pretreatment, converter and secondary metallurgy to run in rhythm continuously or high frequent periodically. In the upstream section of steel production process, continuous casting is the source of pulling force for the continuous running of the process. The pulling force can be formally expressed as

$$F_{\mathrm{CC}}^{\mathrm{pull}} = \int_{t_0}^{t_1} \frac{S\rho v_{\mathrm{c}}}{t_{\mathrm{SE}}^{\mathrm{CC}}}\,\mathrm{d}t$$

where $F_{\mathrm{CC}}^{\mathrm{pull}}$ is the pulling force from continuous casting on mass flow in the upstream production section , t/min; S is the cross-section area of slab billet, m^2; ρ is the density of molten steel, t/m^3; v_{c} is the casting speed, m /min; $t_{\mathrm{SE}}^{\mathrm{CC}}$ is the time-interval of continuous casting operation, $t_{\mathrm{SE}}^{\mathrm{CC}}=(t_1-t_0)$, min; t_0 is the time-point of cast start of continuous sequence casting, min; t_1 is the time-point of cast end of continuous sequence casting, min.

The casting speed of caster is constrained by the metallurgical length of continuous casting.

$$v_{\mathrm{c}} = \frac{4K^2L}{D^2}$$

where L is the metallurgical length of continuous casting, m; K is the solidification coefficient, mm /min$^{1/2}$; D is the thickness of slab/billet, mm; v_{c} is the casting speed, m /min.

7.4.3 *Pushing force and pulling force in downstream of steel manufacturing process*

1. Continuous casting. Slabs are cut and offered in different length, in different

weight, in different temperature and in different rhythm to form the pushing force for ensuing reheating furnace and rolling mill. The pushing force has the significance not only of the energy but also of the mass flowrate. It also expresses an extent of continuity in time scheduling. If hot slabs could not be transported to reheating furnace in time, it would result in increasing the energy consumption and the slab stock and even decreasing the continuous working time of hot rolling mill. For continuous casting, slabs can not be transported in time and accumulated, and the casting speed slow down and enlarged the quantity of overstocked slabs. The advanced technologies such as thin slab casting—rolling (TSCR) and strip casting require that the slab storage must be canceled and slabs should move forward fluently. It is obvious that continuous casting is the source of pushing force too for the continuous running of the downstream section of steel production process. The pushing force can be expressed as

$$F_{\mathrm{CC}}^{\mathrm{push}} = \int_{t_0}^{t_1} \frac{S\rho v_{\mathrm{c}}}{t_{\mathrm{SE}}^{\mathrm{CC}}}\,\mathrm{d}t$$

where $F_{\mathrm{CC}}^{\mathrm{push}}$ is the pushing force of continuous casting for the downstream production on mass flow, t/min; S is the cross-section of slab, m^2; ρ is the density of slab, t/ m^3; v_{c} is the casting speed, m/min; $t_{\mathrm{SE}}^{\mathrm{CC}}$ is the time-interval of continuous casting operation, $t_{\mathrm{SE}}^{\mathrm{CC}}=(t_1-t_0)$, min; t_0 is the start time-point at run-out slab from the sequence casting, min; t_1 is the end time-point at last slab run-out from the sequence casting, min.

In practice, for various type of reheating furnaces and the different hot-rolling mills, the pushing force is represented specifically on a single slab with different length, different weight and different temperature or enthalpy.

2. Hot continuous rolling mill. The running essence of hot continuous rolling mill is the alternately continuous operation and with intermittence discussed in 7.3. It is expected that the time passing rolls of hot mill extends as long as possible or much more pieces pass through the mill during a determined time-interval. It is advantageous for energy-saving, yield-gaining and productivity-increasing. To extend the steel passing time in rolling mill was carried out by adoption of various means even by extending the length of the work piece such as semi-endless rolling or endless rolling. This shows that in the downstream section of the steel manufacture process, hot strip mill is the *pulling force* on mass flow for former procedures and devices (caster, slab stock, holding pit, reheating furnace, etc.). The pulling force is expressed as

$$F_{\mathrm{HR}}^{\mathrm{pull}} = \int_{t_0}^{t_1} \frac{S\rho v_{\mathrm{r}}}{60 t_{\mathrm{SE}}^{\mathrm{HR}}}\,\mathrm{d}t$$

where $F_{\mathrm{HR}}^{\mathrm{pull}}$ is the pulling force from hot rolling mill in the upstream section on mass flow, t/min; S is the cross-section of finished steel, m^2; ρ is the density of finished steel, t/ m^3; v_r is the rolling speed at outlet of the last housing of mill, m/s; t_{SE}^{HR} is the time-interval of hot rolling mill running, $t_{SE}^{HR}=(t_1-t_0)$, min; t_0 is the time-point at roll piece entering the rolling mill train, min, t_1 is the time-point at roll piece leaving the rolling mill train, min.

7.4.4 *Strategy of the continually running of mass flow for steel manufacturing process*

From the analysis about the sources of pushing force and pulling force in the upstream and downstream sections of steel manufacturing process, it is known that the blast furnace plays the role of pushing force in the steel manufacturing process, and the hot rolling mill plays the role of pulling force for the downstream section. But the continuous casting has the dual action which means that it plays the role of pulling force for the upstream section and of pushing force in the downstream section.

However, this is just the general description to the normal operation state for the three procedures (BF, CC and hot rolling mill). As a matter of fact, BF can not be a complete steady running, CC can not always keep a steady state of incessantly casting, and hot rolling mill can not pass pieces under rolling continuously. In a word, there are always interferential factors in continuation and steadiness of operation in steel manufacturing process. Moreover, these factors may be prearranged or occur at random. Thus, it is necessary that the more effective strategy and measure for the continuous/quasi-continuous mass flow in the steel manufacturing process to be investigated, i.e. how to coordinate and buffer the differences between pushing and pulling force regarding contination/quasi-contination. This running strategy, which generally can simulate the "loop" function between housings of hot strip mill, up to make per second flowrate equal. Therefore, it is necessary to establish a "*generalized loop engineering*", or generally speaking, *flexible buffer engineering* in the steel manufacturing process. For such a large-scale, complex systems of the steel production process, the time scale is chosen to be *minute*, nor *second* nor *hour*. That is to say, the concept of "*per min flowrate equal*" should replace the concept of per second or per hour flowrate equal to keep continuous/quasi-continuous running of steel manufacturing process. That means to establish some buffering procedures or devices between the sources of pushing and pulling force to be as the "flexible loops" for the mass flow of steel manufacturing process. Different "loop" functions, various "loop" capacities and "loop" numbers may be applied to make the mass flowrate buffer, temperature/energy parameter buffer, quality/shape parameter buffer, time-characteristic parameter buffer etc. The coordination of *push-pull* makes the mass flow continuous running without intermittence and accumulation, that increases the productive efficiency and benefit remarkably. The coordination among pushing force, buffering and pulling force fills in fact the role of "*generalized loop engineering*". The positions of buffering loops in steel production flow are shown in Fig. 7.4.

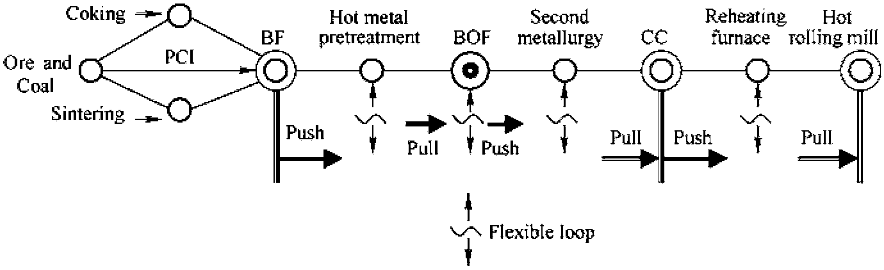


Fig.7.4 Diagram of pushing force, buffering loop and pulling force in the running of steel production process

According to the above operation strategy, different procedures and devices play different roles such as pushing force, buffering loop and pulling force which will be further discussed.

A. Operation control strategies in the BF—BOF—CC section (EAF—CC section), and different roles played by every procedures/devices

The upstream section in the steel production process can be divided into the BF—BOF subsection and the BOF—CC subsection. There are also running dynamics features of pushing force, buffering loop and pulling force in these two subsections.

1. Converter(BOF). The converter since modification has become the metallurgical reactor of rapid decarbonization, rapid heating-up, proper dephosphorization, optimal consumption of steel scrap and secondary energy(steam, gas)production. Its rational tonnage depends on the produced type of rolled steel(Yin, 2001) (Fig.7.5).

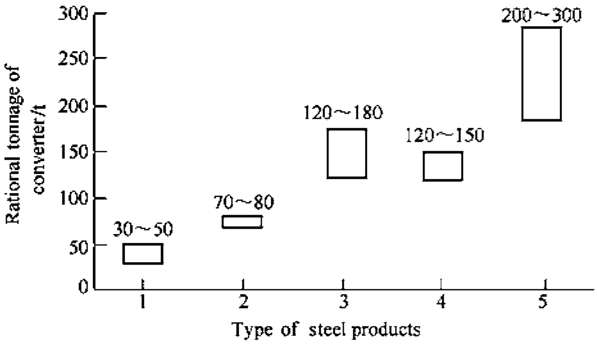


Fig.7.5 The relation between steel product type and the reasonable tonnage of converter

1—Common long products; 2—Quality long products; 3—Plates;

4—Thin slab cast-rolled coil; 5—Traditional hot-rolled strip

The tap-to-tap time of a large converter for slab casting is about 40~32 min, even down to 28 min. The tap-to-tap time of smaller converter for common long products is about 20~32 min. As converter is located between BF and continuous caster(CC), it is promoted by the pulling force of CC and the pushing force of BF. However, converter and CC often belong to a same workshop, converter is more directly effected by the pulling force of the continuous caster. In order to achieve a long sequence casting length, converter must supply molten steel to CC in time, in temperature and in quality coupling with the corresponding secondary refining. Therefore, the integrative optimization of steel manufacturing process requires to obey the one-by-one principle of BOF and CC. And the following rules should be abided:

$$t_{BOF} \leqslant t_{CC}$$

$$t_{SM} \ll t_{BOF} \leqslant t_{CC}$$

where t_{BOF} is the tap-to-tap time of converter min; t_{CC} is the casting time of one heat in continuous caster, min; t_{SM} is the refining operation cycle of secondary metallurgy, min.

2. Electric Arc Furnace(EAF). The EAF through several times of improvement becomes a metallurgical reactor of rapid melting, rapid heating-up and treating ferruginous materials including decarburization with dephosphorization during hot metal charging. It should regenerate exergy of waste gas much more. The reduction period had been eliminated in the modern EAF process. Its reasonable tonnage depends also on the type of products. The capacity of electric arc furnace is 80~100 t for common long products, 60~100 t for alloy steels, ≥80 t for stainless steels and 150~180 t for the process of thin slab casting-rolling.

In the modern steel plant EAF is forced by the pulling force from the continuous casting. EAF must be adapted for the sequence casting of CC and coupled coordinatively with the corresponding secondary refinding ladle to provide molten steel in time, in temperature and in quality. Of course, EAF may be also regarded as a source of pushing force on CC. The molten steel tapped from EAF has the significance of pushing force on mass flow, including time parameter push, temperature parameter push, quality parameter-chemical composition push, flowrate continuity push etc. Therefore, the reasonable principle for the modern EAF process is to estabulish one-by-one correspondence between EAF, secondary metallurgy(SM) and CC. And the following operation rule should be satisfied:

$$t_{EAF} \leqslant t_{CC}$$

$$t_{SM} \ll t_{EAF} \leqslant t_{CC}$$

where t_{EAF} is the tap-to-tap time of electric arc furnace, min; t_{CC} is the casting time of one heat in continuous caster, min; t_{SM} is the refining operation cycle secondary metallurgy, min.

If the tap-to-tap time of EAF becomes smaller than the casting time of CC, the significance of pushing force source of steel production is more obvious. The EAF requires the procedures of continuous casting and secondary metallurgy in responses to quicken their running.

3. Secondary Metallurgy. Since the 1950 s secondary metallurgy had developed and fitted in the steel manufacturing process gradually. At the early phase, secondary metallurgy is used for purification of liquid steel, to improve its quality and to make new steel grades. It may not be listed in the daily operation schedule, i.e. off-line commonly. Since the 1970 s, the production system of fully continuous casting has been adopted globally, meanwhile, the functions of secondary metallurgy are becoming comprehensive more and more. The role played by secondary metallurgy in production has changed principally. Now secondary metallurgy has the functions of the metal quality improvement (including temperature, nonmetallic inclusions control), energy saving and lowering material consumption in steel manufacture as well as the synergic buffer of the mass flow between BOF and CC to increase the number of heats per sequence. Therefore, secondary refining should become on-line operation in process. The off-line secondary metallurgy operation increases cost of the investment and production.

Now the secondary refining takes various technologies and different advantages. They are applied for different products and in different production processes. Generally, LF, LF + VD is primarily applicable to the EAF production process. The relative simple device of ladle argon injection mainly applies to the production of common long products with smaller BOF. The rapid reactors such as RH, CAS or powder injection are mainly applied with the larger converter with tap-to-tap$\leqslant$36 min to produce competitive flat products especially strips. Sometimes, LF is introduced into the production process of BF–BOF route to produce the qualified slabs. The LF is used mainly for ultra-low sulfur steel (such as pipeline steel, etc.) or for low sulfur high-carbon steel. When LF as a major secondary refining treatment applying on-line in converter process route, most attention must be paid to that the limited rhythm and efficiency between BOF and LF arise. That may also be a corresponding constraints of caster's speed, Therefore, to select the secondary refining technology ought to analyze its functions and effects comprehensively and carefully.

However, regardless of different products and different production processes, the following rule about the operation time of secondary metallurgy should be satisfied

$$t_{SM} << t_{BOF} \leqslant t_{CC}$$

or

$$t_{SM} << t_{EAF} \leqslant t_{CC}$$

The rule $t_{SM} < t_{EAF} \leqslant t_{CC}$ should be satisfied at least, otherwise secondary refining treatment would be out of line or interrupt the sequence casting of CC.

Time-interval t_{SM} is just a part of the interval from the tapping end of BOF/EAF to start casting from tundish. Before t_{SM}, there are the time of ladle carrying (including ladle lifting) and the time of ladle positioning; After t_{SM}, there are the time of ladle lifting, the positioning on the ladle turret and the time of filling the tundish. Even more there are the time of waiting and shelving before or after secondary metallurgy. Therefore, to the applicable range of the processing time of secondary metallurgy should be paid much attention during the equipment selection and its operation.

In the running of sequence casting of BOF—secondary metallurgy—CC process, the time-rhythm must be coordinated as

$$t_{\mathrm{BOF(EAF)}}=t_1+t_2+t_{\mathrm{SM}}+t_3+t_4+t_5+t_6+t_7=t_{\mathrm{CC}}$$

where t_1 is the time-interval from the tapping end to the ladle arrival at work position for treatment, min; t_2 is the time-interval from the ladle arrival at work position for treatment to the operation start of secondary metallurgy, min; t_3 is the time-interval from the operation finish of secondary metallurgy to the ladle arrival at ladle turret of caster, min; t_4 is the waiting time of ladle nearby the ladle turret, min; t_5 is the swived operation time of the ladle turret, min; t_6 is the time-interval from the swived finish of the ladle turret to start casting from ladle, min; t_7 is the time-interval from the start of molten steel filling tundish to start casting from tundish, min.

Above all, the function and running principle of secondary metallurgy are to provide qualified steel in time, in temperature and in quality for the sequence casting. Therefore, secondary metallurgy still plays the role of coordination-buffering in the steel manufacturing process. The function of the "*generalized loop engineering*" expressed in the temperature and time reliability to the production process and also in the precise chemical composition and accurate cleanness of the molten steel.

4. Hot metal supply. The hot metal tapping from blast furnace is carried to charge into converter like a material flow. Its "pushing source force" must be the blast furnace. The continuous caster pulls the converter with more heats incessantly for the continuous sequence casting. Therefore in BF-BOF section of the production process, converter plays the role of pulling force for the iron ladle, torpedo car, mixer, hot metal pretreatment, deslagging device (station), charging ladle etc. These procedures and devices all have the buffer function in mass flow and form a "*generalized loop engineering*" during process operation concerning the parameters as temperature, time, hot metal composition control, supplying batches and tonnage, they behave with the "link and match" role as well. Of course, this kind of link-match action was influenced or constrained by the BF number, BF volume, blast furnace utilization coefficient, number of converter workshop, converter number, converter capacity, layout, railway capacity and other factors.

It is necessary to study the regularity of optimum combina and synergic running between BF and BOF, because there are many different constitution modes and combination ways among blast furnace—hot metal receiving—hot metal transport and holding—pretreatment and charging, which should not be superimposed simply and directly. The BF-BOF interface technique in respect of posed simply and directly. The BF-BOF interface technique in respect of selecting the hot metal pretreatment ways, the type and capacity of hot metal holding transporting vessels, the railway transportation capacity, the BF number and layout etc. is very important. That should meet the requirements for steel production and cost saving.

The mass flow of production process between BF and BOF is generally characterized by:

1) Different types, distance and corresponding waiting or delaying time in hot metal transportation;

2) Different hot metal receiving and holding, including type, capacity and shape of vessels, and the corresponding heat transfer or heating-up, which would result in some changes of hot metal ladle shifts, process temperature drop, running time etc.;

3) Different hot metal pretreatment ways and methods, which would result in the hot metal composition, temperature and the time of charging into converter.

Therefore, the targets of mass flow running between BF and BOF should be:

1) Minimum but rhythmic time-interval between blast furnace tapping and converter charging in order to adapt and promote continuous operation of sequence casting;

2) Minimum hot metal temperature drop between BF tapping and converter charging under the condition of hot metal composition to meet steelmaking;

3) Higher efficiency and lower cost of hot metal pretreatment;

4) Reasonable layout of BF—BOF section to improve the efficiency of railway transportation, to optimum-coordinate the space-time factors for blast furnace, hot metal pretreatment and converter running, and to comprehensively increase the efficiency of hot metal pretreatment, steelmaking, secondary metallurgy and continuous casting.

B. Operation control strategies in the continuous casting-hot rolling section and roles played by different procedures and devices

The caster as a pushing force and the hot rolling mill as a pulling force have been discussed in chapter 7: 7.4.3 by analyzing the downstream section of steel manufacturing process.

Since the fully continuous casting production system was established, the operation control strategies between casting and rolling have attracted more and more attention. Different ways and devices have been applied to link and coordinate casting and rolling in order to minimize the energy consumption, the stock amount, the processing time, to compact the layout and to maximize the metal yield. Based on the defect-free slab casting technique, many advanced techniques such as continuous casting-cold charge rolling(CC-CCR), continuous casting-hot charge rolling(CC-HCR), continuous casting-direct hot charge rolling(CC-DHCR), continuous casting-direct rolling(CC-DR), thin slab casting-rolling(TSCR) and strip casting-rolling(SC-R) had been adopted (Fig.5.5). The semi-endless rolling technique should also be adopted in some cases.

In the section between casting and rolling, the devices such as reheating furnace, holding furnace, hot slab pit, intermediate furnace and hot coiler play the role of coordination and buffering in different degree, in different parameters and in different functions. Their combination and adjustment consist of the "generalized loop engineering" with different capacities and functions.

The stock capacity and the loop capacity index of different hot linkage ways between continuous caster and hot rolling mill have been studied (Peng, 2001).

Generally, the rational stock capacity between casting and rolling consists of the basic inventory and the flowrate undulation inventory. The basic inventory capacity I_B depends on the passing time from caster to reheating furnace t_{ch}. For continuous casting-hot charging rolling process, t_{ch} contains

the time-interval from the slab cutting start to the loading start, t_{ich}, min;

the time-interval from the loading start to the loading end, t_{che}, min;

the transporting time between steelmaking workshop and hot rolling workshop, t_t, min;

the time-interval from the unloading start to the unloading end, t_{dche}; and

the time-interval from the slab entering warehouse to charging into reheating furnace, t_{wh}, min.

$$t_{ch}=t_{ich}+t_{che}+t_t+t_{dche}+t_{wh}$$

In the time-interval t_{ch} the output of hot strip mill is Q_{RP}. To maintain a steady production, the basic invetory should

$$I_B=Q_{RP}$$

The flowrate undulation inventory capacity I_F means the difference due to the unbalance between slab input and rolled product output. I_F depends on the frequency and occupied time of the failures and their repair in caster, reheating furnace and rolling mill. And I_F contains:

- the flowrate undulation capacity caused by failure, $I_{F,D}$ and
- the flowrate undulation capacity caused by repair, $I_{F,R}$.

Therefore, the total inventory capacity can be calculated by the following formula theoretically, i.e.

$$I=I_B+I_F=I_B+I_{F,D}+I_{F,R}$$

Similarly, the inventory capacity for other hot linking ways between caster and hot rolling mill can be obtained.

In order to compare the different hot linking ways between casting and rolling, the loop capacity index I_{bu} is introduced to represent the basic buffering value.

$$I_{bu}=\frac{I_{ac}}{I_h}$$

where I_{bu} is the loop capacity index, i.e. the incessant normal working time by storage, h; I_{ac} is the actual inventory capacity between casting and rolling, t; I_h is the hourly output under normal synergetic operation of rolling mill, t / h.

Research on loop capacity index I_{bu} is of great significance. If the actual inventory is more than the needful loop capacity index I_{bu} for corresponding casting-rolling coordination in a steel plant, the process from continuous casting to hot rolling would run with superabundant stock, more costs and higher energy consumption. Under such circumstances, efforts should be made to reduce the inventory. Inversely, if the actual stock is less than loop capacity index I_{bu}, the steel plant takes too low inventory, the hot-rolling mill would have abnormally lower production output. The calculated inventory capacity (I) and loop capacity index (I_{bu}) of different matching ways of slab casting—rolling are shown in Table 7.1.

Table 7.1 The calculated inventory capacity, actual inventory capacity, and loop capacity index between slab caster—hot rolling mill

Linking ways Inventory	CC—CCR	CC—HCR	CC—DHCR	CC—DR	TSCR	SC-R
Basic inventory capacity I_B/t	10.0~15.0 I_h	4.5~7.0 I_h	→0	→0	→0	0
Flowrate undulation inventory by failure $I_{F,\,D}$/t	1.5~3.5 I_h	1.5~3.5 I_h	1~3 I_h	0.5~0.8 I_h	0.3~0.6 I_h	0
Flowrate undulation inventory by repair $I_{F.R}$ /t	5.5~7.5 I_h	5.5~7.5 I_h	1~3 I_h	0	0	0
Calculated total inventory capacity, I/t	18.0~21.0 I_h	10.5~16.5 I_h	2~4 I_h	0.5~0.8 I_h	0.3~0.6 I_h	0
Calculated loop capacity index, I_{bu} /h	18.0~21.0	10.5~16.5	2~4	0.5~0.8	0.3~0.6	0
Actual inventory capacity I_{ac}/t	90.0~110.0 I_h	65~75 I_h	5~15 I_h	<0.8 I_h	0.3~0.6 I_h	0
Actual loop capacity index I_{bu}/h	90.0~110.0	65~75	5~15	<0.8	0.3~0.6	0

C. Buffer-coordination capacity of some procedures/devices in the steel production process

As shown in Fig. 7.4, the hot metal pretreatment, the secondary refining, the reheating furnace, and even the converter play the role of buffer-coordination to some extend. i.e. for some "flexible loop function" with equal minute flowrate. However, the buffer-coordination function of these procedures/devices is generalized. Of which, the buffer function is often manifested in quantity, such as the matter flowrate, the heat transfer and the temperature change per unit time, but the coordination function is often reflected in the qualitative variation, such as the sequence arrangement in chemical composition changing, deformation control, structure control and metal performance. Generally speaking, the process running essence of the whole steel production is the organization, coordination and coupling of such factors as matter, energy, space, time. So it is actually the spatio-temporal coupling of the chemical composition factor, the physical phase state factor, the geometry factor, the surface feature factor, the energy and temperature factor and also the space-location factor, the time-sequence factor etc. in the steel production process. As the space-location factors e.g. layout, vertical arrangement have been determined and fixed in steel plant design, so the coordination of steel plant is synergistic coupling of all factors on time axis mainly. Therefore, the buffer-coordination capacity of some procedures/devices can be simply manifested by the functions of time-order and time-rhythm parameters. Of course, it not means that the space factor is unimportant. Irrational layout and process network are likely to result in mass flow confusion, which can not be recovered through scheduling of production process.

Taking the secondary metallurgy device as an example for buffer-coordination calculation, for the purpose of continuation of mass flow and long sequence casting in BOF—CC section, the condition should be

$$t_{SM} << t_{BOF} \leqslant t_{CC}$$

$$\text{i.e. } Q_{CC} \leqslant Q_{BOF} < Q_{SM}$$

where Q_{CC} is the mass flowrate in effective operation of caster, t / min; Q_{BOF} is the mass flowrate in tap-to-tap time of converter, t / min; Q_{SM} is the mass flowrate in one cycle of secondary metallurgy, t / min.

Thus, the buffer-coordination capacity of secondary metallurgy for caster is

$$Q_{SM} - Q_{CC} = \frac{C}{t_e^{SM} - t_s^{SM}} - \frac{C}{t_e^{CC} - t_s^{CC}}$$

where C is liquid steel weight of one heat, t; t_s^{SM} is start time of secondary refining cycle, min; t_e^{SM} is end time of secondary refining cycle, min; t_s^{CC} is start of caster running time, min; t_e^{CC} is end of caster running time, min.

It is shown that buffer-coordination capacity of a device here can be embodied not only in time (min), but also in mass flowrate (t/min).

Similarly, the buffer-coordination capacity of secondary metallurgy to converter is

$$Q_{SM} - Q_{BOF} = \frac{C}{t_e^{SM} - t_s^{SM}} - \frac{C}{t_e^{BOF} - t_s^{BOF}}$$

where $t_e^{BOF} - t_s^{BOF}$ is tap-to-tap time of converter heat, min.

The buffer-coordination capacity of different hot metal pretreatment to blast furnace process, or to converter process, the buffer-coordination capacity of reheating furnace to caster, or to hot rolling mill operation can be calculated respectively by similar method.

7.5 Interface Techniques of Steel Manufacturing Process

Since the World War II, some common technologies such as oxygen steelmaking, continuous casting, strip rolling and large blast furnace ironmading have been put into use worldwide. These technologies had differently influenced on the structure and running dynamics of steel plant. The development and integration-combination of these technologies have lead to the evolvement of the set of procedure's functions, the redistribution of procedure's functions and the change of the set of procedures' relations in steel production process. The analysis-optimization of procedure function set and the coordination-optimization of procedure's relation set provide the technological support for re-ordering and high-efficiency of the steel manufacturing process. Accompanying with the evolvement and optimization of the set of procedure's functions and the set of procedures' relations, the modification and optimization of a series of interface techniques and even some new interface techniques have appeared. These new interface techniques and the combination with them in different processing sections have affected on the structure of steel manufacturing process including technical structure, equipment structure and product structure.

7.5.1 *The meaning of interface technique*

Interface technique refers to the method and device which plays the role of linking-matching and coordinating-buffering among the main procedures such as ironmaking, steelmaking, casting, blooming and rolling. It should be noticed that the interface technique contains not only the relevant technology and device, but also a series of engineering problems such as the arrangement of time-space and the adjustment of quantity-capacity.

From the view point of engineering science, the interface technique of steel manufacturing process is mainly intended to realize the connection, matching, coordination and steadiness of ferrugenius mass flow including flowrate, composition, structure, shape, energy flow, process temperature and process time and so on. It is necessary to research and develop the interface techniques for improving the steadiness, coordination, effectiveness and continuation of the steel manufacturing process.

Before the World War II, the main procedures such as ironmaking, steelmaking, teeming, blooming and hot rolling ran separately and in batch operations, their relationship was connected as the simple link of input and output with some waiting and big inter-stock. With these interfaces, there are many times of temperature drop and reheating, blooms/ slabs entering into and leaving from stockyards repeatedly, intermission frequently as well as transporting back and forth. These interfaces result in long manufacture cycle, high energy consumption, low production efficiency, unstable quality of products, and much more land occupied by steel plant. Accompanying with the development, and integration of technologies and devices of BOF—CC—hot rolling mill(HRM), of large blast furnace and converter, of UHP—EAF—CC—HRM, different kinds of interface techniques within BF—BOF, BOF(EAF) —CC and CC—HRM have appeared in the steel manufacturing process.

7.5.2 *Interface techniques of BF—BOF section*

According to the effective capacity, BF—BOF manufacturing process may be divided mainly into two types: large BF—BOF process for flat products and small BF—BOF process for long products. The interface techniques between BF and BOF have diversity and can be expressed as following types:

1. The hot metal tapped from smaller blast furnace and charged into iron ladle is transported and charged into a hot metal mixer for preservation. When hot metal is needed, the metal is tapped from mixer, filled into charging ladle, and then charged into converter (Fig.7.6). During this case, the hot metal has undergone two shifts, i.e. tapping and charging. At the same time, the hot metal is exposed to air and absorbed heat by ladle lining. Moreover, the mixer must be heated in order to hold the temperature of hot metal. Therefore, problems such as environmental pollution, higher energy consumption as well as graphite and fume formation during recharging process are arisen for this type of interface technique.

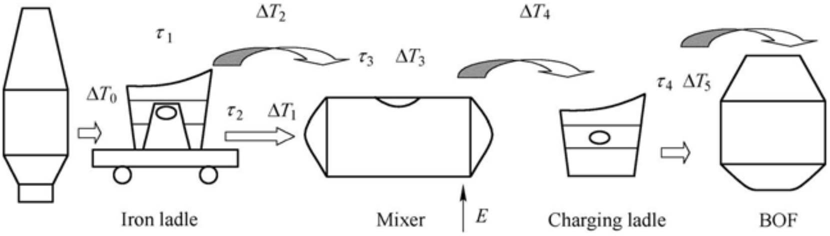


Fig.7.6 Hot metal transport from blast furnace via iron ladle—mixer—charging ladle, into smaller converter

ΔT—Temperature change of hot metal, ℃; τ—Time of hot metal transport, storage, charging, min; E—Supplementary energy, GJ

2. The hot metal tapped from smaller blast furnace is filled into iron ladle. When the capacities of ladle and converter are same, the hot metal is directly charged into converter. In this case, there is only one time of exposure to the air for hot metal. When the capacities of ladle and converter don't match each other, the excess hot metal must be poured into charging ladle, then charged again into

converter(Fig.7.7). In this case, there are a large surplus heat loss due to more times of shifting.

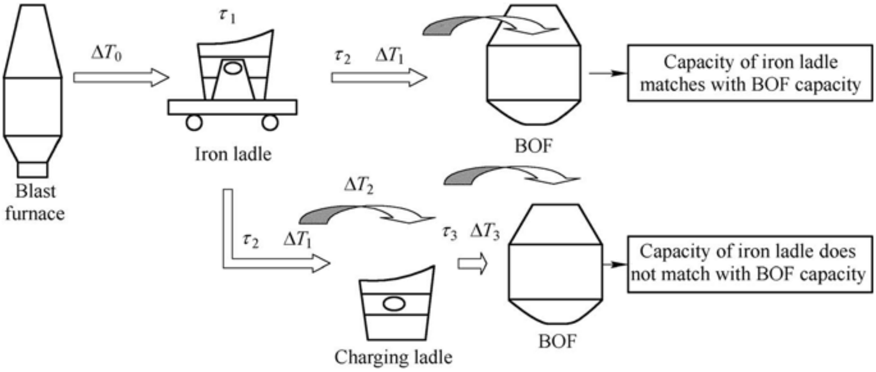


Fig.7.7 Different types of the hot metal shifting and transporting via iron ladle

ΔT—Temperature drop of hot metal, ℃; τ—Time of hot metal transport, storage, charging, min

3. With the higher quality requirements for steel products and the technical development of pretreatment, the interface technique including hot metal desulphurization should been adopted in smaller BF—BOF route.

When the capacities of ladles and converter are same, the hot metal in the iron ladle is directly transported to the pretreatment station for desulphurization after deslagging. After the treatment, desulphurization slag should be removed and the hot metal is directly charged into converter (Fig.7.8). For this interface technique, the hot metal is only one time of exposure to air without excess heat loss caused by shifting.

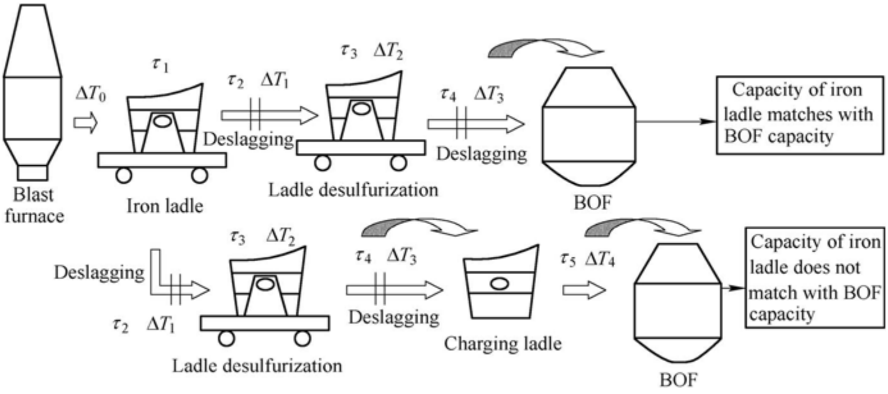


Fig.7.8 Desulphurization pretreatment of hot metal between smaller BF and smaller converter

ΔT— The temperature drop of hot metal,℃; τ—The transport, storage, pretreatment and shift-pouring time of hot metal, min

If the capacities of ladles and converter are not same, it is necessary to add or to reserve excess hot metal in an iron ladle after treatment and then shift into charging ladle. Thus, this way increases one time of heat absorption of lining and one time of exposure to air.

4. The hot metal tapped from large blast furnace has filled into torpedo and then transported at an iron-accepting pit. Here, hot metal is poured into a charging ladle and then directly charged into converter without treatment (Fig.7.9). In this case, there are one time of heat loss by shifting, one time of heat absorption by lining, and two times of exposure to air. In another case, the torpedo goes to pretreatment station and undergoes desulphurization and deslagging, then the hot metal is transported to iron-accepting pit, poured into charging ladle, and charged into converter. There are also one time of heat loss by shifting, one time of heat absorption by lining and two times of exposure to air. However, the temperature decreases much more due to desulphurization and deslagging. Of course, it is required that the capacities of torpedo, charging ladle and converter are same in the two cases.

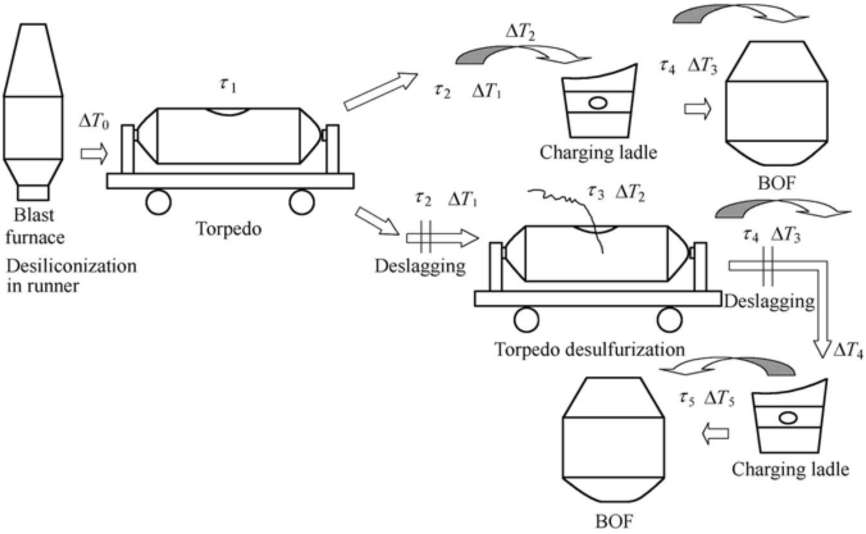


Fig.7.9 Transportation via torpedo between large BF and large converter

ΔT—The temperature drop of hot metal, ℃ ; τ—The time of transport, storage, pretreatment, deslagging and shift-pouring of hot metal, min

5. The hot metal tapped from large blast furnace is desiliconized in runner and fills into torpedo. Then the torpedo is transported to the pretreatment station. Firstly desilicon slag must be removed. Then desulphurization and dephosphorization are carried out in the torpedo simultaneously. After deslagging, the hot metal is poured into charging ladle, then charged into converter (Fig.7.10). For

this case, there are only one time of shifting heat loss and two times of exposure to air, but the complex pretreatment processes take a long processing time with much more heat losses, the metal temperature drop is remarkable. This technology is mainly applied to the large BF—BOF route to produce the high grade steels. It requires the capacity matching among torpedo, ladle and BOF to avoid excess hot metal.

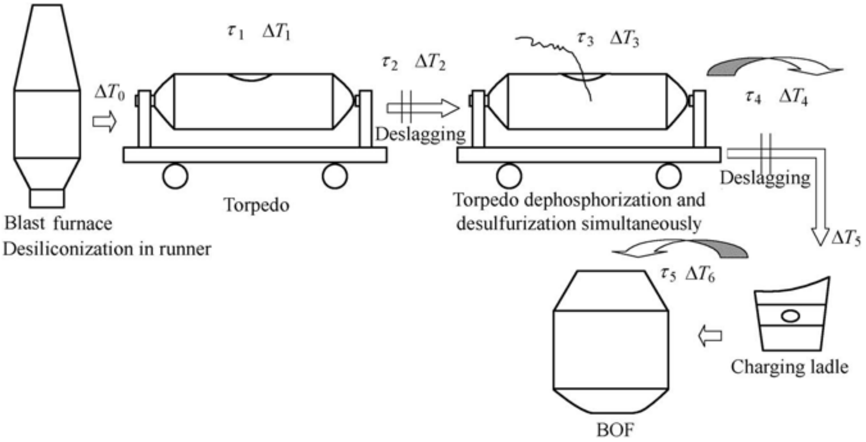


Fig.7.10 Hot metal pretreatment of desiliconization, desulphurization and dephosphorization in torpedo and its transportation between BF and BOF

ΔT—The temperature drop of hot metal,℃ ; τ—The time of transport, storage, pretreatment, deslagging and shift-pouring, min

6. The hot metal tapped from large blast furnace is desiliconized in runner, filled into torpedo and transported to pretreatment station. After disilicon slag removed, the hot metal is poured into a ladle and desulphurized. Through desulphurization and deslagging, the hot metal is charged into dephosphorizing converter. Low phosphor metal (semi-steel) tapped and deslagged from the converter is charged into decarburization converter by charging ladle, rapid decarburization and heating-up would be finished(Fig.7.11). This pretreatment process takes the better thermodynamic and kinetic conditions for dephosphorization than that of torpedo. Meanwhile, the metal heat loss and the temperature drop are greater due to the four times of exposure to air, two times of hot metal shifting. Generally speaking, the process is high efficient and stable, and is good for high quality sheet production with high speed casting especially.

The above six types of interface technique have been applied in steel production process. Among them, the former three types are often applied to smaller BF—BOF route and the later three types to large BF—BOF route.

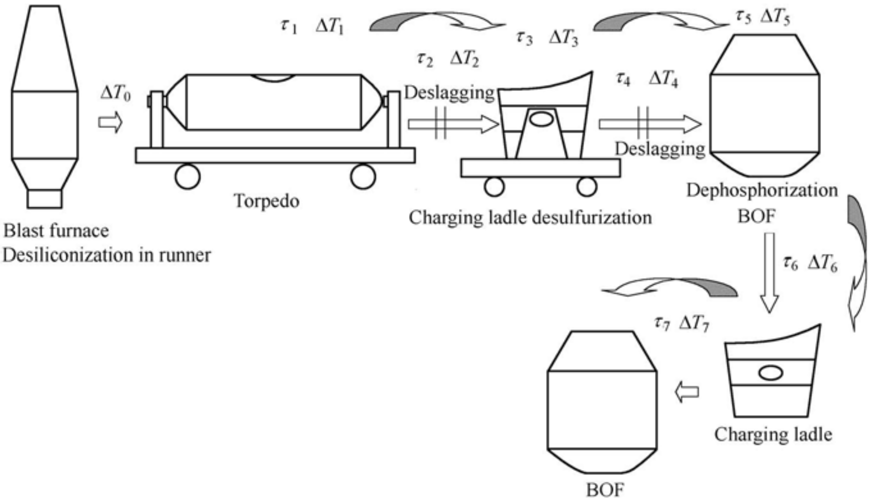


Fig.7.11 Step by step pretreatment of desiliconization, desulphurization and dephosphorization of hot metal between large BF and large BOF

ΔT—The temperature drop of hot metal, ℃; τ—The time of transport, storage, pretreatment, deslagging and shift-pouring, min

7. The hot metal tapped from large blast furnace is desiliconized in runner and filled into iron ladle, whose capacity should match with the capacity of converter. The iron ladle is covered by thermo cover and transported to the pretreatment station. After desulphurization and deslagging, the hot metal is charged into dephosphorizing converter. Low phosphor metal (semi-steel) tapped and deslagged from the converter is charged into decarburizing converter by charging ladle, rapid decarburization and heating-up would be finished(Fig.7.12). Thus, desiliconization, desulphurization, dephosphorization and decarbonization in different reactors are realized at the optimum thermodynamic and kinetic conditions. Therefore, the metallurgical effect is remarkably improved, the consumption of flux agents much more decreases and the processing time is far shorten. But there are two times of shift-pouring, three times of exposure to air and heat loss during treatment and deslagging. The temperature drop is much greater. The process is mainly applied to the large BF—BOF route to produce high quality sheets in terms of quick time-rhythm, stable metal quality and high productive efficiency.

It must be considered that the higher silicon content and the higher temperature of hot metal are beneficial for desulphurization, therefore, a new interface technique between blast furnace and converter is recommended as following.

8. The hot metal tapped from blast furnace is filled into iron ladle (its capacity should match with converter) without runner desiliconization. The ladle, covered for insulation, is transported to the pretreatment station. After ladle slag removal,

the hot metal desulphurization is practized in the ladle. Skimming desulphurization slag, the hot metal is charged into dephosphorizing converter to remove silicon and phosphor, then tapped into another ladle and charged into converter for rapid decarbonization and heating-up(Fig.7.13). If the silicon content in hot metal is more than 0.4%, the runner desiliconization is still necessary.

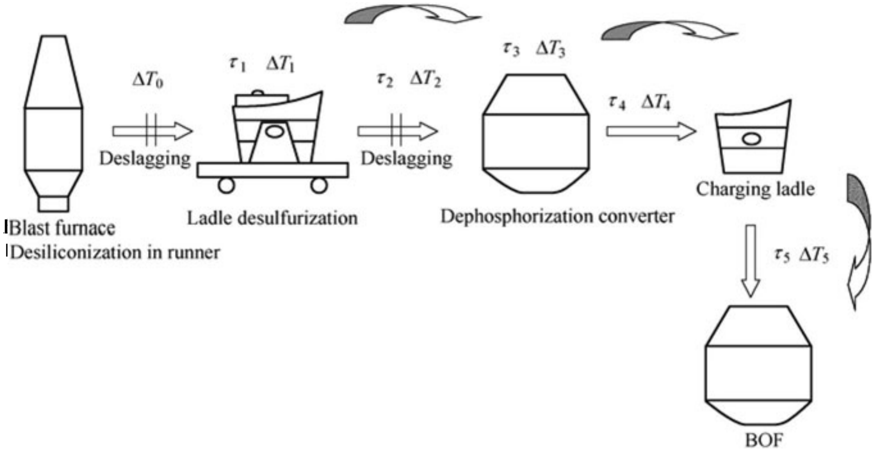


Fig.7.12 Step by step pretreatment of desiliconization, desulphurization and dephosphorization of hot metal in large scale BF—BOF route without torpedo

ΔT—The temperature drop of hot metal, ℃; τ—The time of transport, storage, pretreatment, deslagging and shift-pouring, min

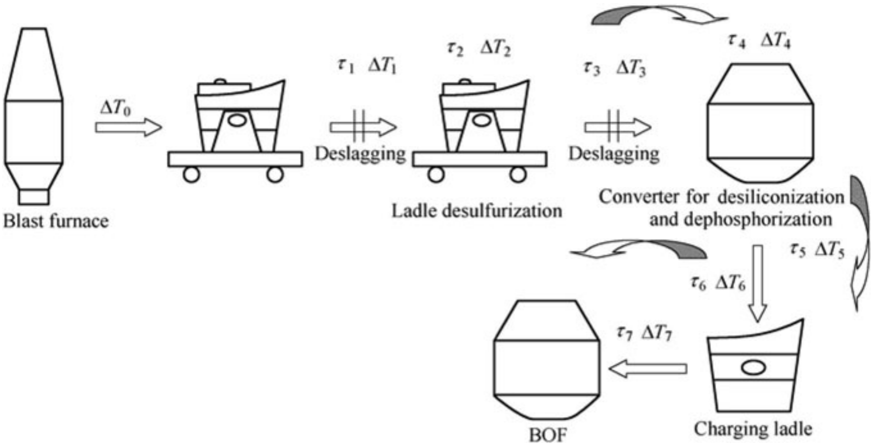


Fig. 7.13 Simplified step by step pretreatment of desulphurization, desiliconization and dephosphorization of hot metal in large BF and BOF route without torpedo

ΔT—The temperature drop of hot metal, ℃; τ—The time of transport, storage, pretreatment, deslagging and shift-pouring,min

This process route takes better thermodynamic condition of desulphurization than that of the former two process routes shown in Fig. 7.11 and Fig. 7.12. So the process is worth to investigate experimentally. There are still two times of shift-pouring, three times of exposure to air. But owing to the quick time-rhythm and the short operation cycle of charging ladle, the temperature drop will be reduced. Omission of torpedo and mixer is also beneficial for energy saving and environmental protection.

According to above discussions of different interface techniques between blast furnace and converter, some problems should be considered and emphasized. The capacity matching relationship among blast furnace (the quantity of tapped hot metal), iron ladle or torpedo, pretreatment equipment, charging ladle and converter is very important. The layout and the railway transport capacity in the section between blast furnace and converter play a key role in linking-matching of the interface. The rational number of blast furnace, steel workshop or converter inside,and different ladles considering heat loss of returning empty ladles must be studied. All these problems have affected the optimization of the running dynamics between blast furnace and converter.

7.5.3 *Interface technique between steelmaking furnace and caster*

The steelmaking—caster sections are of two types as following:

1. Converter—secondary refining—tundish—caster;
2. EAF—secondary metallurgy—tundish—caster.

The capacity and function of steelmaking furnace, secondary metallurgy and caster depend on the performance and specification of products as well as the reasonable scale of hot rolling mill. So there are two major types of process routes: flat product type and long product type.

The steelmaking—continuous casting interface technique consists of secondary metallurgy, ladles, tundishes; transportation and layout of steel plant; as well as the quantity (capacity) of devices and their matching relations.

A. Function and classification of secondary metallurgy

With the development and the improvement of secondary metallurgy, and especially the application of fully continuous casting, the secondary metallurgy has become one of the on-line procedures necessary for the steel manufacturing process. Meanwhile, the functions of this procedures have become

1. to improve quality of products, especially to control the cleanness and the temperature of liquid steel,
2. to take a portion of steelmaking functions for time shortening of steelmaking furnace and the speedy frequency of tap-to-tap operation, and

3. to be as a buffer between steelmaking furnace and caster to provide liquid steel to caster in time, in temperature and in quality, increasing time of sequence casting length.

Obviously, the procedures and devices of secondary metallurgy have to be indispensable for the steady operation, to improve steel quality, to decrease product cost and to increase efficiency of modern steel plants.

Since the 1960's, secondary metallurgy, excluding hot metal pretreatment, had been developed rapidly into various types with different features as

1. Injection treatment by blowing inert gases (Ar blowing and N_2 blowing);
2. Vacuum treatment (RH, VD etc.);
3. Powder injection (including wire feeding);
4. Ladle furnace (LF, ASEA-SKF etc.);
5. Special oxygen refining furnace (AOD,VOD etc.), and
6. Electroslag remelting.

The functions of the tundish in continuous casting had also been evolved and improved. There was no tundish at beginning of continuous casting development. Tundish had been used for stabilizing the level of metal bath in the mould and reducing the impact of stream on the solidified shell. At present, the functions of the tundish have spread over following:

1. to stabilize the static pressure of the metal bath in tundish and to stabilize the liquid level in mould,
2. to protect liquid steel from reoxidation and remove the majority of the large non-metallic inclusions in steel,
3. to adjust and control the overheating degree of liquid steel, and
4. to be as the buffering "loop" in the course of converter—secondary refining—caster in dimension of time and flowrate.

For recent 20 years, the capacity of tundish has been enlarged gradually, the structure has been improved, the campaign has been elongated and a series of techniques about tundish shifts and lining repair have been developed. All the technologies aim at much longer sequence casting time.

B. Interface technique between converter and caster

Generally, there are two main types of interface techniques between converter and caster: the flat product process and the long product process.

1. The converter—caster—hot rolling mill process for flat products. The flat product process refers to the hot rolled coil production, consisting of converters with capacity 120~300 t, traditional casters with slab thickness of 210~300 mm or thin slab casters with slab thickness of 50 mm, 70 mm or 90~135mm respectively. The productivity per strand of these casters is about 1 Mt/a or even more. These process are characterized by high efficiency, speedy rhythm and high quality.

In terms of the interface technique between large converter and slab caster, the representative ways are as following

CAS (OB)
Large converter — RH — Large tundish—Traditional slab caster
(180~300t) LF

In these processes, liquid steel is mainly refined by CAS (homogenization and heating-up) and RH(vacuum refining), which are on-line operation. LF is mainly applied for producing ultra-low sulfur and/or medium-carbon steels with less on-line operation. In order to avoid unnecessary ladle lifting, long distance transporting and cranes interfering each other, the layout of steelmaking workshop should be designed carefully. The converters, secondary refining devices and casters should be properly arranged and distributed separately in different bays such as furnace bay, teeming bay etc.

The thin slab caster can also be used in the converter- caster process as another type of coil production. Converters with the capacity 120~150t are often used. One caster after one converter is favour installation. The casting productivity of a caster strand may be 1.0~1.5 Mt/a. The representative processes are as following:

RH
Converter — CAS (OB) — Large tundish—Thin slab caster
(120~150t) LF

It is obvious that the interface technique has the characteristics of one-to-one matching. If LF is used for secondary refining only, the rational operating time rhythm of converter is 40~45 min. When the tap-to-tap time of converter is reduced to 36min, refining time of LF becomes the bottleneck. This bottleneck problem must be solved in order to adapt the production capability of hot rolling mill in thin slab casting-rolling process. To improve the steel quality and processing efficiency of thin slab casting-rolling, the rapid secondary refining such as RH or CAS must be applied on-line, which is a useful measure.

2. The smaller converter-billet caster process for common steel bar(wire) products. The process of smaller converter-billet caster for producing common steel bar(wire) products has broadly distributed in China with some significances. It had experienced developing for many years. And the products produced by the process are with strong competitiveness in market. The main features of this process are as follows:

1) The billet casters with section from 120 mm×120 mm to 150 mm×150 mm under high-speed casting get productivity per strand about 0.14~0.20 Mt/a. This process has become integrative technical facilities of fully continuous casting system.

2) The intensive blowing and slag splashing of converters with capacity

30~80 t can produce 12~15 thousand heats of steel annually per one vessel It is developed independently in China.

3) Meanwhile, the bar mill and the high speed wire mill have made great progress. The productivity of bar milling from billets with section of 150 mm×150 mm or 160 mm×160 mm can reach 0.7～0.8 Mt/a or 0.9～1.2 Mt/a respectively, The productivity of wire milling from billets with section of 135 mm×135 mm or 150 mm×150 mm can reach 0.4～0.5 Mt/a or 0.6～0.7 Mt/a respectively.

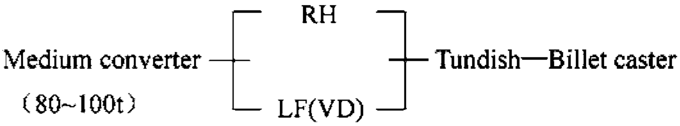
The tap-to-tap time of converter with capacity 30~50t is around 30 minutes. According to this time-rhythm, the billet caster should be high speed with 4~6 strands, and the interface technique should be argon-blowing and wire-feeding between converter and caster. The representative way is as following:

Smaller converter — Argon-blowing+Wire-feeding — Tundish—Billet caster
(30~50t) (4~6 strands)

In order to produce high quality carbon structure steel in some steel plants, the process of 80 t converter with LF is applied. Thus, the tap-to-tap time of converter reaches 38~45 min.

3. The medium converter-billet caster process for alloy steel bar (wire) products

The process of 80 t converter with bloom caster to produce alloy bar or wire products has been used abroad. The interface technique between converter and caster may be RH or LF(VD). The time-rhythm of this process reaches about 45 minutes. It is still quicker than that of electric furnace. The representative process is as following:



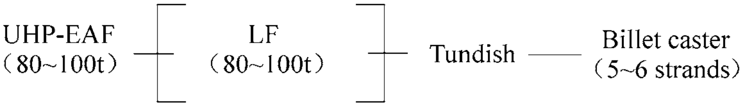
It must be pointed out that the capacity of converter matched with RH should be not less than 80 t to bear the temperature drop in RH treatment. If converter capacity is smaller, e.g. about 50 t, the higher tapping temperature is necessary to compensate the temperature drop in vacuum process. The too high tapping temperature of converter is harmful not only to liquid steel quality, but also to techno-economic index of the process. The worldwide practice shows that the capacity of RH which may run on-line should be more than 80 t.

C. Interface technique between electric arc furnace and continuous caster

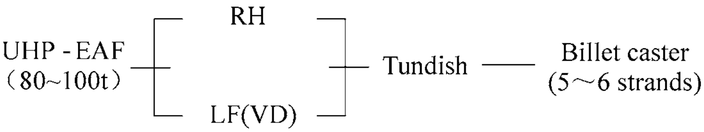
There are three types of interface technique between electric arc furnace and caster:for the carbon steel long products, for the alloy steel long products and for the flat products.

1. EAF—billet caster for carbon steel long products. The electric arc furnace

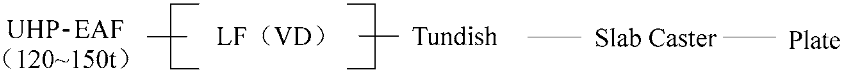
with capacities 80 ~ 100 t is often used in this process. In order to assure the tap-to-tap time adaptable for sequence casting, the oxygen blowing rate of 30 Nm^3/t is necessary for electric arc furnace. The corresponding caster is the billet caster with 5~6 stands and section of 150 mm×150 mm, and the interface technique should be LF, which is often used with the tap-to-tap time of 50~ 60 min and can be equipped with bottom argon-blowing. The typical process is as follows:

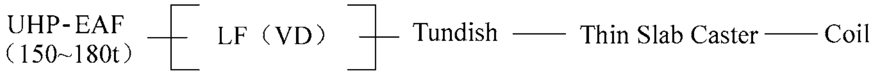


2. EAF—billet caster for alloy steel long products. To produce alloy steel long products, the UHP-EAF with capacities 60~100 t is often used with time-rhythm 50~60 min for sequence casting. In that case, the oxygen blowing rate of 30 Nm^3/t is equipped for each furnace. Because alloy steel long products are mainly used in machinery manufacture and automobile production, their sections are in the range from ϕ16 mm to ϕ 75/90 mm. The billet casters with sections from 220 mm×220 mm to 300 mm×300 mm are often used. The interface technique should be LF(VD) or RH. If RH is used, the corresponding capacity of electric arc furnace should be more than 80 t. The representative ways are as follows:



3. EAF—slab caster(thin slab caster) for plate(coil). The flat products with EAF process are of two types: plate or coil. In that cases, the EAF tonnage is usually larger, for example, 150~180 t with≥30 Nm^3/t of oxygen injection. Plate is produced by slab caster and coil is produced by thin slab caster. The interface technique is often LF(VD) with time-rhythm 55~65 min for sequence casting. The representative processes are as follows:



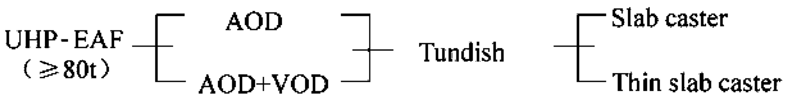


4. EAF—slab caster for stainless steel coil/plate. From the tech-economic point of view, the tonnage of electric arc furnace for stainless steel production should be

more than 80 t. This is beneficial for the stability of product quality and the rational economic scale as well as production efficiency. The rational capacity of a steel plant for stainless flat products had been more than 0.5 Mt/a in the past, but now it should be more than 0.8 ~1.0 Mt/a due to the technology progress and market growth.

The EAF for stainless steelmaking is charged mainly with two kinds of burden material: stainless steel scrap or chromium-rich hot metal. All of them works with capacity≥80 t, even ≈150 t. At present the conventional slab caster is for stainless steel plate/coil.

In terms of the interface technique between stainless steelmaking electric arc furnace and continuous caster, AOD or AOD+VOD is often used. The representative processes are as follows:



7.5.4 *Interface technique of section between caster and rolling mill*

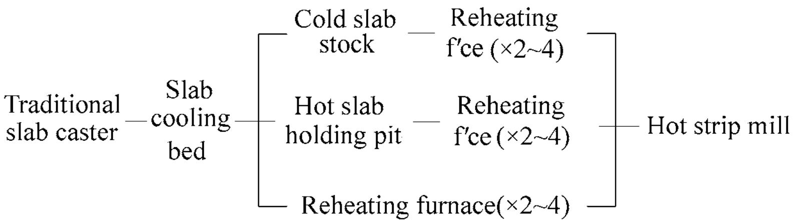
The slabs/billets with a regular cut-length are often transported into the cooling bed. If the cut-length is more than 9 m, the walking beam cooling bed should be adopted to prevent the billet from bending. This is beneficial to regular operation of walking beam furnace. Some ultra-long slabs/billets are directly put into tunnel furnace instead of cooling bed. For example, thin slab casting or some new semi-endless rolling for bar steel, the length of slab/billet is generally 40~50 m. The process of ultra-long pieces charging into tunnel furnace can obtain the more obvious effect of energy saving. Moreover, it is beneficial for improving the steel quality. Generally, after leaving from the cooling bed, slabs/billets would pass through intermediate heating or holding devices such as hot billet soaking pit, holding hearth and reheating furnace. These devices become the different interface techniques between continuous caster and hot rolling mill.

A. Process of continuous caster-hot tandem mill

This is the last region in steel production process. The processes for flat or long products are described respectively.

1. slab caster—flat rolling mill. There are three types of interface techniques between slab caster and flat rolling mill.

1) Traditional slab caster—hot strip mill:

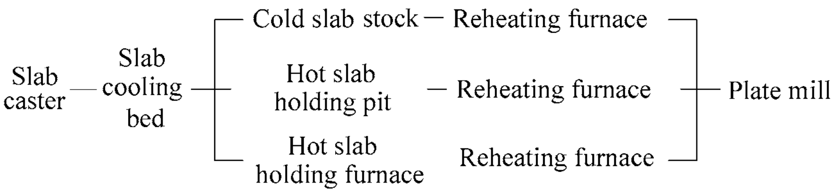


2) Thin slab caster—hot tandem mill:

Thin slab caster (×2)—Tunnel furnace (×2)—Hot strip mill (×1)

Thin slab caster (×2)—Walking beam f'ce (×2~3)—Hot strip mill (×1)

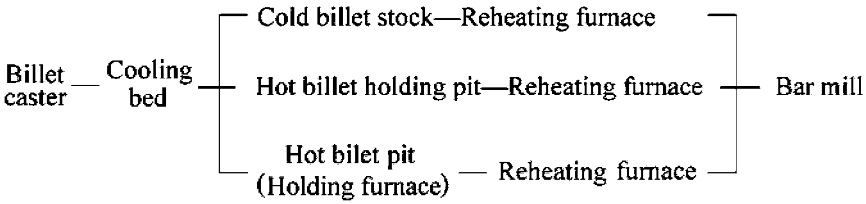
3) Traditional slab caster—plate mill.



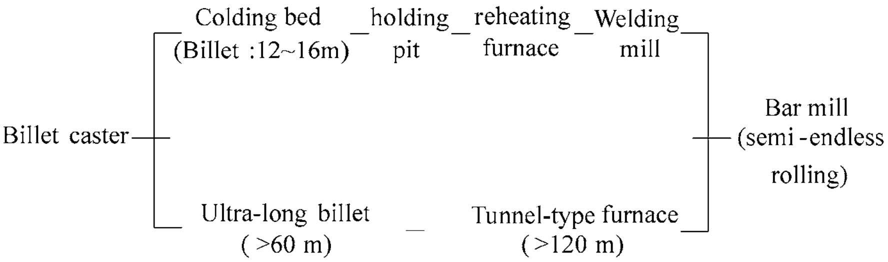
2. Billet caster—bar mill:

The billet caster here indicates billet caster also including bloom caster, the long product mill usually refers to bar mill and high-speed wire mill. There are two types of interface technique as follows:

1) Billet caster—bar mill:



2) Billet caster—semi-endless bar mill.



B. Development tendency of interface technique between continuous caster and hot rolling mill

The interface techniques between continuous caster and hot rolling mill are applied to keep high temperature of slabs/billets and to get the time rhythm and compactness. Therefore, a series of buffer-coordination units with different functions and different capacities are applied to link the continuous caster with hot rolling mill efficiently. In present, the development of interface technique between continuous caster and hot rolling mill proceeds by the following rules:

1. In the case of rational inventory of slabs/billets, it is necessary to set different running routes on different temperature levels, that means different "temperature loops". Firstly, slabs/billets should be directly charged as many as possible into walking beam reheating furnace. Therefore, the layout and running time- rhythm coordination of caster, walking beam furnace and hot rolling mill should be considered. Secondly, when slabs/billets can not be directly charged, they should be charged into the buffer holding furnace in priority. This should be regarded as the first candidate solution to keep the hot tandem mill running incessantly for the unsteady charging rhythm. Finally, when the reheating furnace and holding hearth are all in "full house" state, the off-line slabs/billets should be stacked according to steel grades and sections. When the vacancy emerges in hot charging furnace or buffer holding hearth, the waiting slabs/billets should be supplemented according to the order list.

2. The semi-endless(even endless)rolling with high efficiency and minimum inventory is the target. There are many types of routes to put into practice. The slabs/billets with ultra length (e.g.50~150 m) can be rolled into flat or long products by endless rolling through tunnel furnace. This method gets maximum energy saving and high efficiency. However, the "loop" capacity of this method is limited, and the on-line equipment and corresponding control system with high reliability and stability must be required.

3. The billets with normal length (e.g. cut-length of 12~16 m) can be welded into ultra-long billets before rolling. Certainly, the enough distance between reheating furnace and first mill stand is needed for semi-endless rolling. The producing efficiency of rolling mill and the billet yield could be improved by this way, but the energy saving is limited.

4. The devices such as hot coiling box and welding mill between rough rolling and finish rolling are installed to weld the intermediate rolled pieces for semi-endless rolling and thin-gauge product rolling. It is useful to improve the rolling efficiency and increase the proportion of thin-gauge products. But the energy saving is not obvious. Meanwhile, the proportion relations between hot rolling product mix and cold rolling product mix should be considered.

7.6 Influence of Steel Plant Structure on the Operation Dynamics of Steel Manufacturing Process

The steel plant structure depends on the arrangement and combination of procedures/devices as well as the arrangement of time-space relationships. The arrangement relationships include sequence order, series or parallel linking of procedures/devices. The combination relationships include quantity and capacity of procedures/devices. The time-space relationships contain the layout, the vertical chart, the transport way, speed and running order as well.

There are two types of the steel plant structure:

1. Series structure: for example, EAF×1—LF×1—CC×1—hot rolling mill×1 for producing long products in mini mill.

2. Series -parallel structure: for example, BF×3—BOF×(3~6)—CC×(3~6)—hot rolling mill×2 for producing flat products in integrated steel plant.

The workshops in the manufacturing process are also of two types:

1. Series structure: for example, EAF×1—LF×1—CC×1 in EAF steelmaking workshop;

2. Parallel structure: for example, BF×3 in ironmaking workshop.

It should be point out that the series structure is the serial linkage of procedures with different functions; the parallel structure includes the parallel running of procedures with same functions (e.g. blast furnace, converter or reheating furnace) and with different functions (e.g. RH and CAS).

The operation dynamics of steel manufacturing process is mainly applied to study the mechanism and rules of the change of running state for the mass flow under the support of the energy flow. In general, as the space structure is relatively fixed for a given steel plant, so the mass flow and the energy flow change mainly with time. The characteristics of mass flow and energy flow changes with time introduce the information flow in the steel production process.

In a steel plant, the "flow", including the mass flow, energy flow and information flow, may refer to the movement of resources and events among the nodes (procedures or devices) and along the connectors (ladles, conveyer, roll table, railway, crane etc.) in a network structure. Thus the movement forms mass flow, energy flow and information flow (Holland, 1995). Different flows in different structure networks have different running characteristics in some aspects such as speed, flowrate and efficiency.

The study of operation dynamics of steel production process shows that the controlling-coordinating of flow should meet the following rules:

1. To make the batch operation and quasi-continuous operation synergic with the running rhythm of the continuous process. For instance, the sequence casting of continuous caster requires the batch procedures such as converter steelmaking

and secondary refining synchronized with the casting rhythm.

2. To integrate the different types of batch, quasi-continuous and continuous procedures into a quasi-continuous running system. For example, when designing semi-endless rolling rhythm, it should be considered that batch output of reheating furnace would be changed into a long time continuous rolling of ultra-long pieces by welding and tunnel furnace.

3. To establish a principle that batch devices be subordinative to quasi-continuous and continuous procedures/devices. For example, the coke quenching and the blast furnace burden charging are batch operations, all of them should be obedient to the continuous running of blast furnace.

4. The regional production processes should be synchronized with the whole production process in order to further improve the continuity/quasi-continuity of the whole production process, for example, the process of EAF - thin slab casting-rolling.

The guiding principle for integration of steel production process should be that all procedures/devices can coordinate on the time axis by technical innovation, procedure function optimization, especially the development and optimization of interface techniques among procedures. The target is to realize the continuous/quasi-continuous time scheduling.

The goal of the operation dynamics in steel plant is to get the optimization of multi-objectives but not the single objective optimization. In some cases, if the single objective optimization such as maximum productivity or best product performance is needed, the operation dynamics of the whole production process may reduce the losses in some extent.

The study of operation dynamics in steel production process should focus not only on the stability, synergism and optimization of the present production process, but also on the engineering philosophy of technical innovation and new plant design. The operation dynamics in steel production process is applied to investigate the operation characteristics of the whole or the regional production process for the coordination-optimization of the flow running in the process network based on the different structures of different plants.

References

John H H （1995） Hidden Order: Adaptability builds Complexity, Zhou Xiaomu and Han Hui translated. Shanghai Scientific & Technological Education Publishing House, Shanghai, （2000） 23-24

PENG Q C （2001） The Issues on Continuation of Continuous Billet Hot Charging and/or Direct Rolling. Doctor Eng. Thesis,. USTB （in Chinese）

Yin R Y （1977a） On Multi-demensional Matter Flow Control System of Steel Manufacturing Process. Acta Metallurgical Sinica33 （1）： 29-38 （in Chinese）

Yin R Y（1997b）The Teneral Trend of Iron and Steel Industry, Iron and Steel 32（supplement）: 16-28(in Chinese)

Yin R Y（1998）The Issues on Continuation of the Production Process in Steel Plant. In: Proceedings of the Eight Japan-China Symposium on Science and Technology of Iron and Steel, Chiba, Japan. 10-16

Yin R Y（2001） Cognition of Several Problems on Steel making Techn. Progress to the early part of 21st Century. Steelmaking 17（1）: 1-6（in Chinese）

Chapter 8

The Structure and Mode of Steel Plant Process

Evolution and innovations about the functions of diverse procedures/devices in the steel manufacturing process have brought about integration and optimization among procedures and thereby promoted structural changes in the steel manufacturing process.

Studies of the steel manufacturing process will promote the updating of steel plant design concepts. In the course of such updating, special attention should be paid to the integration and innovation of process systems and to avoiding a simplistic superimposing or piecing together of components. Research in new design concepts means conducting systematic analysis and integration at different levels and different sections of the manufacturing process system, and, in particular, understanding and considering matters from the perspectives of analysis-optimization of set of procedure's functions, coordination-optimization of set of procedures' relationships, and reconstruction-optimization of set of procedures within the manufacturing process, whereby to study static structural optimization and dynamic continuous operations within engineering projects and, on this basis, to construct optimized steel plant models that operate in a dynamic- orderly, continuous and compact manner.

In previous chapters, the contents already discussed in theory were issues of multi-factor mass flow control in the manufacturing process of steel enterprises ("steel plants" in short), and issues of operation dynamics in the production process of steel plants as well as issues of time foctors in the manufacturing process. Based on such discussion, the structure and mode of steel plant will further be analyzed and studied.

In Chapter 4, when the concepts and operation elements of manufacturing process were discussed, it was pointed out that, from the physical point of view, the steel manufacturing process operation is essentially a phenomenon where a multi-factor "flow" moves according to a certain program in a complicated network structure(process network frame) composed of numerous nodes (procedures

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and devices) with different kinds of connections(connectors). The steel manufacturing processes could not be separated from the three elements, namely *flow*, process network and *order*. It was also pointed out that the steel manufacturing process is an open, irreversible, and far from equilibrium dissipative process. As a dissipative structure, the dynamic running entire system of steel manufacturing process should not be studied with theory based on isolated system and equilibrium. It must be studied and analyzed with theories of dissipation, synergism and system sciences (of course, knowledges of metallurgy, materials science and mechanics must also be included). In previous chapters, discussions and studies were more on *flow* and *order* of the manufacturing process. *Network structure* and its framework were also involved in the discussions, but not expanded enough. Based on above analysis and studies, the structure and mode of steel plant will be studied by means of discussing the functions of process network in metallurgical manufacturing process.

8.1 Relation between Process Functions' Evolution and the Process Structure in a Steel Plant

The procedures and devices are important components in the system of a manufacturing process. They are the composition units of sub-layers in the system of manufacturing process.

8.1.1 *Positions and functions of procedures in a process*

From the perspective of static structure of process network frame, procedures and devices, which basically have three functions (see Fig. 8.1), are the nodes in a network structure:

1. Receiving (input), transfer or heredity(output) functions.A certain procedure or device is always openly receiving mass flow, energy flow and information flow (input flow collection) from outside of the manufacturing process network or from its previous procedure or device, and is openly transferring mass flow, energy flow and information flow (output flow collection) to its next procedure or device. Therefore, procedure or device has receiving, transfor and output functions.

2. Processing, transforming or even mutation functions. Manufacturing process system is composed of lots of procedures and devices with different functions, and each process or device has its own unique function which processes the mass flow and energy flow in the manufacturing process by consuming energy and materials, thus making them under conversion, transformation or even "mutation". It should be said that, processing, conversion, transforming and mutation are fundamental functions of procedures and devices in the manufacturing process, and

are the basic reason why procedures and devices could co-exist in the manufacturing process framework.

3. Adaptation function to changes of external circumstances. Manufacturing process is an open, irreversible, far from equilibrium dissipative structure. Due to its openness the conditions of raw materials and energy are fluctuating and the market demands for products are changing, therefore, the manufacturing process should be put at a relatively optimized state by use of the adaptive ability (to changes of circumstances) of each procedure and device. It is helpful to minimize the dissipation of operation, such as minimizing material consumption, energy consumption, processing time or even positioned space of the manufacturing process.

Of course, it must be also recognized that in the manufacturing process, the above-mentioned functions of each procedure or device are not independent, but mutually correlated, coordinated and conditioned.

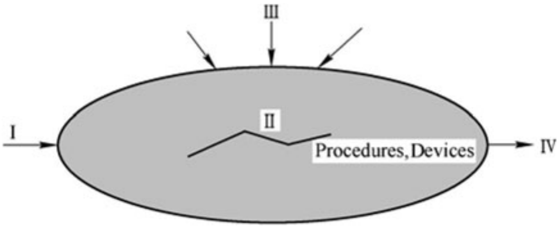


Fig. 8.1 Functions of procedures and devices

I —Receiving, transfer or heredity; II —Processing, transforming, conversion or mutation; III—Adaptation to surroudings; IV—Output, transfer or heredity

8.1.2 *Evolution of procedures' functions of steel manufacturing process*

In the steel metallurgical production process, the function of procedure refers to the behaviors and the major role it plays in the manufacturing process, particularly the processing, converting, transforming and even mutation for mass flow and energy flow. In steel manufacturing process, functions of many procedures are multi-component, and some functions could be realized among a number of procedure. Therefore, people also propose a topic to what extent a function or several functions would be realized in different procedures and about the complementary, mutually replacing and optimized matching relations among these functions, and also to study the topics about the combination and integration of the functions among different procedures.

Here, it is going to seek to analyze and generalize the main functions of related procedures in the steel manufacturing process from the perspective of process engineering (Yin, 1993).

A. Functions of the raw material yard

1. Storage and classification of the raw materials and fuels;
2. Physical blending, stabilizing and adjusting the quality of materials;
3. Matching-orderly output of the materials and energy;
4. Receiving the raw materials and fuels as a "buffer" seasonally;
5. As an environmental function to avoid various dust flying and control the leakage of the unhealthy water, etc.

B. Functions of sintering

1. Pelletizing and adjusting the size and property of the particles;
2. Slightly prereduction and the chemical composition change, and new mineral phases formation;
3. Treatment for the iron-containing waste or BOF slag, etc.;
4. Desulfurization of the flue gases and dioxin control;
5. Recovering the low exergy waste heat.

C. Blast furnace (BF)

After gradual development, BF has had the following basic functions.

1. Reactor of oxide reduction and carburization.BF is mainly characterized by its shaft process. With the progressing of raw material preparation, the development of coking and pulverized coal injection, the improving of hot blast system, the developing and application of bell-less top, high pressure blast operation and new generation of charging system, particularly with the BF enlargement technology and the prolonging of BF campaign, the utilization coefficient of BFs with different volumes has been stabilized at 2~4 t/(m^3•d). It is the most efficient minerals oxide reduction device so far. The flexible selections of daily production between 1000~12000 t per unit BF could be made now. On account of the irreplaceability of coke column on which the shaft process is established, and the requirements on its smooth operation at high temperature, the oxide reduction in BF process is always accompanied by hot metal carburization at varied degrees.

2. Generator and continuous supplier of liquid metal. BF is the first step in the manufacturing process to produce liquid metals with minerals-oxides as the ferrous resources. It is the basis on which converter relies for existence. Although BF process is a moving bed in shaft furnace moved slowly, the generation of hot metal is continuous. Particularly due to the extension of BF campaign (already up to 12~20 years) and the development of multi-hole

tapping, the function of BF as hot metal continuous supplier could be fully displayed with longer time limitation.

3. Energy conversion reactor. BF process is accompanied by bulky energy consumption with conversion. It characterizes the conversion of chemical energy of coke, coal, natural gas and heavy oil into sensible heat and chemical energy of BF outputs (they are all energy carriers, including hot metal, BF slag and gas). With the progress of process technologies, BF heat efficiency has been increasing gradually. The developing and application of blast furnace top pressure recovery turbine unit (TRT) power generation technologies and implementation of other residual heat, surplus energy recycling technologies, the function of BF of energy conversion has become increasingly prominent.

4. Controller and regulator of metallurgical quality. Generally, the influences of BF process on metallurgical quality of products are mainly reflected in control- of S and Si contents in hot metal and hot metal tapping temperature. In consideration of in-depth knowledge of BF process and different S content requirements by various steel products, under reasonable cost conditions, the optimized control values of S and Si contents in hot metal have been clear and could be regulated. While hot metal tapping temperature would have significant influences on possible subsequent hot metal pretreatment and hot metal carriage, particularly it prominently influences on the quality of sequence treatment desulphurization-disiliconization-dephosphorization. Therefore, the quality of hot metal plays an important fundamental role in regulating the metallurgical quality of steel products.

D. Hot metal pretreatment

Hot metal pretreatment process is the new procedure based on in-depth study on thermodynamics and kinetics of metallurgical process. From the perspective of process engineering, its actual functions have already extended beyond its original quality control functions; it has the following main functions.

1. Regulator of metallurgical loads and quality among procedures. Generally, hot metal pretreatment is divided into two categories: hot metal desulphurization and hot metal disiliconization, desulphurization, and dephosphorization. Both would impact on the metallurgical loads of BF and BOF processes, and thus directly impact on metallurgical quality of steel products. Owing to the good thermodynamics and kinetics conditions for sulfur removal, hot metal pretreatment has high efficiency with its economic value. Table 8.1 shows a comparison of costs spent on removing 1kg sulfur with different procedures (Hubbard, 1990).

Table 8.1 Cost to remove 1kg sulfur by different procedures

Procedure	Desulphurization in BF	Desulphurization by hot metal pretreatment	Desulphurization in BOF	Desulphurization in ladle
Cost needed to remove 1kg sulfur, USD	27	10.5	177	64

Of course, for the steel product quality, hot metal desulphurization only helps to control the sulfur content in final products in an economic and effective way, and it is not able to completely and effectively control the shape and distribution of sulfide inclusions in steel. Hot metal disiliconization and dephosphorization are of great significance in reducing BOF's dephosphorization metallurgical loads even by using iron ores with higher phosphorus contents. It is effective way in steadily producing ultra-low phosphorus content steels with phosphorus content of below 0.004%. Hot metal disiliconization, desulphurization, and dephosphorization could reduce the slagging loads of BOF, to remove carbon quickly and reduce ferromanganese consumption by utilizing directly charged Mn-enriched ores, thereby to shorten the smelting cycle of large BOFs. Therefore, 100 percent hot metal desulphurization, disiliconization, and dephosphorization could constitute a platform of producing low-cost clean steels in a highly efficient way.

2. Energy regulator.Hot metal pretreatment can regulate chemical energy of hot metal by moderate disiliconization, providing economic and rational preconditions for alleviating steelmaking slag loads, moderately using scraps and controlling proper BOF tapping temperature.

3. Continuous operation coordinator- buffer of BF—BOF section. As BF has a continuous reaction and a batch tapping, while BOF has a batch operation based on certain cycle, the connection-buffer relation of BF—BOF was once realized by mixer for a period of time. The establishment of hot metal pretreatment procedure had led to the abandonment of mixer, while large hot metal carrying vessels (torpedo cars, hot metal receiving ladle, etc.) have gradually become coordinators and buffers of continuous operation between BF—BOF based on the optimization and matching of such important parameters as hot metal composition, operation time, temperature.

E. Oxygen converter (BOF)

Through 30~40 years for BOF evolution and the replacement of open hearth by it, now it has become the major steelmaking equipment from hot metal. With the development of related procedures like BF, hot metal pretreatment, secondary metallurgy and particularly continuous casting, BOF has already taken the following major functions:

1. Fast and high efficient carbon remover. It is still the major task of BOF steelmaking to quickly remove carbon from hot metal with more than 4% C content. Owing to the technical progress in vessel design, oxygen lance design and combined blowing, BOF's oxygen supply rate has been up to more than 3

$Nm^3/(t \cdot min)$, its oxygen blowing time could be shortened to 12~16 min per heat, which is the fastest decarburizer. If the hot metal is pretreated by desulphurization, disiliconization, and dephosphorization, slag-less smelting might be adopted. In this case, even for BOF with capacity more than 200 t, the oxygen supply rate might reach 3.8~5 $m^3/(t \cdot min)$ and the oxygen blown time of one heat could be shortened to 9~12 min. That is of practical economic value for large BOF to be coordinated with high speed slab caster. Large BOF (for instance, with more than 120 t volume), in effective combination with vacuum treating devices, could produce advanced low carbon steels, ultra-low carbon steels and ultra-low sulfur steels efficiently. It is one of the fundamental technologies, on which a large modern, highly efficient plate/strip steel plant is established.

2. Fast heating up vessel. The fast oxidizing reactions of elements like C, Si, P, and Fe of hot metal in BOF lead to the fast heating up of metal bath, normally the metal bath can be heated up from 1280~1350 ℃ to 1640~ 1680 ℃ quickly within 12~16 min, and besides that, it is still capable of melting certain quantity of scraps (for instance, not more than 25%).

3. Energy conversion reactor. BOF has become a reactor with energy conversion function, relying on the physical heat and chemical energy of hot metal, the rational oxygen supplying technique, and the recovering of BOF gas and steam. A well operated BOF can recover BOF gas 100~108 Nm^3/t and steam 40 kg/t, thus basically compensating the energy consumed by the whole BOF heat, sometimes it could even make steels with “excess energy”. As far as only BOF is concerned, a large BOF might be able to recover energy 5~10 kgce per tonne of steel.

4. Optimum de-phosphorizer. Owing to BOF’s thermodynamic and kinetic conditions, the moderate dephosphorization operation in a BOF is an optimized and low-cost one. When used as a hot metal pre-treater, when Si content in hot metal is reduced to 0.18% and under proper smelting system, BOF can prioritize dephosphorization process in the metal bath with high carbon content. BOF can also treat hot metal with different phosphorus contents. On the other hand, it is also suitable to make ultra-low phosphor steel. To take an overall view of the dephosphorization indexes of different smelting devices, BOF is still a optimum de-phosphorizer. And desulphurization and disiliconization, should no longer be the tasks of modern BOF.

F. Electric arc furnace (EAF)

With the development of high-power, ultra-high-power EAFs and the existence of the relative technologies, such as water-cooled wall, water-cooled roof, eccentric bottom tapping, oxy-fuel burner, door oxygen lance, scrap preheating and partial hot metal charging, particularly elimination of reduction period of EAF smelting by their combination with secondary metallurgy, the tap-to-tap time of EAF has been reduced to 60 min or even shorter

(Fig.8.2), thus the coordinating-buffering with sequence casting could be achieved. The EAF—fully continuous casting production system under the principle of one after another had been practiced. This is the key reason why the overall advantages of EAFminimill process could be fully displayed.

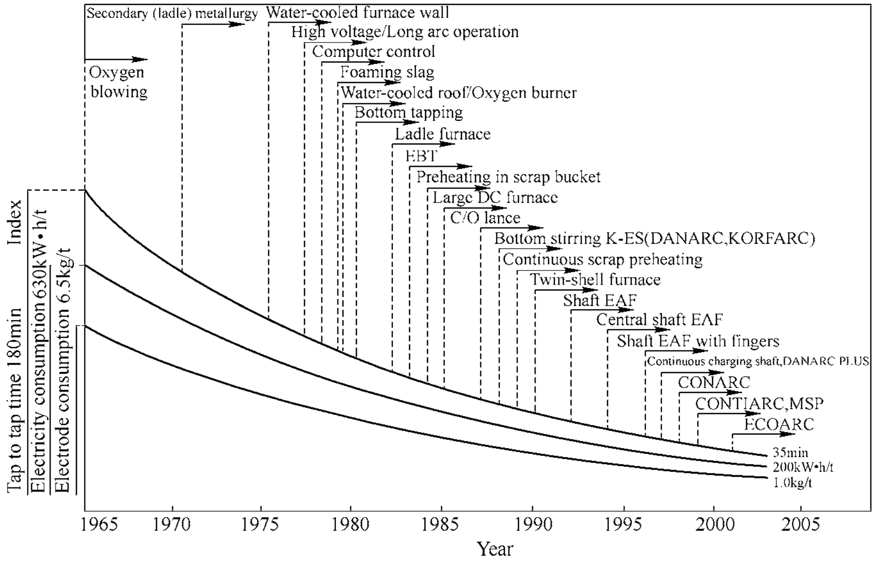


Fig. 8.2 Development of modern EAF smelting technologies

Under these conditions, EAF functions are mainly reflected in the following aspects.

1. Fast scrap melting unit. All the mini-mills are the plants with 100 percent continuous casting system, in which caster is the core procedure for the dynamic-orderly operation of the whole plant. In order to ensure the continuous operation of sequence casting in such plant, EAF functions must be optimized. To eliminate the reduction period, to strengthen scrap melting function, and to shorten power-on smelting time and auxiliary time by use of the new technologies shown in Fig. 8.2, the crucial functions—scrap fast melting and liquid steel fast heating-up are succeeded. The power-on smelting time of modern EAFs has been shortened to 40~50 min against the basic target of EAF smelting cycle in 60 min. Some EAFs have advanced moving ahead towards the target of smelting 36 heats per day. In this course, the EAF function of scrap fast melting has become increasingly prominent.

2. Moderate remover of phosphorus and carbon. It is not only feasible, but also economic to moderately remove phosphorus and carbon in ferrous materials of scrap and pig iron with suitable smelting technique in the oxidizing and heating-up conditions of EAF fasting melting.

3. Energy conversion reactor. EAF's energy conversion function is mainly reflected in effectively converting electric energy and chemical energy into thermal energy, realizing fast melting, fast heating-up and correct control of tapping temperature. As EAF emits bulky high temperature gas in the course of strengthened energy supply and consuming a great quantity of chemical energy and oxygen, to recover the energy of the hot gas has become one of the important goals of EAF as an energy converter.

G. Secondary metallurgical equipment

The functions of secondary metallurgy come partly from the separated functions of BOF and EAF, partly from newly developed functions (vacuum treatment, powder injection, etc.) after in-depth research and partly from the requirements by the continuous operation of a steelmaking plant under the production system of fully continuous casting. In modern steel plants, almost 100% liquid steels are treated by various secondary metallurgical devices. Secondary metallurgical devices have become indispensable procedure in steel manufacturing process and its main functions include:

1. High-efficient refining reactor. Most refining functions of traditional steelmaking furnaces have been largely replaced by secondary metallurgy at higher level and with stronger ability. For instance, to deeply remove the elements like C, O, H, N, S, P, trim the chemical composition in steels, carry out precise alloying and homogenize composition, remove or control the shapes of non-metallic inclusions, regulate or homogenize the liquid steel temperatures. Table 8.2 shows the evolution of refining function of secondary metallurgy.

Table 8.2 Evolution of refining function of secondary metallurgy

Procedures	Classification of secondary metallurgy functions									
Year	De-gassing	Alloy-ing	Homo-genization	Decarbu-rization	Deoxi-dation	Desulphuri-zation	Inclusion modifi cation	Inclusions floating up	Composition trimming	Heating up
End of 1960s	○	○	○							
End of 1970s	○	○	○	○	○	○		○	△	
End of 1980s	○	○	○	○	○	○	○	○	○	△
End of 1990s	○	○	○	○	○	○	○	○	○	○

Remarks: ○ commonly used functions; △ functions under development.

2. Coordinating-buffering unit. In the coordinated operation between steelmaking and continuous casting, one of the important functions of secondary metallur-

gical devices is to coordinating-buffering, realizing longer time continuous operation of steelmaking furnace and caster. This coordination and buffer function is reflected in the control of important technical parameters like mass flow, temperature, quality and time. The coordinating-buffering function of secondary metallurgical devices is indispensable for implementing advanced technologies, such as the long route hotlinkage between steelmaking furnace and rolling mill, the development of fully continuous casting and thin slab continuous casting-rolling.

3. Efficiency multiplier. Under numerous production conditions, the secondary metallurgy function as efficiency multiplier is appeared in enhancing the productivity of the whole manufacturing process, increasing product quality and optimizing cost. It is caused by replacing the reduction phase of EAF smelting, by releasing BOF from decarburization (low carbon content stage), de-sulfurization and de-gassing, and by shortening smelting cycle.

H. Continuous casting(CC)

The steel continuous casting had replaced the processes ingot teeming and blooming, its functions include:

1. Efficient solidification processing. Because caster is cooled by a high-speed water flow, the temperature gradient between metal (solidified shell) and mould wall stays at a fairly high level (in contrast, in the course of ingot casting, the temperature gradient between mould wall and solidified shell is gradually lowering). Thus continuous caster characterizes as highly efficient solidification. Of course, what more manifests the characteristic of efficiency is the fact that cast slab section is nearer to final steel product section than ingot, and the casting is continuous.

2. Optimized forming vessel. The advantages of caster as a forming vessel lie first in the fact that it could get a rational and economic slab section, which is coordinated and matched with final product of hot rolling mill much more. And owing to its long length and heavy piece weight of unit slab, the blooming-breakdown procedure could be eliminated. Meantimes, this solidifying way would help to realize mechanized, continuous and automatic operation. The near net shape continuous casting-direct rolling technology is about the further optimization of forming, and it promotes a new generation of metallurgical processes.

3. Terminal metallurgical reactor. With the maturity of caster process and equipment, the role of metallurgical reactor is manifesting itself more and more clearly. The caster has both the connotation as chemical metallurgy and the function of improving metal-physical process, both correlate with the quality of steel. From the perspective of chemical metallurgy, the stream sealing technique has prevented liquid steel from re-oxidizing, tundish metallurgy mould flux behavior have provided further cleaning, and composition control for steel. Soft-reduction with liquid core and dynomic control of secondary cooling have

noticeable effects on reducing segregation and dendrite columnar crystal zone in the slab. Concerning metal-physical process, mould powder and mould oscillation techniques have provided important conditions for gaining good surface quality. Electromagnetic processing and rapid solidification technologies have provided good control for improving slab structures.

4. Energy saving device. On the one hand, continuous casting is energy saving relative to teeming—soaking—blooming process. As compared with this process, continuous casting process saves energy of 6.3~8.4 GJ/t and increases productivity by 10%~15%. On the other hand, its energy saving function is also reflected in the mass flow high temperature linkage of steelmaking—secondary metallurgy—continuous casting—hot rolling. It is reflected not only in reducing energy consumption of metal reheating and yield increasing, but also in the overall energy-reduce effect brought by process optimization and fluent transportation from BF through to final products. Table 8.3 shows a comparison of energy consumption among different steelmaking—rolling processes.

Table 8.3 Comparison of influences on energy consumption by different steelmaking-rolling processes

No.	Process	Passing procedures								Fuel consumption for rolling /GJ • t^{1}
		Steel making	Ingot teeming	Soaking	Blooming	CC	Surface conditioning	Reheating	Rolling	
1	IC—CCR	O	O	O	O		O	O	O	2.01
2	IC—DR	O	O	O	O				O	0.920
3	CC—CCR	O				O	O	O	O	1.34
4	CC—HCR	O				O		O	O	0.878
5	C—DHCR	O				O		O	O	0.334
6	CC—DR	O				O		ETC	O	

I. Reheating furnace

In the steel metallurgical process, changes have also taken place in the functions of reheating (soaking) furnace, and to some extent, these functions have been different from the functions of the operation coordinated with breakdown and blooming. On the whole, reheating furnace's heating-up function has been relatively alleviated, while its function of linking-buffering-coordinating has become increasingly prominent, reheating furnace's main functions include:

1. Heating and energy conversion unit. Reheating furnace's fundamental func-

tion is to heat up different kinds of slabs/billets and homogenize inside temperature of them, by putting in different energy resources and converting into thermal. On account of high temperature of slabs exiting from high speed caster and the development of hot conveying and hot charging technologies, the entry temperature of the slabs/billets into the reheating furnace has been increasing. For the thin slab continuous casting-rolling process, the entry surface temperature of slabs into the reheating furnace has been up to 1050~1080 ℃ (Fig. 8.3). It is thus clear that reheating furnace's heating up function has been relatively weakening for the near-net-shape caster and high speed caster, meantimes, its function of recovering waste heat and residual energy has been gradually enhanced.

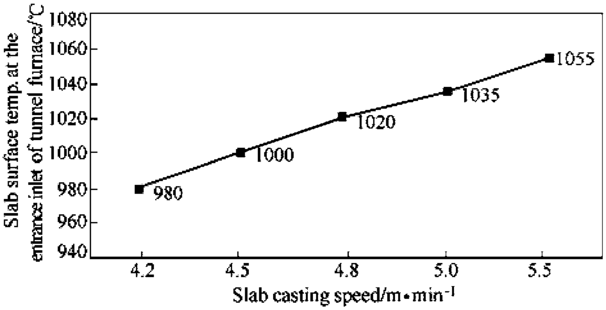


Fig. 8.3 Relation between casting speed and slab surface temperature

2. Buffering-coordinating equipment. For the continuous casting—hot rolling section, reheating furnace plays a role of linkage between different temperature interval and different time rhythm. Its capacity and heating up speed take the function of buffering and coordinating, on the continuation and operation of the process. Particularly the tunnel reheating furnace is long extended (for thin slabs, the tunnel furnace is as long as 180~300 m, and for billets or blooms, it is also as long as over 120 m) and closely linked with caster, its buffering coordinating function must be much higher, as the requirement for process continuation is high. It has become an increasingly significant task to give full play to the buffering-coordinating function of the tunnel type reheating furnace.

3. Metal quality and performance controller. For a lot of steel g rades, their property and performance are directly related with slab/ billet cooling and heating-up processes, as in these courses the nucleation, growth, dissolution and precipitation of some particles take place in slabs/billets. The cooling and heating processes affect phase transformation, particle separation, and grain sizes. Therefore, the control of heating temperature and time length also impact the quality and performance of many products. Furthermore, the control of atmosphere inside the furnace and the control of temperature and time also impact the surface quality of steels. Obviously, the reheating furnace is an important controller for qual-

ity and performance of steel products.

For the hot linking processes for steelmaking—hot rolling, like continuous casting—hot charging—direct rolling, the reheating furnace's role has gone beyond its own functions to expand to the whole reheating region, including slab holding pit, holding furnace and slab conveying table system.

J. Rolling mill

Rolling mill is a procedure that provides commercial steels to the market. Therefore, it is a very important for the economic benefit of a steel plant. In modern steel plants, the functions of rolling mill can be summarized as:

1. Continuous deformation unit. Continuous deformation means the deformation of a rolling piece is realized on a set of mill hou sings in a continuous and integrated way according to optimum deforming extent on each stand. The connotation of its "continuous" is not only about the inter-stand matching of deformation and matching of flow rate per second, but also about the continuation with mass flow of caster outputs, and about the continuation of uncoiling-pickling-cold rolling-coiling-heat treatment while cold rolling follows. Another figure of modern tandem rolling mill is its higher and higher rolling speed, for instance, the exit speed of the high speed wire rolling mill has been up to 110 m/s, while that of the cold rolling mill up to 25 m/s; its continuation degree of flow rate per second is getting higher and higher, and its time proportion in high speed rolling in the course of continuous rolling is becoming greater and greater.

2. Metal structure and performance controller. With the controls on temperature and deformation getting increasingly improved and accurate, based on them, the deformation-transformation controlling technology developed and has matured. The control of steel structure and performance could be realized on one and the same continuous rolling mill. Of course, such optimum control is linked with the metallurgical quality control on steelmaking—secondary metallurgy—continuous casting.

3. Multi-supplementary processor. The rolling is the finish process that provides products to the market. Faced with multi-level and diversified market demands, the rolling process is advancing towards the trend of producing high value-added products, such as surface treatment, deep processing (for a large integrated steel plant mainly producing plate/strip, 60%~70% of the hot rolled strips would be processed into cold rolled strips, while 50%~80% of the cold rolled strips surface—treated or deep—processed) and tailoring components or parts. And the flexible rolling is getting more and more active, which represents one of future developing trends of steel industry. And for the rolling process itself, the synthesis of materials, processes and technologies have opened up a broad prospect for further development of rolling process.

8.1.3 *The optimization for the distribution and combination of procedural functions in the steel manufacturing process*

To sum up, the distribution of the procedural functions of chemical metallurgy—solidification, and the procedural functions of solidification—rolling as well as the effects of these functions, which are listed in Table 8.4 and 8.5, could be inducted. Thus the suitable process and equipment based on the requirements of products in consideration of conditions like resources, energy, capitals and transportation could be selected to display such optimum procedural fuctions.

Table 8.4 Function distribution and composition of iron and steel smelting procedures

Procedures Functions	BF	Hot metal pretreatment	BOF	EAF	Secondary metallurgy	Tundish	Mould
Carburization Reduction	√	×	×	×	√/○	×	×
Decarburization	×	×/○	√	○	√	×	×
Desulphurization	√	√	○	○	√	×	×
Dephosphorization	×	√	√	○	○/×	×	×
Desiliconization	×/○	√	√	○	×	×	×
Heating-up	√	×	√	√	√/○	○/×	×
Deoxidation	×	×	○	○	√	○	×
De-gassing	×	×	○	○/×	√	○	×
Inclusions removal	×	×	×	×	√	√	×/○
Alloying	×	×	○	○	√	×	×
Homogenization	×	×	○	○	√	√	×

Effect: √ remarkble; ○ common; × no effect.

Table 8.5 Distribution and composition of functions of solidification and rolling procedures

Procedures Functions	Mould	RheaJing furnace Soaking furnace	Rolling mill	Interstage reheating furnace	Finish mill
Solidifying and forming	√	×	×	×	×
Structure and properties	○/√	○/×	○/√	○/√	√
Temp. controlling	×	√	○	√	○
Deformation	×	×	√	×	√
Surface quality	√	○/×	○/×	○/√	○/√
Internal quality	√	×	○/√	○	○/√

Effect: √ remarkble; ○ common; × no effect.

Another characteristic of the technical progress of steel production process is reconstruction of the improved procedural functions based on analys is, decomposition and optimization of these functions. As an origin and supporting point of reconstruction-optimization, it is primarily the optimization of individual procedure or device, then of the process section and finally of the whole production process.

There are lots of mature technologies as the optimization of individual procedure and device, such as coke dry quenching (CDQ), BF top pressure recovering turbine unit (TRT), recovery of BOF gas and steam, extension of BOF campaign, increasing BF campaign, top-bottom combined blown converter, compositive energy saving technology of reheating furnace as well as the computer-centered automatic control and basic automation in combination with individual procedure and device.

There are also lots of mature technologies of the re-combination and the optimization of process sections, such as the combination system of coking—sintering (pelleting)—ironmaking, the optimum system of hot metal pretreatment—BOF—secondary metallurgy—continuous casting, the optimum system of scrap preheating—EAF—secondary metallurgy—continuous casting, and the techniques of high temperature defect-free slab casting, hot transportating-charging or direct rolling, controlled temperature-controlled rolling-controlled cooling (the technique of TMCP) and MIS control.

The re-combination and optimization of the whole production process are based on such two kinds of re-combination and optimization. This modern re-combination and optimization could be achieved both on BF—BOF process or EAF process. What symbolizes the re-combination and optimization of the whole production process is to realize the integrated automatic control of the whole process and the improved compatibility between steel plants and environment, to form eco-industrial chain related with the steel manufacturing process, under the precondition of the optimization of process, equipment and process network (e.g. layout).

8.2 Transportation in the Production of Steel Plant

In a sense, steel industry should be called "transportation industry", as its large throughputs of materials (raw materials and auxiliary materials), energy (e.g. fuels), intermediate products, final products inevitably require different ways of transporting and conveying.

The mass flow, energy flow and conversion, and material transportation are very important factors influencing the steel plant structure and investment costs, production costs, productivity and market competitiveness of a steel plant. In the meantime, the transporting conditions outside steel plant even have a direct relation with important macro-decisions like the plant site selection and the geographic location of a steel plant. The evolution of the above-mentioned procedural functions has brought about profound changes in the ways, routes and speed of mass flow and material transportation in a steel plant, and raised higher requirements in dynamic-orderliness, continuation and compactness. The original railway transporting pattern had changed remarkably. Now the overall trends are:

1. The input-output outbound transportation of steel plant's materials, energy and important products still relies on railways and ships, particularly the transportation of bulk raw materials and fuels like ores and coals rely more on huge ships because of their increasing dependence on international resources. A new large integrated steel plant usually tends to be located close to deep-water harbor, with ships of more than 150000 t capacity to transport iron ores, which unloaded from ships are conveyed to the steel plant's raw material yard via a belt conveying system instead of railway.

2. As far as the inter-workshop and inter-procedure material transportation is concerned, apart from the transportation of BF hot metal, which still relies upon the railway transport (some individual plants have started to transport hot metal by special trucks), the transport of other raw materials, semi-finished products and final products has switched to inter-procedure "online" process transporting ways (such as belt conveyors, roller tables and cranes), where the materials or products are not unloaded to the ground. The main trends of such transporting ways are: not unloading to the ground, direct transferring without bypass, non-railway transporting, reducing or eliminating as far as intermediate storage, so as to pursue "least transport work" and shorten mass flow time cycle. Table 8.6 shows the process time comparison between different steelmaking—rolling processes.

Table 8.6 Process time comparison between different steelmaking—rolling processes

SN	Process	Passing procedures									Time from liq. steel to products
		Steel making	Ingot casting	Soaking	Blooming	Second refining	CC	Surface conditioning	Reheating	Rolling	
1	IC—CCR	○	○	○	○			○	○	○	85~110
2	IC—DR	○	○	○	○					○	60~85
3	CC—CCR	○				○	○	○	○	○	30~40
4	CC—HCR	○				○	○		○	○	5~10
5	CC—DHCR	○				○	○		○	○	3~5
6	CC—DR	○				○	○		○	○	2~4
7	TSC—CR	○				○	○		○	○	1.5~2.5

3. The transportation of some auxiliary materials relies mainly on large trucks and belt conveying, not on railway as possible. As the railway system occupys too large land because of its curvature radius and switches, the traditional railway transporting way in a steel plant might produce a scenario where up to 40% land cannot be utilized. That is a noteworthy lesson.

To sum up, great changes have taken place at present in the network structure (including general layout) of a steel plant. The number of BFs in a modern integrated steel plant has been reduced to less than 4, while its steelmaking plant number has been reduced to 1~2. The workshop layout is getting more continuous and compact. Particularly significant changes have taken place in the layout of caster—reheating furnace—hot rolling mill, where the cast slab/billet exiting direction is aligned as far as possible with axis of reheating furnace or even with the axis of hot rolling mill, and the distances among them are shortened as far as possible. This is fully reflected in the thin slab continuous casting- rolling production line. It is also shown in the newly designed layout of slab caster-strip rolling or the layout of billet caster—bar/wire rolling mill. It will also reduce the volume of semi-finished products or final products storage, thus the number of its operators, and also the total land occupancy of the plant will reduce.

8.3 General Layout of a Steel Plant

The rational positions of each procedure and device (productive or non -productive) and the connection between them should be determined in accordance with its functions and relations with adjacent procedures, devices (connecting-matching relation, coordinating-buffering relation). The space positioning between procedures and devices not only include "point positioning", but also include "plane positioning" of procedures and devices and their mutual connections. And "plane positioning" is also called arrangement of procedures and devices or their configuration.

8.3.1 *"Flow" is the corpus in the operation of a steel production process*

The layout inside a steel plant is closely related with the dynamic operation of steel manufacturing process. When discussing the concept and elements of manufacturing process in Chapter 5: 5.1.1, it was pointed out that the steel manufacturing process operation is essentially a phenomenon where a multi-factor flow moves along a complicated network structure, which is composed of numerous procedures with different performances/functions, in accordance with a certain program. Steel manufacturing processes include three elements, namely *flow*, *process network* and *program*, among which, *flow* generally refers to mass flow (flow with complex changes like chemical and, physical changes and energy conversion) in processing. and material flow in the course of transporting and conveying(mainly space shift) *Process network* actually is the matter-energy-time-space structure to integrate "flow of resources", "nodes" and "connectors" in an open system. Process *network* static structure is the spatial structure (mainly general layout) and, of course, the static spatial structure should fit the orderliness, continuation and compactness of the *flow* in the dynamic operation. *Program* refers to the integration of "orders" (including function order, space order, time-characteristic order), and the collection of rules, strategies and routes of operation. It is thus clear that the *flow* is the corpus of process dynamic operation; *process network* is the optimized configuration of "nodes" and "connectors" in the course of *flow* operation, and the time-space boundary formed by them. *Program* is a "software", to drive the optimal operation of process.

8.3.2 *The importance of general layout*

A. The general layout of a steel plant should represent the overall project concept of the dynamic operation of the manufacturing process

Once determined and implemented, the general layout would form a "solidified" static network frame, which is difficult to change arbitrarily. The general layout is the reflection of a steel plant's static spatial structure; to a great extent, it is the norm of time-space boundary.

Steel plant's general layout is to configure the spaces (which are occupied by personnel, machinery, tools and materials) in a most rational and most thorough way in the process starting from receiving raw materials and fuels through to final product transporting, and then combine them in an effective way in order to achieve best economic benefit and environmental-ecological benefit (Chu, 1995).

Plant layout is virtually a technology used to plan mass flow, energy flow, human flow and information flow of the whole plant, and so a technology used to form balanced, orderly and highly efficient action to organize the persons and materials between complicated procedures and various devices.

In planning the material flow-matter flow system in a steel plant, if the variety and quantity of material flow and energy flow are basically fixed, the length of route determines the magnitude of transportation work. The shorter the route is, the less the work needs, and accordingly the less the energy consumes. The selections of driving methods and transporting facilities are also related with energy consumption, then their selections largely depend on economic judgments.

B. The steel plant should represent the concepts about "flow" (material flow and mass flow) to be the core

A highly efficient planning of material flow-matter flow is an important prerequisite for economic production. If it is effectively arranged for the procedures and devices according to the material flow-matter flow diagram, all processes would be operated efficiently (Chu, 1997). Good plant layout would bring about long-term effects of economic operation. The standards raised by Mr. James J. Moore to assess plant layout (process network) include:

1. the most simplified material flow in production;
2. the least material transporting cost;

3. to change process flow sheet in a quickest way;
4. to utilize space in the most effective way;
5. the safest, most comfortable and most pleasing working environment;
6. to avoid unnecessary investment;
7. to arouse the enthusiasm of labors.

Plant layout and workshop layout are interdependent. The general layout of a plant is not merely about the optimum arrangement of each workshop or procedure more importantly, it is about the optimization of the production process of the whole plant. As a result, the mutual coordination of matter-energy-time-space could be achieved, thus the material flow-matter flow, driven by energy, can move along the shortest route in the simplest and quickest way. That means the least transportation work to produce unit products. For a high temperature production process, short transporting route, short operation time and small temperature drop of materials mean less heat losses, which is a reflection of energy saving. Therefore, the optimization of plant general layout and workshop layout would make it possible for the plant to maintain long-term economic operation to the greatest extent, this is one of the significant prerequisites for the survival and development of a steel plant.

C. The general layout of modern steel plant should represent the progress of manufacturing process

In modern steel plants, with the evolution and progress of BF—BOF interface techniques, with the development of such interface techniques as the high - temperature linkage between steelmaking—secondary metallurgy—continuous casting—reheating furnace—rolling mill, particularly with the development of thin slab continuous casting and rolling process, the plant general layout has taken on lots of new characteristics.

1. Layout between BF—BOF. The layout between BF—BOF should reflect the requirements of the quickness, buffering and coordination in transporting hot metal, particularly it should reflect the coordination of BF tapping-hot metal transport with BOF blowing-sequence casting due to development of technologies like BF enlargement and intensified smelting, the diversification of hot metal pretreatment, as well as BOF intensification. Thus the number of BFs could be reduced to 2~4 (particularly 2~3), which would promote the simplification of times and ways of BF tapping-hot metal output and its fast operation. Of course, that requires the rational selection of hot metal pretreatment pattern and its rational “plane positioning” in the layout, and so convenience for dynamics-orderly BOF blowing-sequence casting. The overall trend is to minimize the distance between BF tapping and BOF charging, the time for Transporting hot metal and the number of iron ladles, to charge hot metal correctly and directly into BOF, and to maximize the speed of returning the empty ladle.

2. High temperature heat linkage between BOF—secondary metallurgy—

continuous casting—reheating furnace—hot rolling mill. In modern steel plant, the establishment of 100 precent continuous casting system has led to the abandonment of ingot teeming—blooming—twice reheating. In this section, in order to save energy and reduce consumption, different types of long distance high temperature linkage to varied degrees (such as CC-HCR, CC-DHCR, CC-DR), which reflect the enhancement of the continuation between steelmaking and hot rolling mill, have been developed. The development of these processes has brought about changes in the general layout (spatial structure) of a steel plant, they are:

- Shorter and shorter distance or even roller table linkage between steelmaking plant and hot rolling mill;
- Production capacity matching, or even one-to-one matching or integer matching between continuous caster and hot rolling mill;
- Not only the distance between continuous caster and reheating furnace is getting shorter and shorter, but also the slab conveying way has switched to roller table conveying (or supplemented by cranes for shifting);
- Based on the above, the slab conveying ways are simpler and quicker in the latest design of steelmaking plant—hot rolling mill, that is to align the slab exit with the tunnel furnace to charge the slab by the quickest and the simplest way. Fig. 8.4 shows a newly designed layout diagram between steelmaking and hot rolling plant in a Chinese steel plant.

3. Compact layout of thin slab continuous casting and rolling production line. In most thin slab continuous casting and rolling production, the continuous caster and hot rolling mill are linked with tunnel furnace. The layout characterizes the direct alignment of slab exit with the tunnel furnace. The cut slab with 950~1080℃ surface temperature directly enters its own tunnel furnace, after moderate heat soaking-reheating up it is bitten by the hot rolling mill. The layout is very compact with the processes directly linked. Fig. 8.5 is a compact layout diagram of a thin slab continuous casting and rolling production line.

4. The layout of EAF minimill steel plant. EAF process is established for using scrap from social communities. Particularly for the EAF charged with totally cold materials, one of its figures is that it could be turned on or off at any time. Therefore, the procedure and device structure of minimill steel plant comes into four "one after another" matches—the series connection of one large EAF, one refining furnace, one caster, and one set of rolling mill. For this kind of minimill, the EAF workshop plant is often closely located with hot rolling, also as a compact steel plant. Furthermore, in some of the layouts, hot conveying routes are also designed for slabs with different temperatures, which makes the mass flow fluent and thus saves more energy. Fig. 8.6 shows a layout of an EAF minimill for long products with optimized design.

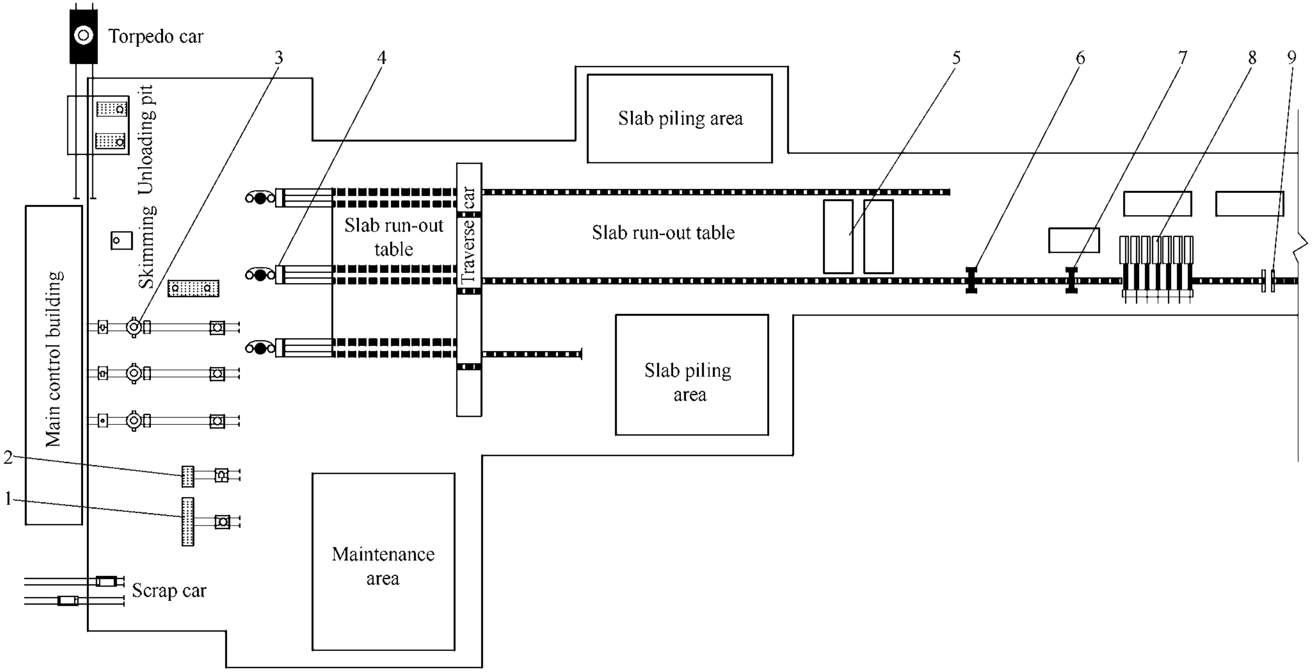


Fig. 8.4 Layout of newly designed steelmaking workshop and hot rolling mill in a steel plant in China

1—RH;2—LF;3—BOF;4—Caster;5—Reheating furnace;6—Edge mill;

7—Roughing mill;8—Finishing mill;9—Coiler

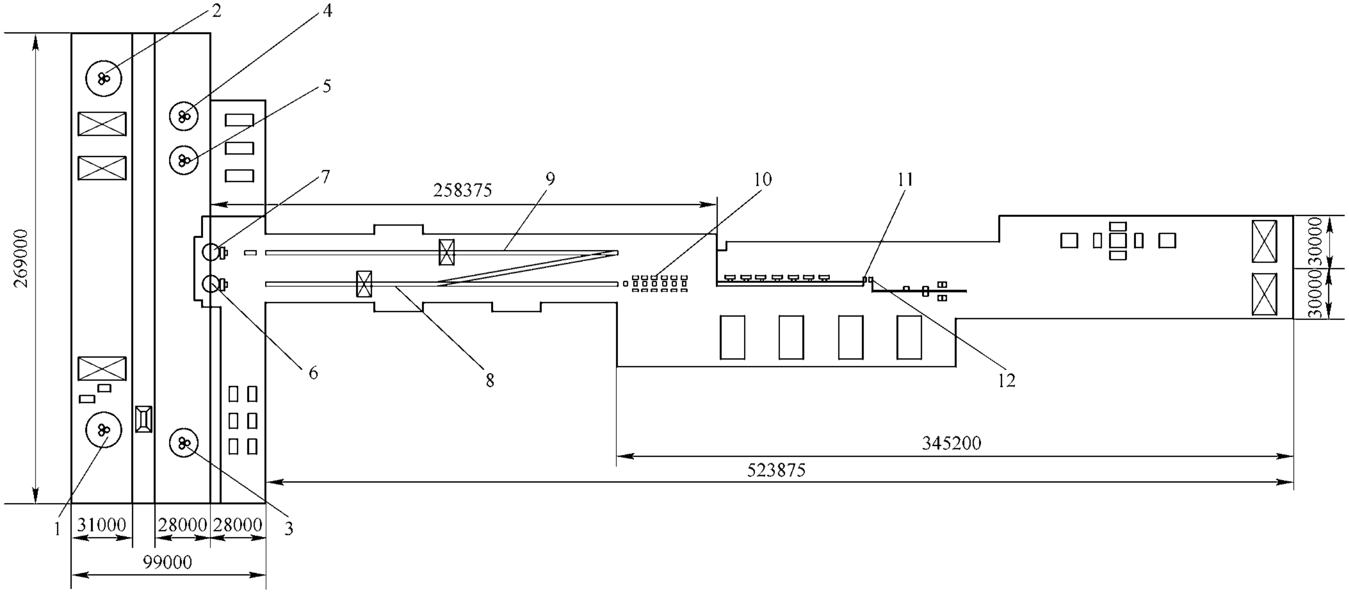


Fig. 8.5 Schematic layout of a thin slab continuous casting and rolling line

1—EAF No.1; 2—EAF No.2; 3—LF No.1; 4—LF No.2; 5—VD; 6—Caster No.1;
7—Caster No.2; 8—Tunnel furnace No.1; 9—Tunnel furnace No.2;
10—6 housings mill; 11—Coiler No.1; 12—Coiler No.2

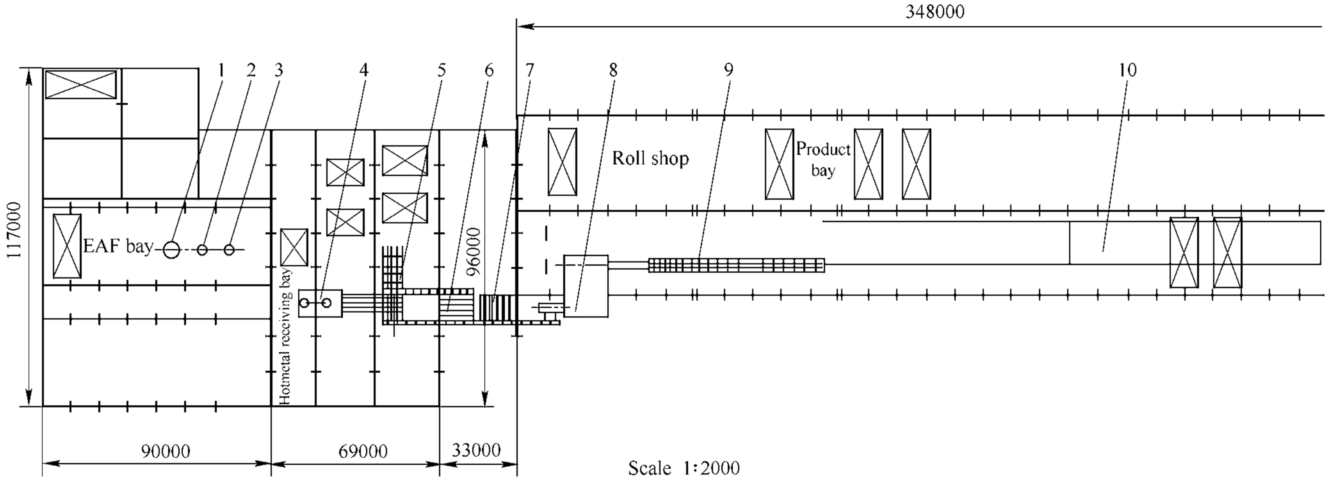


Fig. 8.6 Layout of an EAF mini-mill for long products with optimized design

1—EAF; 2—On-line vertical ladle dryer; 3—LF; 4—Caster; 5—Walking beam slab cooling bed; 6—Auxiliary reheating furnace; 7—Slab slow cooling pit; 8—Main reheating furnace; 9—Rolling mill; 10—Cooling bed

8.4 Issues about Structure Optimization in Steel Plants

From the perspective of socio-economic developing course, when economic expansion in quantity advanced to a certain stage, the structural contradictions would be starting to manifest themselves clearly and becoming the focus of all contradictions in economy. In response to this situation, it is requested to shift the socio-economic operation from traditional developing model, characterized by extensive management and quantitative expansion, to new developing model characterized by intensive management and optimized structure.

8.4.1 *Background and driving power of structure optimization in steel plants*

The steel industry, as a major component of the socio-economic operation, also follows the above rule. Let's look at the development of the international steel industry after the Second World War. Take the first oil crisis in 1973 as a division point. Before that, the international steel industry was mainly characterized by scale development with the quantitative growth predominantly. After that, all major steel producing countries were starting to switch to another developing model where priority is given to structure optimization. Due to the rising energy prices, the changes of market demands, plus the economic restructuring and the shift of investment stress in developed countries, the international steel industry started to shift from the developing stage, characterized by resource-concentration, labor-concentration, tendency to scale expanding and "universal" product mic, into a new stage with characteristics of knowledge-concentration, technology-concentration and optimum structure. The market competition pressure had forced developed countries to switch their developing stress to technical modifications in steel enterprises and then optimizing the enterprise structure based on these modifications. They had invested lots of money for this purpose. While reducing scale, closing factories, laying off staffs, in many countries investment in optimizing enterprise structure was speeded up. It goes without saying that when quantity and scale are no longer the only sign of strength of the steel industry in a country, structure optimization in steel plants and steel industry will play an increasingly prominent role. For developed countries where the consumption of steel per capita is up to a fairly high level, structure optimization will inevitably become the fundamental measure to be taken to strengthen the competitiveness of steel industry. Other countries will also be driven by worldwide competition into the trend of structure optimizing in steel plants.

Structure optimization of steel plants and steel industry is influenced and driven by numerous factors (Yin, 1994), the most important of which are:

1. The pulls or constraints of market demand;
2. Progress of technology and their integration in engineering;
3. Competitions in cost, quality, price and related economic factors like capital investment;
4. The variations of resource, energy supplies and their prices;
5. Influences of transporting conditions and prices;
6. Increasing requirements on environment and ecological compatiBility.

What needs to be emphasized here is the profound impacts on the environmental and ecological problems have brought on steel industry's structure changes. Since the end of the 20th century, environmental and ecological issues have become the focus of global attentions. Different state governments and international communities have invested a lot of money and restricted pollutant emissions through such efforts as parliament legislations. The traditional steel industry is the first to be restricted for its ultra-large scale and the massive consumption of energy and raw materials. This is a new topic for future development of steel industry; it also provides an opportunity for the reconstruction of steel industry.

The pollutants emitted by the steel industry could be roughly divided into three categories: the first includes the globally diffusing ones, such as CO_2, SO_2, NO_x and hazardous gas emitted from coke oven, that directly influence global atmospheric circumstances. The second includes pollutants (mainly industrial waste water) diffusing in river areas, that impact on river systems and soil circumstances, and may trigger regional ecological problems. The third includes locally diffusing pollutants (mainly noises, dust, solid wastes), that directly affect the living circumstances of steel plant workers and the neighboring residents.

Under the current circumstances, major environmental problems caused by steel industry, which have attracted common attentions from the international communities, include emissions of CO_2, SO_x, NO_x, hazardous materials emitted from the coking system and the recycling of scraps and slag.

Owing to the large quantity of CO_2 produced in reducing iron ore in manufacturing steels, plus the CO_2 generated in BOF steelmaking and in the course of energy consuming, the overall CO_2 emissions by the steel industry accounts for a fairly high share of the total industrial CO_2 emissions. Therefore, reducing CO_2 emissions in the steel industry is obviously one of the important topics. Three major solutions to this problem are: firstly, to make great efforts to develop energy-saving steel manufacturing processes; secondly, to reduce iron ore consumption, thirdly, to develop a new technology to reduce the carbon using in of iron smelting.

Under the current international economic and technical background, one of the direct solutions is to reduce share of BF—BOF process route, and duly increase the proportion of steels by EAF process. According to analysis, BF—BOF process produces 2000~2100 kg CO_2 per tonne of steel, while EAF process produces only 800 kg (Umezawak, 1992). This will undoubtedly have a deep impact on current and future structure of steel industry.

Coke is an indispensable fuel and reductant for traditional BF—BOF process. Therefore, emissions from the coke system have become a critical constraint for BF—BOF process development. In addition, the increasing shortage of qualified coking coal resources, will also constrain, to some extent, the survival and development of BF. Non-coke ironmaking processes will enjoy greater development in the future.

The issues of how to make full use of scrap and how to solve the problem of scrap piles occupying too much land and environmental problem have become important economic - environmental topics. It is believed that steelmaking process capable of making full use of recovered scraps would be supported.

In a word, environmental problems, which are drawing more and more concerns from the society, will lead to profound changes in the structures of steel industry.

8.4.2 *Connotations of steel plant structure and the trend of steel plant restructuring*

Structure refers to the ways of organic connection and interactions among numerous elements in system under certain circumstances conditions, also to the organization form. Structure connotation includes not only the simple quantitative accumulation and quantitative proportion among various elements, more importantly, but also their quality advancedness, organization rationality and dynamic adjustability, as well as their inherent vitalities.

Steel plant structure refers to the ways of intrinsic connection and interactions among various elements in a steel plant. These ways are relatively stable and conform with such rules as socio-economic, technological progressing, enterprise organizational and market competition rules. Fundamental elements for forming steel plant structure include market, capital, energy and resources, transporting conditions, quality of human resources and environment status. Steel plant structure and its various elements are inter-connected and interacted. It plays a decisive role in a steel plant's overall function and performance. It can combine these elements in an effective way, thus forming comprehensive advantages of the whole plant. Steel plant structure, once formed, will have comparative stability and independence. Therefore, what determines the competitiveness of a steel plant, as the main body of market competition, is its own product mix, process flow sheet structure, equipment levels and capabilities, rational economic scale, and the group quality and organizational structure of its staffs. Meanwhile, the market competition among steel plants will considerably facilitate the structural changes in steel industry. Therefore, the structure optimization of steel industry is based on the structure optimization of steel plants. Today, the objectives of a new round structure optimization in the international steel industry are the structural equilibrium based on original renovation to make full use of the functions of steel manufacturing process and to play rational role in the circular economy, and the integrated optimization targeted at a series of advanced techno-economic indexes. Looking at the development trends of international steel industry since the 1980s, we can see that, under different circumstances, sometimes the structure optimization in some steel plants is accompanied by sharp increases in scale and quantity, for instance, some steel plant shifted from mainly producing long products to producing flat products. But some enterprises reduced their numerous and jumbled, ultra-large scale to an appropriate competitive one in the course of structure optimization. For example, some large integrated steel plants started specializing in producing flat products, abandoning long products production or moving the long production plant out to other place as an entity with independent management. Some steel plants attach great importance not only to low-cost, high quality, high-efficiency, but also to energy conversion function as power generation, to recycling and processing bulk wastes as scrap and worthless plastics.

8.4.3 *Engineering analysis of steel plant structural optimization*

Steel plant structural optimization is conspicuously inflected in product structure, which is closely associated with market demand, and rational economic scale. Steel plants have always valued the importance of rational economic scale, which means an economic scale with rational structure. It is hard to judge whether or not a steel plant's scale is economic and rational by merely looking at its quantity. One of the decisive assessing factors is whether the structure is optimized or not.

Shown in Fig. 8.7 (Yin, 1993) is the logic conception of steel structure optimization. The figure shows the connotations of steel enterprise structure. The first thing to do in optimizing steel enterprise structure is to select products series that fit the market demand and then select the optimized process, equipment level and capabilities, starting from the requirements to manufacture these products. What should be pointed out is the selections of process and equipment, not only depending on the selection of products, but also are influenced by other factors, such as resources, energy, transportation, environment, human resource quality and capitals. Therefore, the optimization of steel plant structure is in fact an optimization with constraints. The rational economic scale of steel production (products) is not determined arbitrarily. Apart from outside conditions like market demand, it mainly depends on the level and capabilities of the process and equipment to produce these products. Of course, under certain constraints, this rational scale can fluctuate moderately within certain range.

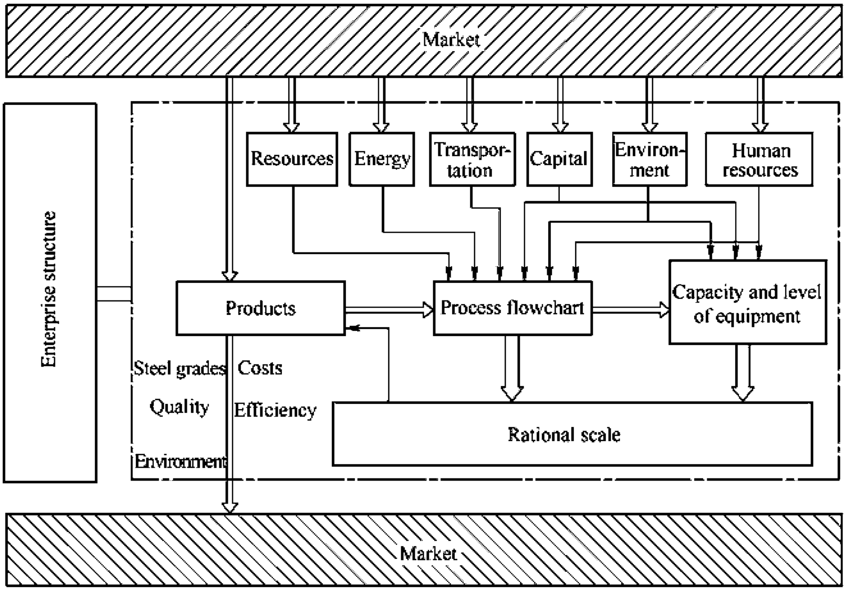


Fig. 8.7 Logic block diagram of steel plant structure

For describing the structure of steel manufacturing process on viewpoint of metallurgical process engineering, it is bound to involve the functions of procedures and the relations among procedures. This is of great significance to steel plant structure optimization, characterized by batch/quasi-continuous process pattern.

Taking a comprehensive view of the technological progress in steel manufacturing process, the thinking of structure optimization of steel plant is principally based on the following:

1. Analysis-optimization of set of procedure functions;
2. Coordination - optimization of set of procedures, relations;
3. Reconstruction - optimization of set of procedures.

The optimization of such three sets has been described theoretically in Chapter 4—analysis and integration of manufacturing process. The three sets have been boosting the progress of steel manufacturing process and the optimization of steel plant structure, thus forming a modern steel enterprise based on the procedural functions' optimization and on the relations' coordination-optimization among various procedures.

8.4.4 *Resources, energy and steel plant manufacturing process*

The selection and reconstruction of steel manufacturing process are closely associated with resources and energy. For a period, most steel plants used the iron ores as the raw material take the process starting from BF, that is BF—BOF-slab casting—flat products (mainly). In the developing counties, there're also steel plants producing long products with a process of smaller BF—BOF—billet casting—wire and bar mill. The steel plants with scraps as the raw materials produce long products take the a process of electric arc furnace—continuous casting (mainly). Of course, the former uses coals, pulverized coals and coke (including coking oven gas), the latter mainly uses electricity as their energy sources.

With the global development of EAF based process, the demands for scrap resources are soaring, then the scrap price is rising, and triggering the developing of scrap substitutes (e.g. DRI, HBI). At the same time, with the advancement and improvement of EAF technologies as well as the breakthrough in thin slab continuous casting and rolling technologies, the EAF based process is starting to enter the domain production of flat products. Active changes are emerging in the relation between energy, resources and manufacturing process in steel plant (Fig. 8.8).

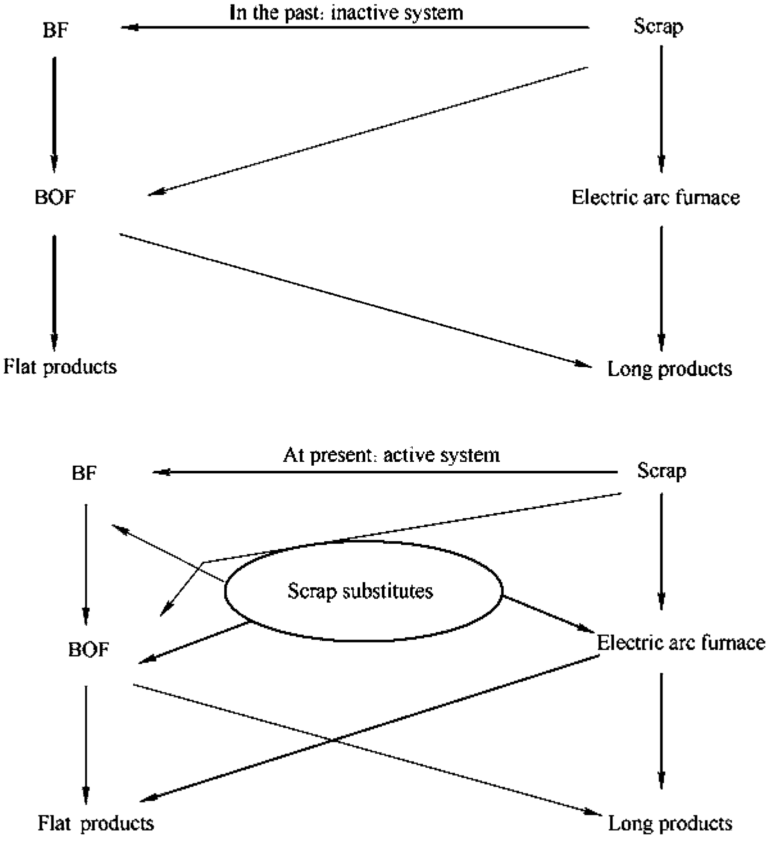


Fig. 8.8 Evolution of relation between steel manufacturing process and resources & energy

From a global perspective, the corresponding relations between resources, energy and steel manufacturing processes have entered into a new stage where active changes have taken place. BF—BOF process can use ferrous resources like iron ores, scrap substitutes, scraps to mainly produce flat products, while EAF based process can use scrap substitutes, scraps or rather big amount of pig irons (including hot metal or cold pigs) to produce long products or flat products. New changes have also emerged in the relations between energy varieties and steel manufacturing processes. The developing trend of energy used by blast furnace process is to vigorously develop pulverized coal injection to minimize the coke rate. The overall trend is to shift from full coke in smelting to 50% cokes and 50% pulverized coals. Currently, the practice of ironmaking in BF using 250 ~ 400 kg/thm cokes plus 120 ~ 230 kg/t coals has been proved viable by the production experiences in many steel plants. As a result, the coke rate has reduced, the pollution from the coke-making system has decreased, thus the investment in coke-making system has been postponed or reduced, with outstanding economic benefits. In addition, what deserves to be mentioned is that some large integrated steel plants set such as target: "BF-based integrated steel plants buy only coals, no electricity". By building highly effective electricity generating devices, making full use of various energies emitted in the course of manufacturing and buying proper quantity of coals for power generation, modern BF-based integrated steel plants can achieve a power balance by themselves, to generate 1kW · h electricity per 250~270 g equivalent coals. As electricity cost is quite low, that no longer needs to buy electricity, even sell electricity to market. The economic benefits are noticeable under the circumstances in China. As far as a region is concerned, the environmental pollution from power generation would be reduced partly. In EAF-based process, the developing of energy consumption is dramatic. The modern EAFs no longer solely depend on electricity, which in addition to great efforts have been made to develop and use different kinds of chemical energies (pulverized coals, gases, oxygen, exothermic elements in pig iron, post-combustion of CO) and physical heats (hot metal charging and scrap preheating) to strengthen the energy supply for EAFs as an important reason. It is reasonable and necessary to blow 30~40 Nm^3/t oxygen into EAF. As a result, smelting cycle of EAF can be shortened to one hour or even less, which would be easy for EAF to match the operation of caster to realize the long length sequence casting. The electricity consumption is reduced to 400 kW · h/t or even less than 300 kW · h/t, to accelerate the EAF process optimization, to increase its productivity, and to enhance its market competitiveness.

Diversified trends have also emerged in the processes using iron ores to produce hot metal. Generally, in ironmaking process, Corex is the appropriate process to produce hot metal with high grade lump ores, coal and pure oxygen. It needs to be pointed out that Corex process poses high requirements on the fixed carbon and volatile content in coals. Too high volatile content would increase coal consumption per tonne of iron; too low volatile content would make it hard for the Corex process to run smoothly. On the contrary, BF can produce hot metal using lump ores, ore fines, cokes, pulverized coals and blast. Smelting reduction with melt bath is a suitable process to produce hot metal using large amount of ore fines, coals and pure oxygen (or oxygen enrichment). But generally speaking, in the foreseeable future, BF would remain the main equipment for producing hot metal. And solid reduced iron, produced by various direct reduction process, should be used as one kind of ferrous burden for EAFs or BOFs, as it differs with hot metal.

From the above, it is obvious that international steel industry has entered an active stage while burden structure, the energy structure and steel plant process structure are diversified.

For better market competitiveness, steel plants are facing with tasks of reorganizing their manufacturing processes. They should select the right product varieties in accordance with the market demands and their own changes. They should select corresponding manufacturing process by taking overall consideration of resources, energy, products and their transporting conditions, by analyzing price variation trend of resources, energy, products and by paying full attentions to environmental protection. And they should make assessment and decisions in combination with financial cost and manufacturing cost in the course of investment, construction and production.

8.5 Steel Plant Structure Optimization and Engineering Design

Engineering design of steel plant structure is the fundamental step to practice the manufacturing process of steel production. During the projection of new plant and the reforming-reconstruction of current plant it should think about the advanced technologies in steel manufacture and their rational coordination at all points.

8.5.1 *The importance of process engineering design*

Design is intended to form a system that can operate in an effective and rational way through correcr, orderly and coordinated combinations. A key concept of system science is that a system has two natures:

The first nature refers to the entire nature of a system that can be deduced from the natures of its elements(parts). For instance, the weight of a vehicle or a plane is determined by the weights of various parts and components.

The second nature is a nature only of the system (entirety), not of its individual elements. For instance, a vehicle can carry passengers or goods, a plane can take off, fly and land safely, and none of its parts has such nature.

It is worthy of emphasis that the second nature is just produced by the interaction and mutual coordination among its elements. To obtain the second nature of entirety, design of system, including overall processes, and manufacturing process must be counted on, in order to achieve correct and coordinated interactions among various elements in a system, thus forming a structure, where the functions manifest themselves.

Most engineering, technical and management problems essentially belong to the second nature-that is to get a desired, optimized system. Therefore, people should pay special attentions to the importance of design of manufacturing process, the design of process entirety. What deserves to be mentioned is that traditional engineering designs tend to focus on product variety and quantity, separately consider the rationality of each individual device, while the design of the whole plant is merely the simple superimposition of these devices. Up till now, in the engineering designs of steel plants, there're still many empirical, merely-piling-up issues, which make it hard to achieve system optimization. When designing a steel plant, it cannot pre-manufacture a sample first just like the materials production designing. The manufacturing process design should be considered from the perspective of process engineering to value conceptual research. Particularly when designing for some complex and important projects, the strategic research and conceptual research should be earnestly done, particularly to value integrated innovations and carefully to avoid designing in merely-piling-them-up or superimposition way, furthermore, it could not be designed by simply enlarging or diminishing or by slavish imitation-just like drawing a tiger after a model of a cat. All these are prerequisites for the success and optimization of process engineering designs. Conceptual research, in accordance with the targets the engineering system is required to achieved, means doing systematic analysis-integration research on the technical feasibility, economic rationality, and environmental compatibility of new theories, new technologies and new systems, on different levels of the manufacturing process system, and then researching on static structure and dynamic operation order in engineering technologies. Dealing with this kind of analysis-integration research, it is necessary not only to make use of knowledge, ways and methodology of system science, but also more importantly, to abstract new concepts and new values, by proceeding from the new analysis-integration theories and engineering innovating strategies in the individual profession, and then turn these new concepts and new values into new design theories. This conceptual research about designs (including process design) is crucial for us to assess international technical and economic developing trend, to outline our developing thinking, to understand technical connotations, to select the right technical proposals and the right critical technologies, or even to carry out self-innovations in order to gain late-developing advantages and to surpass the early starters as a late-comer (particularly as a late-comer in investing).

The conceptual design is a process where we try to find possible solutions for realizing functions, fulfilling different techno-economic indexes and then finally determining overall optimized proposals. Conceptual design is a process of divergent thinking and innovative design, and also characterizes obvious creativity, multi-solution, coordination, and comprehensiveness. It is a complex process of judgment-decision making. The design must be rooted in the concept: to represent in-depth understanding of knowledge at different levels and different scales as well as creative thinking. Designers should be good at heuristic expression of knowledge; good at solving complex problems in design; good at using dialectical thinking to solve some incompatible contradictions.

For designs, particularly process design, it is necessary to concern the actual situation and make comprehensive use of numerous scientific achievements in high-techs and modern management sciences, in order to boost the innovative practices of the new generation technologies and integrated engineering, by means of forming new theories, new concepts and new methodology through analysis-integration.

For a process design, the so called “analysis” refers to the logic ways of disintegrating procedure, device or process into various parts, units and components, as well as procedure functions, and then studying, examining them respectively. The so called “integration” is to combine various parts, units and procedure functions to form an entirety (process engineering) and then study, examine, reason and feed back on a higher level.

From the perspective of thinking, analysis and integration are reversal and reciprocal processes. Generally, integration come after analysis, in some cases, the integrated topics need to be reanalyzed still more.

8.5.2 *Trend of technological progress in steel plants*

A. Reconstruction evolution of international steel industry in the 20th century

Looking back at the past, the development history of international steel industry (Yin, 2001a) in the 20th century is the right restructuring history. With respect to the internal structure of steel plant, some outmoded processes and installations were abandoned, some were gradually improved and some developed as innovative technologies, which enable the steel plants to realize the restructuring and optimizing reorganization gradually. This was the fundamental factor for the optimization of steel plants’ structure in the 20th century. As far as the macro-structure of steel plant is concerned, some steel plants with outmoded structures were eliminated, some survived and developed after restructuring through technical modifications, and some steel plants with innovative technologies and structures have been established, this is the inevitable phenomenon from the market competition. Throughout the whole 20th century, the international steel industry had tremendously developed with continuously restructuring and industrial upgrading in the meantime. In a word, the technological advances are often the causes and drives of restructuring and structure optimizing, while supply and demand in the market, availability of resources, energy, investment profits and environment compatibility play a promoting or constraining role.

When steel plant restructuring is being carried out, there are always certain premises, that different perspective of thinking would project different mappings, and reflect different viewpoints. Steel industry is facing an epochal topic of the 21st century. When thinking about how to restructure China's steel industry, comprehensive consideration must be concerned for such factors as market demands, availability of resources and energy, technical progress, investment profits, environment protection (environment friendly). The diagram of investment decision and investment profits (Fig. 8.9) shows the projection of multi-target thinking, but not the "steel grades and quality centered" projection without considering comprehensive market competitiveness under the old planned economy system.

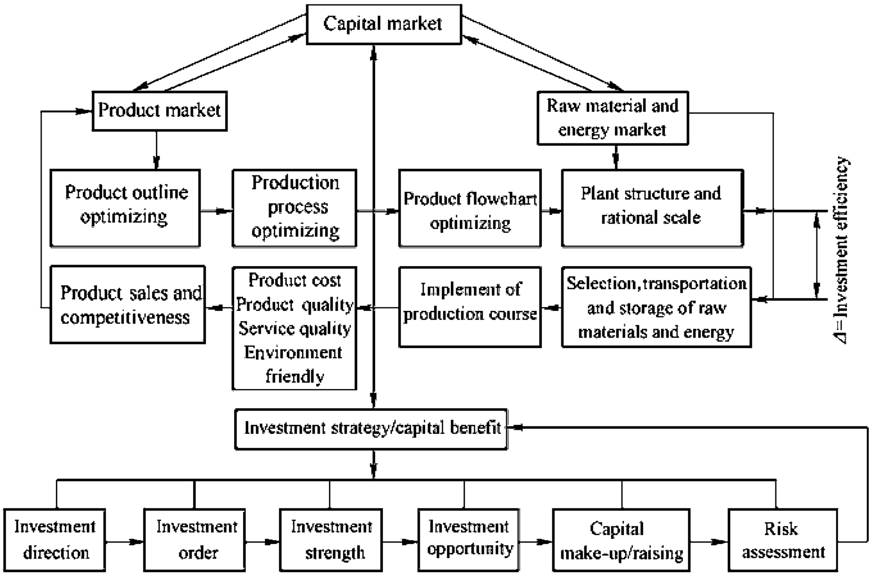


Fig. 8.9 Block diagram of investment decision-making and efficiency

Under the circumstances of fierce market competition, what a steel plant pursues would be the overall optimized targets, including product market share, costs, quality, delivery time and investment profits, but never individual of steel grades and quality. Both topics are on different levels. The former is a complete and strategic topic about enterprise survival and development, and the latter a topic about technologies or about local market development. It has been proved by experiences that topic about individual technologies should be dealt with simple ways (e.g. research in lab, onsite problem tackling), just like "to catch a flea by one finger". While topic about overall situation and strategy should be coped with the whole, synchronized and more broadened knowledge, like "to play a piano with ten fingers". It must be necessary to take an overall approach, to pay attention to time sequence and rhythm, and to solve numerous different problems coordinatively.

B. Analysis on the optimization and capacities of production processes of flat and long products (Yin, 2001b)

1. Strip production—impact from thin slab casting-rolling. The thickness distribution of traditional hot-rolled wide strips include: 2.00~2.99 mm (about 47.5%), 3.00~4.99 mm (about 25.7%); 1.50~1.99 mm (about 14.3%); <1.50 mm (only 0.3%).

Since the 1990s, the development of thin slab continuous casting-rolling process has made it possible to produce strips with minimum thickness below 1mm, and the majority thickness of its products ranges from 1.0 to 6.0 mm.

The thickness of traditional cold strip is 0.6~1.2mm(over 60%), only~15% products take 1.2~1.6mm. Therefore, the market of traditional cold-rolled strips would be influenced by the thin slab continuous casting-rolling process. It seems that the thickness of traditional hot rolled strips would gradually be squeezed to produce >3mm thick strips and to supply semi-products for <1.0 mm cold strips. Therefore, it would cause a series of chain reactions. The hot rolled products from thin slab continuous casting-rolling process would partially share the market of cold rolled strips with thickness ranging between 1.0~2.2 mm, while the market of cold rolled strips with thickness less than 1.0mm will still be dominated by traditional strip mills. The products of traditional hot strip mill with more than 3 mm thickness would edge into the market of medium-sized plates produced by 2300 mm and less than 2300 mm medium plate mills. Such scenario has emerged in China, for instance, in 1999, it consumed about 13.83 Mt medium-sized or heavy plates, among them about 4Mt medium-sized plates produced by hot strip rolling mills. In 2003, 47% of the medium-sized or thick plates consumed in China were produced by wide strip hot rolling mills.

This is because the thin slab continuous casting-rolling process has been increasingly matured with outstanding market competitiveness. According to the data from SMS, the advantages of thin slab continuous casting-rolling process lie mainly in its lower investment cost (about 58% of the investment of conventional continuous casting-hot rolling mill), lower energy consumption (about 50% lower), lower production cost (about 78% of that with conventional mills), higher product yield (1.8% higher than that of conventional mills) and lower maintenance costs (about 39% of that of conventional mills). Currently, two strand thin-slab caster with a set of hot strip mill is capable to produce 1.60~2.50 Mt products per year and could match with EAF process or BF-BOF process. Therefore, under different market conditions, the flat product (particularly thin strips) steel plants can select appropriate product mix, rational production line and rational economic scale, for instance, plate or strip plant with capacity 2~3 Mt/a, plate or strip plant with capacity 4~5 Mt/a, and plate or strip plant with capacity 7~9 Mt/a. So, the different choices and different combinations could be available.

An important fact worthy to be pointed out is that, from a global perspective, most of the existing traditional hot strip mills were installed around the 1970s, after twice complete modifications, they could be used for about 40 years. Till around 2010, most of these mills will come to the end of their lifetime. By that time, the owners of most mills would have to make choices for their future development in order to maintain market competitiveness. Therefore, great attentions must be paid to the selection of process technologies and the judgment of investment strategy.

2. Plate production—restructuring caused by "chain reaction".

The market share of plates with width less than 1.8 ~ 2.0 m would inevitably be partially occupied by hot strips produced by traditional hot strip mills. So, existing 2300 mm plate mills in China will be facing with grave challenges. Even the 2500 mm and 2800 mm plate mills would be influenced due to the reasons of quality, specifications and costs. Thus, existing plate mills in China are facing with choices of being either modified or abandoned.

It appears that some conditional steel plants should be considered to convert their 2300mm plate mills into 3300~4200mm ones, mainly producing medium plates with width 2.5~3.8m that are quite valuable in the market of shipbuilding, bridges, pipelines or pressure vessels. Generally, the rational annual capacity of a 3300~4200 mm plate mill is 0.8~1.5 Mt/a (of course there is still potential), and the unit weight of slab to be rolled should be more than 10~16 t. When modifying 2300 mills into 3300~4200 mm mills, attentions must be paid to configuration or modifications of finishing lines and heat treatment lines. At the same time, it should also be noted that owing to the requirements on quality and slab weight, the capa cities of caster, refining vessel and steelmaking furnace would be changed.

As far as a 3300mm plate mill is concerned and the slab increases to the unit weight over 10~14 t, the tundish capacity should be 30~40 t more, then it can be inferred that the capacity of steelmaking furnace should be about 120 t, the width of caster should range between 1600~1800 mm, and the slab thickness should be 200~300 mm. The increase of ladle capacity (to 120 t or even greater) would facilitate the usage of vacuum treatment, which will of great benefit to the new steel grade development and steel quality.

In this case, it is hard for the steel plants, previously installed with 30~50 t BOFs, to match with 3300~4200mm plate mills in production. These 30~50 t BOF based plants should be oriented to mainly produce bar and wire. This would bring about restructuring and product differentiation for some local steel plants.

For a period of time, the consumption of plates with more than 4m width accounts for 1.5% of the plat product consumption in China. If medium and heavy plate consumption accounts for 25% of the flat product consumption, the consumption of plates with more than 4 m width would account for 6% of the total consumption medium and heavy plates. Of course, though it is not necessary to manufacturing some products with plates more than 4 m wide, the rolling force of the mills with more than 4 m width is needed to process special materials or steel grades. For China, it is necessary to install 4800mm or wider medium and heavy plate mill, as this would facilitate the development of huge ship building and UOE pipes. Of course, these 4800mm or wider plate mills must be equipped with perfect finishing and heat treatment station. When rolling ultra-heavy plates, a room-shaped oven (with a capacity of heating up 80 t ingot) should be installed. At the same time, a steelmaking plant with fairly high level also should be necessary.

3. Bar production.

Bars play an important role in the steel consumption in developing countries.

The bars mentioned here mainly refer to carbon steel, low-alloyed steel bars, which are used in architecture and structures. Normally, their diameters range between 12~40 mm, most of them fall within 12~25 mm. It is suitable to produce this type of bar with 30~50 t BOF or 60~100 t EAF. Normally, the section of billets is with dimensions of (120 mm × 120 mm) ~ (150 mm×150 mm), some even match with 160 mm×160 mm. Refining methods include argon injection and wire feeding.

For the bar rolling, the twice-reheating and the open train mills should be abandoned acceleratively. Generally speaking, all of them would be replaced by tandem rolling mills. The technology of continuously bar rolling is already matured; the tandem rolling mills made in China have been up to a fairly high level, with capable of normal operation and an annual capacity of 0.6~0.7 Mt/a. Its investment per tonne of product is much lower than the imported mill. Therefore, it should be strongly promoted to increase the levels by further developing. Some imported bar mills have a capacity of 1 Mt/a while unit weight of billets about 2.4t has been used.

For reconstruction of current bar mills, attention should be paid to six technologies The first one is the hot charging of billets, with the temperature no less than 600℃. The second is the unit weight of billets up to 1.5~2.4 t normally. The third is the "semi-endless rolling" technique. The billet with size of (120 mm ×120 mm) ~ (150 mm×150 mm) would be welded by a special welding machine to increase the hourly production and metal yield rate, the strength at the welding gap is still stable. It might also be considered to realize "semi-endless rolling" by passing ultra-long billet (about 60 m length) through tunnel reheating furnace (150~180 m length) (Fig.8.10). The fourth is the rationalized length of cooling bed (0.8~1 Mt/a capacity for bar mill, the length of cooling bed should not be less than 120 m) and product packaging capacity which usually influences the smooth running and effect of rolling lines. The fifth is the application of controlled-rolling and controlled-cooling technology. The sixth is splitting rolling (including two-strand and four-stand splitting) to resolve the problems of too low productivity (for products of small size specifications) and the unbalanced output rate (when producing products with different dimensions), which even has negative influence on hot conveying and hot charging of billets.

Generally, modern small section steel mill will mainly produce bars, in individual cases, it produces some narrow flat bar steels. The production of merchant bars like channel beams, I-shaped bars, angle steels etc. will affect the efficiency of mills, and their finishing and packaging are complicated, thus the production efficiency is low, the cost is high. The production of merchant bars should gradually switch to cold-bending forming process, some of them may even be produced by universal mill for H section steels. By means of hot conveying, hot charging and increasing billet weight, the production continuation of bar mill has been greatly enhanced, the production efficiency, energy consumption, product yield, production costs have been considerably optimized. Currently, the annual capacity of bar mill production line should include different classes of 0.6 Mt, 0.8 Mt and 1 Mt.

4. Wire production.

Wires are also the major varieties in the steel consumption of developing countries.

Wires here refer to the application for construction. The diameters generally fall within 5.5~16 mm, but might be up to 22 mm produced by some individual lines. The Coil weight is 1.6~2.4 t. It is suitable to produce such wires with 30~50 t BOF or 60~80 t EAF to produce billets with section dimension of (135 mm ×135 mm) ~ (150 mm × 150 mm), followed by the ladle refining including argon blowing and wire feeding.

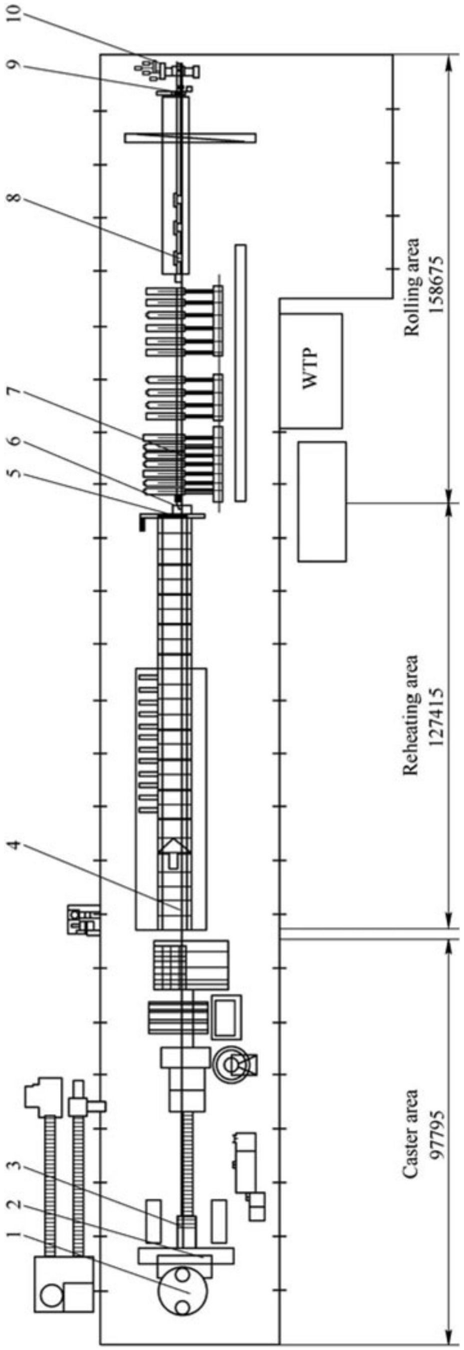


Fig. 8.10 Bar production (semi-endless rolling) line layout of a steel plant abroad

1—Lade turret; 2—Caster; 3—Dummy bar assembly ; 4—Tunnel furnace; 5—Pinch roll;
6—Emergency shear; 7—Rolling mill; 8—Laminar cooling devices;
9—Shearing and de-scaling devices; 10—Kocks reduction mill

Generally, high-speed wire mills have experienced six generations (see Table 8.7) according to wire rolling speed.

Table 8.7 Evolution chronicle of rolling speed of high-speed wire mill

Years	1965~ 1970	1971~ 1976	1977~ 1979	1980~ 1984	1985~ 1995	1995~
Guaranteed rolling speed/ m • s^{1}	43	50	60	75~80	100~105	110~130

Existing twice-reheating and double duo, open-train wire rolling mills in China should be abandoned, and reformed to high speed wire mills. Since 1990s, the high-speed wire mills made in China have encouragingly progressed that high-speed wire mill already could be designed and manufactured with speed up to 90~105 m/s to produce 0.4~0.5 Mt/a wires. Its investment per tonne of product and its spare parts prices have been reduced considerably. While the actual annual production of some high-speed wire mills with partial imported components have been up to 0.6~0.7 Mt.

Currently, the annual capacity of wire rolling can be divided into two ranges: 0.4~0.5 Mt/a and 0.6~0.7 Mt/a. To successfully fulfill these targets, it is very important to charge hot billet, increase billet weight (1.6~2.4 t, preferably more than 2 t) and enhance packaging capacity.

Generally, it's better to install one wire production line in a plant. If two lines must be installed, then full attentions should be paid to the capacity of reheating furnace, the capacity of hanging transporting chains and the capacity of packaging devices. Otherwise, the capacity of two wire mills cannot be brought into full play. One of the wire mills is actually used as a semi-standby mill. Thus, the investment and labor force would be increased accordingly, and the economic benefit is unfavorable.

5. Alloy bar and wire production.

Alloy bars concern mainly alloy steel and structural steel bars (round steel, with a small portion of square bars and flat bars) used in automotive manufacturing industry and machinery manufacturing industry. The sectional size of these bars fall within the range of 16 to 75 mm. It can be made by EAF with capacities of 60~100 t. In some cases, the process route of 80 t BOF—RH—continuous bloom casting could also be used. For some steel plants, it is expected to rise the upper limit of bar size up to 90 mm. It is skillful in terms of technology, but the investment in caster and mill would be increased. Meanwhile, the market share might not be able to offset the investment increase. Therefore, its economic benefit must be assessed.

The mills for alloy bars should not have over capacities, normally 0.5~0.8 Mt/a. Tandem rolling mill is mainly, used. For a wide range of dimension mix and complicated steel grades, in some cases, semi-continuous mill could also be used (this would affect the productivity), neverthless the once-reheating rule should still be followed. If impossible the market competitiveness would be lost.

The existing process of ingot casting-blooming/break down -multi-heating proreciprocating rolling for special steel plants in China needs reconstruction urgently.

As for alloy wires, it would be better to be involved in the alloy bar plant, because their market share is quite small. However, it is not necessary to involve a alloy wire line in every alloy bar plant. Only the special steel plants in a region, where the market conditions are favorable, need such kind of configuration.

C. Analysis on the technical progress of steelmaking and refining

1. Innovation in analysis-integration of BOF functions.

Before the 1950s, it had always been assumed that the more functions, the better for a reactor or equipment, ignoring the overall developing trend of the manufacturing process as a whole. Taking open hearth as an example, it was once the main process for steelmaking because it really had many functions. However, this process was shrinking with the fast growth of the fully continuous casting, as its long duration of heat and high energy consumption. These problems made it difficult to match the arising continuous casting technology. With the scientific research going deeper and with the steel manufacturing process being innovated, it is recognized that attentions must be given to analyzing and integrating the functions of steelmaking furnaces, to eliminate some functions (like the desulphurization) which are not favourable to take by steelmaking furnace, but to develop and integrate some optimized functions (like fast de-carbonizing and fast heating up). It seems to be that the following rules should be followed to optimize the functions of steelmaking procedure:

- Follow the physicochemical principles to select the chemical metallurgical reactions, and concurrently consider the quality, costs and efficiency;
- Optimize the time rhythm and temperature change so as to maintain the fluency and high efficiency of mass flow;
- Coordinate the sequential procedures in the course of dynamic operation by interlocking and optimizing function-structure-efficiency.

It can be clearly seen that modern BOF only undertakes the functions of decarbonizing, heating up and moderate de-phosphorizing. Other functions are to be undertaken by hot metal pretreatment or secondary refining devices (Table 4.1).

2. Effect and economic benefit of 100% online hot metal pretreatment.

Hot metal pretreatment is particularly important for modern BOF steelmaking plant. This process, originally only for some steel grades with extremely high requirement on sulfur content, has now become an inseparable key step in process optimization of ironmaking—steelmaking—solidification. With the development of pre-dephosphorization in converter, an advanced technical scheme of total hot metal desulphurization, desiliconization and dephosphorization is under forming (Fig. 8.11). Total hot metal desulphurization, desiliconization and dephosphorization means all liquid metal for the BOF must be pretreated through desulphurization, desiliconization and dephosphorization.

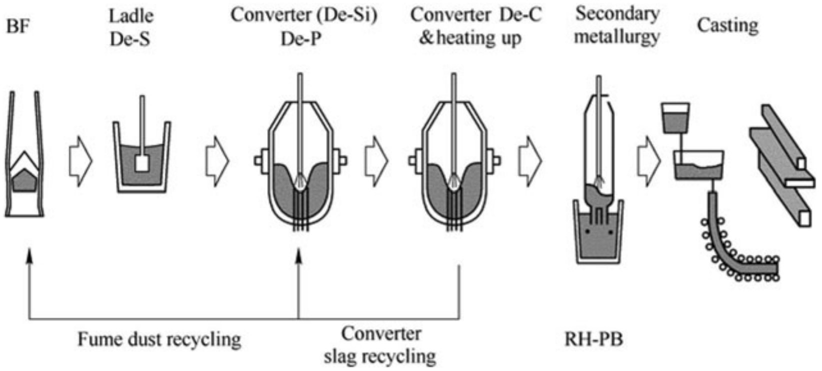


Fig. 8.11 Total hot metal desulphurization, desiliconization and dephosphorization pretreatments

The steelmaking process after total hot metal pretreatment is not only aimed at producing high quality steels, more importantly, it is aimed to establish a clean steel production "platform" of high efficiency, low cost and stable. Of course, this is true mainly for large scale BOF steelmaking to produce plates or strips. Smaller BOF, if using total hot metal pretreatment, would be constrained by temperature.

The process of total hot metal pretreatment would speed up the time rhythm and enhance efficiency. Particularly, the 20 min duration of dephosphorizing heat and the 25~30 min duration of de-carbonizing BOF heat would result in the optimization of layout or even the optimization of a series of parameters, such as furnace capacity. Such a contrast with 32~40 min tap-to-tap time of current large BOFs means that under the total hot metal pretreatment, the productivity of large BOF will be increased by about one-third (Fig. 8.12). Its significance in technologies and economics is different from that of hot metal "offline desulfurization" or partial hot metal desulphurization-desiliconization-dephosphorization. Furthermore, de-phosphorizing pretreatment would reduce the P content in the slag of decarburization BOF, which is favorable for recycling the final slag from the decarburization BOF. For large scale integrated steel plant, the adoption of total hot metal desulphurization-desiliconization-dephosphorization pretreatment will bring about similar technical and economic results with those of "100 precent continuous casting" in a sense. In other words, for a large integrated steel plant with total hot metal pretreatment, it is possible to produce about 9 Mt/a under only one steelmaking work-shop arrangement.

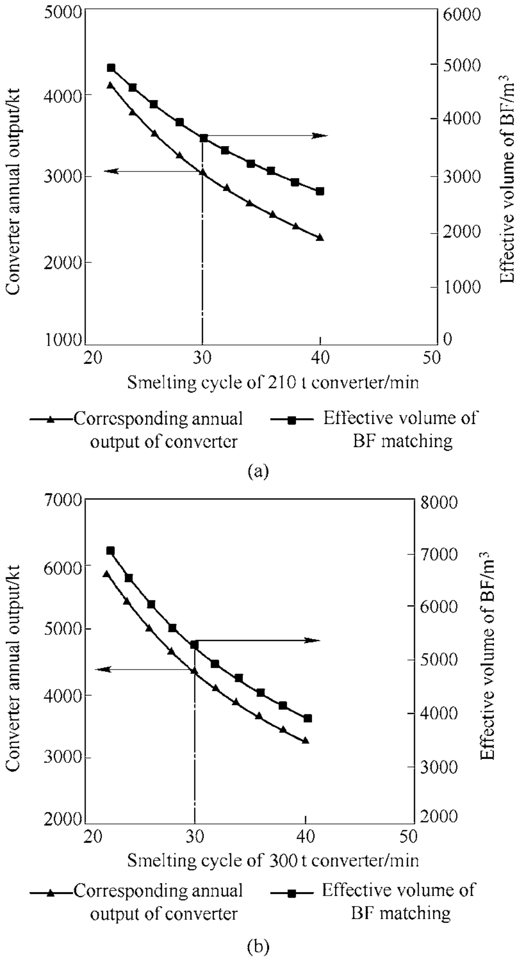


Fig. 8.12 Influences of large BOF's shortened smelting cycle on annual production (calculated values)

(a) Influences (calculated values) of 210 t BOF's smelting cycle on annual production;
(b) Influences (calculated values) of 300 t BOF's smelting cycle on annual production

The total hot metal desulphurization-desiliconization-dephosphorization pretreatment is a technological progressing trend of modern large BOF steelmaking. However, in consideration of the BOF capacities,the variety of steel grades, the different requirements on phosphor content as well as the resource structures of hot metal and scraps in China, it appears that the first thing to do is to put great efforts in raising the proportion of pre-desulphurization of hot metal, then the thing is gradually to achieve total hot metal desulphurization, desiliconization and dephosphorization according to the market demand, the changes of BOF vessels and the changes of raw materials. While a new large integrated steel plant is about to be built in the 21st century, it should use total hot metal desulphurization-desiliconization-dephosphorization pretreatment in a courageous and innovative way, in order to produce quality plates and strips with high efficiency and low costs.

3. Technical tendency of intensified BOF converting.

The technique of rapid converting of large BOF starts to emerge, as its development preconditions are based on the following:

1) The requirement of development in high speed continuous casting;

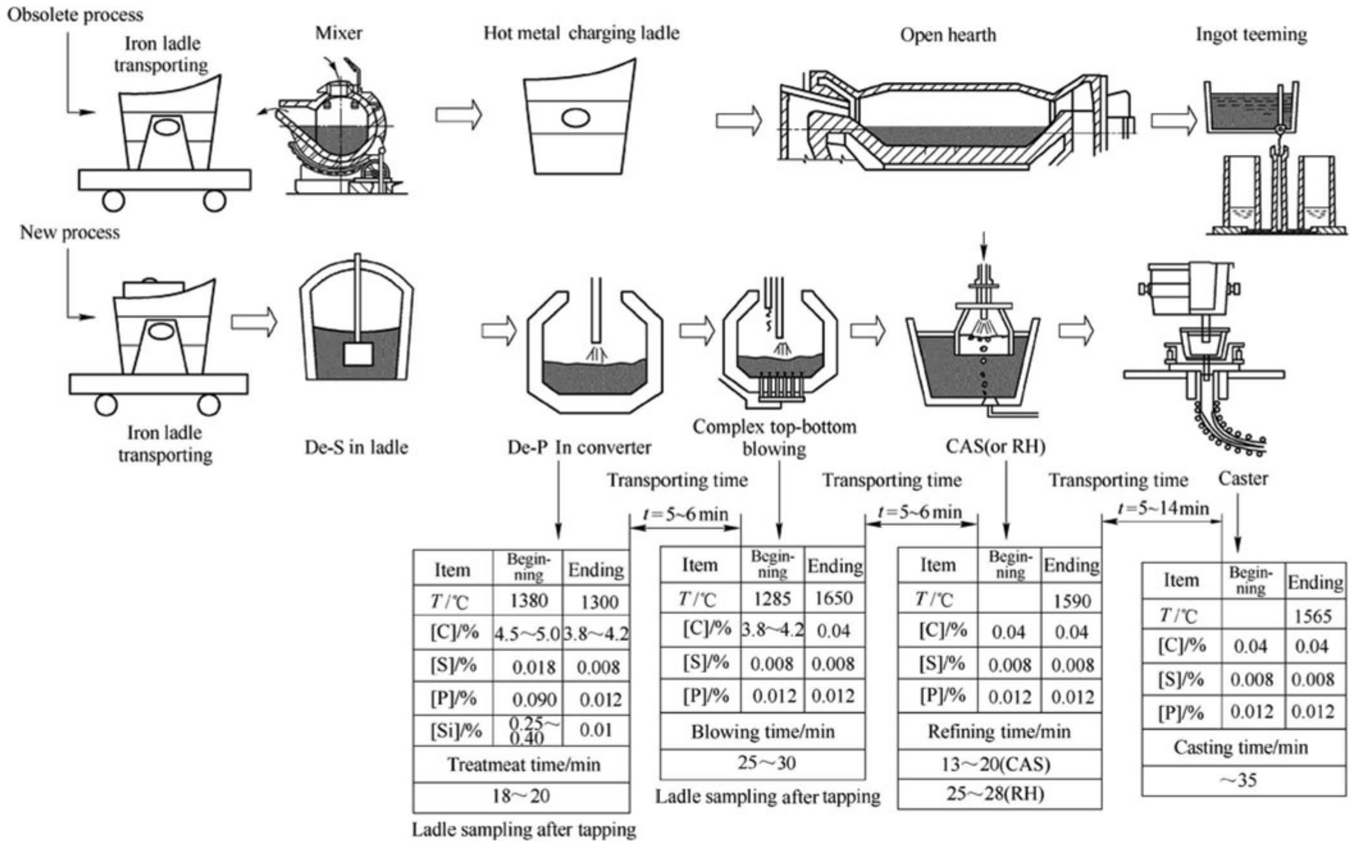
2) The development and maturity of total hot metal pretreatment technologies;

3) The development and steadying about rapid converting technologies and equipment of large BOF.

In some Japanese steel plants have been able to shorten oxygen blowing time to about 9 min, oxygen supply intensity up to 5 $Nm^3/(t \cdot min)$, and get the BOF tap-to-tap time about 20 min. In the meantimes, the H and N contents reduce to lower level, recovered MnO increases, the BOF slag quantity and BOF lining erosion are lowered, and even the specific annual production rises to about 15000 t per nominal tonnage capacity of BOF. Therefore, from the technical-economic perspective, the developing trend of BOF is not the capacity getting greater and greater, but the blown rhythm getting faster and faster. This is favorable for improving cost and quality, for reducing the investment per tonne of steel. For a large integrated steel plant with 8~10 Mt annual capacity to be built in the future, it should not choose 3 steelmaking workshops, but concentrate its production in 1 or 2 steelmaking workshops at most. Fig. 8.13 shows the evolution of steelmaking process and the development of BOF converting technology.

4. The suitable product mix related with BOF capacity.

The local steel plants in China had been booming in the 1990s through their efforts in more than 40 years. Many plants have grown to the scale of 1~4 Mt. With the steel plate demand increasing and the technology progressing, These local steel plants, which have produced products as bar, wire and section before, will gradually differentiate into two main categories: long product steel plants and flat product steel plants. In this course, it should be noted that the development of thin slab casting-rolling will trigger a fierce competition with the traditional slab casting—strip rolling. In the meantime, the market competition of traditional strip rolling mill with plate rolling mill would appear also. Plate mills would mainly produce medium or heavy plates with width of above 2.5 m, the width of these mills should be above 3300mm. The cast slab weight for these mills will be above 10~14 t, therefore, the relevant BOF capacity is above 120 t, and the BOF matched with thin slab casting-rolling process should be 120~150 t.



Item	Begin-ning	Ending
T/℃	1380	1300
[C]/%	4.5～5.0	3.8～4.2
[S]/%	0.018	0.008
[P]/%	0.090	0.012
[Si]/%	0.25～0.40	0.01
Treatmeat time/min		
18～20		

Ladle sampling after tapping

Item	Begin-ning	Ending
T/℃	1285	1650
[C]/%	3.8～4.2	0.04
[S]/%	0.008	0.008
[P]/%	0.012	0.012
Blowing time/min		
25～30		

Ladle sampling after tapping

Item	Begin-ning	Ending
T/℃		1590
[C]/%	0.04	0.04
[S]/%	0.008	0.008
[P]/%	0.012	0.012
Refining time/min		
13～20(CAS)		
25～28(RH)		

Item	Begin-ning	Ending
T/℃		1565
[C]/%	0.04	0.04
[S]/%	0.008	0.008
[P]/%	0.012	0.012
Casting time/min		
～35		

Fig.8.13 Change of manufacturing process and technologies in large steelmaking plants

The capacity of BOF producing common long products might be 30~50 t. For producing bars and wires used in construction, it is hard to say the steel quality produced by 50 t BOF is certainly better than that by 30 t BOF, as the 50 t capacity of ladle is hard to match with vacuum treatment. For a steel plant producing common steels for construction, it is not necessary to change 30 t BOF into 50 t BOF merely from the perspective of enhancing quality. For a BOF steel plant producing high quality long products (steels for machinery manufacturing and automotive manufacturing), the BOF should at least have a tonnage of 80t, because the followed vacuum treatment is necessary. In a large integrated steel plant the tonnage of a BOF matching with BF should be selected rationally between 180~280 t, depending on different cases. Fig. 7.5 had shown the relation between steel product type and the rational selection of BOF capacity in a steel plant.

5. BOF campaign development and cognizance about it.

The BOF campaign is a critical factor for the benefits of a steel plant. The targets of increasing the BOF campaign might be divided into three "stages": first stage aimed at enhancing BOF productivity, reducing refractory specific consumption, with the campaign target is about 1000 heats; the second stage aimed at ensuring caster's operating rate, so as to raise overall productivity, the campaign target is about 2000~3000 heats. The third stage aimed at ensuring the synchronization with the maintenance of BOF, oxygen generator, rolling mill and reheating furnace as well as replacement of BOF fume hood, to benefit the overall coordination. Therefore, when entering the third stage, the BOF campaign should not be assessed by simply looking at the more or less heats (for instance, for a large BOF, it is not true that 11000 heats is necessarily better than 10000 heats), but assessed by overall technical-economic analysis, and study the assessing criteria for different types of steel plants. Otherwise, in this respect, the blind and one-sided understanding might be formed. Of course, the impact of BOF campaign on the overall continuation of steel plant process should be an important reference indicator (Fig. 8.14).

6. "Slag cut-off" technology.

In the course of BOF development, many technical problems have been solved well, only few still unsolved, including the slag-free tapping. For a long time, many steelmaking workshops did not pay much attention to the slag carry over during tapping, now the importance of which has been considered at tentively in progressing. As a matter of fact, the BOF slag which enters the ladle during tapping would influence the subsequent refining procedures (such as resulferization, rephosphorization and oxygenpick-up) and the yield of alloy elements. At the same time, this would also influence the time rhythm, energy consumption and material consumption in the refining processes, as well as the sequence casting. On the other hand, it must be aware that slag carry over quantity could affect the lifetime of the ladle and the tap hole. The last two points must be also noticed, as the short lifetime of ladle would virtually require the BOF to rise tapping temperature (as new ladles are used more often), and the lifetime and operating condition of the coverter tap hole will influence the time-rhythm of BOF and sequence casting、 Irregular taphole will also make it hard to “cut-off slag”, thus finally influencing the productivity. Therefore, from the perspective of productivity, liquid steel quality, and costs, the slag carry- over quantity into ladle should be strictly controlled, and emphasize to develop and use slag stopping devices during tapping. Currently, some large BOF steel plants have started to value this technology.

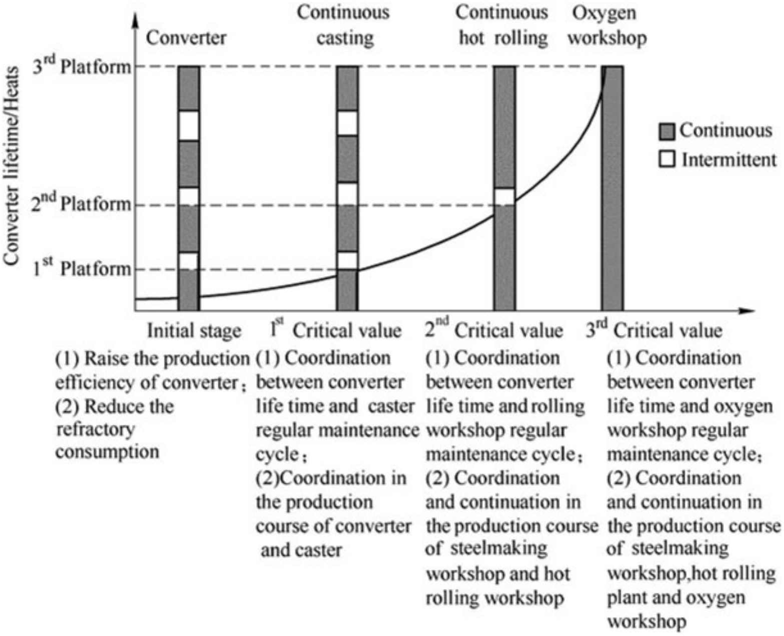


Fig. 8.14 Critical lifetime of BOF and continuation of manufacturing process

7. Functions and tasks of steel secondary metallurgy.

The steel secondary refining started in the 1930s~1950s, which was then aimed at improving product quality. With the advancing of scientific research and technical progress, particularly the emergence of fully continuous casting steel plant, the steel secondary metallurgical technologies have further flourished. Now the steel secondary metallurgy is aimed not only at improving steel grades and quality, but also at alleviating the load of steelmaking furnace by function analysis (sharing) and optimization, such as used LF, AOD or RH to enhance productivity and even reduce costs of producing quality steels. In a fully continuous casting steel plant, the secondary refining devices also play a coordinating-buffering role (in-temperature, time and chemical composition) between the steelmaking furnace and continuous caster. It is like a “flexible loop”, to achieve steady sequences casting with longer length. Therefore, a steelmaking plant should select suitable secondary refining for different furnace tonnage, different steelmaking processes and different its products. For instance, argon blowing and wire feeding are suitable for 30~50 t BOF producing bars and wires for construction, LF is an appropriate choice for EAFs producing long products, plat products or even pipes. Large BOF (mainly producing quality plates/strips), which operates in coordination with hot metal desulphurization-desiliconization-dephosphorization pretreatment, should select quick-running CAS, RH.

8. Purified steel? Clean steel!

With the continuous development of the national economy, the market poses ever-increasing requirements for steel quality. While technological progress makes it possible to reduce the critical content of impurities in steel to lower and lower levels by refining, and raise the steel cleanness up to higher and higher levels accordingly (Table 8.8). At the same time, some new steel-grades have been developed to suit the usage in some extremely harsh circumstances, which is of course a new achievement. However, it must also be pointed out that the purified steels, such as steels for oils and gas pipelines, and IF (interstitial free) steel, account for only a small proportion in the entire steel products. This is a special task undertaken by only a small number of steel plants, but not necessarily by most steel plants. Furthermore, for the critical content of some elements, increasing purity means increasing investment cost and decreasing productivity. Therefore, to the large quantity of steel products for daily use, this should be a concept of clean steel, not purified steel. Concerning the steel purity it is not the more, the better, but should be an economic concept of "cleanliness", to balance between the metal performance and investment costs, production costs, and production efficiency. Discriminating between "purity" and economic "cleanliness" would help to select the manufacturing process and equipment level, control the investment, reduce the production costs etc.

Table 8.8 Theoretical limit of content of impurities in steel

Element	C	S	P	O	N	H
Critical content /%	6×10^{-4}	1×10^{-4}	8×10^{-4}	5×10^{-4}	14×10^{-4}	0.2×10^{-4}

9. Functions of ladle (metallurgical functions, time and temperature coordinating functions, ladle numbers, ladle design).

Further attentions should be given to ladle functions. Ladle has been long called "steel holding vessel", which means a container for liquid steel used for transporting. Now it seems that ladle has undertaken numerous metallurgical functions, or even has become a metallurgical vessel, which has strong correlation with the chemical composition control and liquid steel cleaning. One point worthy of special attentions is that ladle plays an extremely important role in controlling time-rhythm and temperature. In some advanced steel plants, a rational scheduling of the ladle moving route is one of the key factors for stable and coordinated production. Based on the above viewpoints, the ladle design should be further developed and optimized; in the meantime, attention should also be paid to the ladle numbers (including usage state, operation state, and maintenance status) inside a steel workshop. This is because, the most dramatic temperature drop happens during the period when liquid steel is tapped into ladle from the steelmaking furnace. The ladle's heat reserved degree has a direct impact on the factor of temperature drop (normally 30~100 °C). The heat reserved degree of ladle used "online" actually has strong correlation with usage and turnover speed of a ladle. If a ladle within 80~120 min intermittence between two times of filling would be greatly favorable to set a lower tapping temperature of steelmaking furnace. Therefore, a steelmaking plant should not need too many ladles, as too many ladles would sure delay the ladle turnover rate, prolong the intermittance of ladle using, reduce the heat reserved degree of ladle lining, thus affecting the tapping temperature. Fig. 8.15 and Fig. 8.16 show examples of influence of ladle (for a 280 t BOF in China) turnover rate on the ladle wall temperature and on the temperature drop during tapping respectively (Yu, 2002).

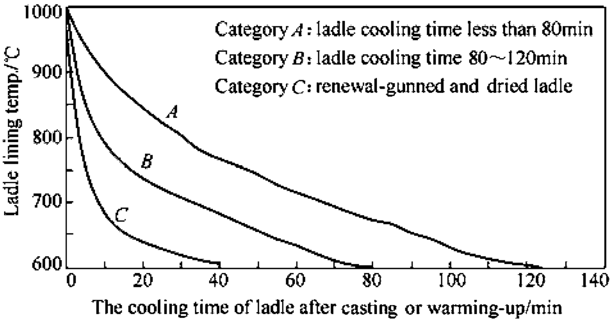


Fig. 8.15 Influences of turnover rate of BOF ladles (280 t) on ladle wall temperature

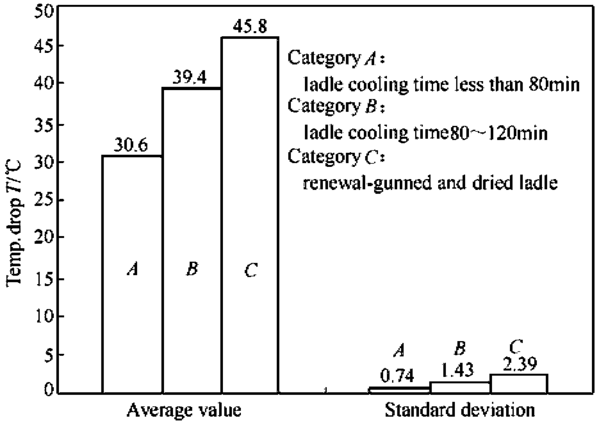


Fig. 8.16 Influences of different ladle turnover rate on liquid steel temp.drop in the course of BOF tapping in a steel plant(280 t ladle, aluminum killed steel)

10. Tundish functions (steady flowrate, steady temperature, constant pressure head, mass flow coordination and tundish metallurgy).

In the early stage, there was no tundish for caster. To equip tundish for caster is a big step forward. This is indispensable for steady and high-efficient operation of caster and for enhancing slab quality. The tundish is first aimed at making the liquid steel charged into the mould steady and continuous, that is putting the liquid steel in a state of steady flowrate, temperature, and constant pressure head by installing tundish. In the meantime, it has been observed that capacity of tundish should not be too small, normally 20% (for large furnace as 300 t) ~ 40% (for small furnace as 30 t) of ladle capacity, which is indispensable for coordinating the mass flow and sequence casting. With the increasing of tundish capacity and requirements on slab quality, tundish metallurgy was gradually developed, optimizing tundish geometry and installing dam and weir or baffles, to which more and more attentions have been paid. Another important issue worthy of attentions is that, to ensure the continuation/quasi-continuation of the steelmaking—secondary metallurgy—continuous casting process, and the extension of tundish (including slide-gate, nozzle, stopper) lifetime has become an urgent task. This is because the weak link, affecting sequence casting cycle, has been shifted to tundish lifetime. Of course, to solve this problem, apart from improvement of refractory quality, lots of technologies have to be developed, such as metal superheat controlling in tundish, continuous detecting of tundish temperature, slide-gate quick changing, high speed casting etc.

11. Caster (section rationalization, strand numbers, slab weight or length, efficiency, sequence casting cycle and casting speed, slab quality, hot charging temperature).

The caster plays a very important role as the intermediate connecting between chemical process of metallurgy and physical process of metallurgy. The technical development of caster had a direct impact on product mix, process structure and steel plant's rational scale. In the future, continuous casting technologies would still have an important impact on the restructuring of a steel plant. In future development, an array of technical developing achievements will emerge, such as rational selection of slab section, rational configuration of strands, optimization of slab weight or slab length, increase of caster capacity, enhancing of efficiency (sequences casting cycle and heats, casting speed), improvement in slab quality (surface, internal), temperature of slab hot charging/direct rolling, as well as a series of new technologies including those of making full use of field intensity. However, this series of technologies will be mainly reflected in high speed, high efficiency caster and various near-net-shape casters in an integrated way.

12. EAF functions (operation simplifying, capacity selecting, waste heat recovering, smelting cycle).

The reason of EAF technologies growing effectively lies in the establishment of technological trend of simplified functions and fast operations, which concentrate the EAF's functions (by optimizing) on two main factors: scrap rapid melting and fast heating-up. Other functions would be distributed to the secondary refining procedure. As a result, the smelting cycle of one heat would be reduced to about 60min, sometimes even to 45~50 min. As far as a modern EAF steelmaking plant is concerned, the EAF must have a duration of heat shorter than casting cycle of caster, but longer than that of secondary refining devices in order to realize high productivity, high quality, and low cost. This is the only way to realize sequence casting. Other requirements, including those on improving quality, sequence casting of different steel grades, energy saving and lower consumption, should also be considered to be incorporated with such principle. The practices have proved that an EAF has already been capable of producing 8000 t/a, or even 10,000 t/a per nominal tonnage. For a special steel plant, it must be firmly convinced that all large quantity commercial steels could be finally produced via continuous casting to guide the overall thinking in technical modifications. For the very few steel grades, or products with depressed market, there is no relations to the overall situation with or without continuous casting. Therefore, the EAFs in special steel plants should also follow these principles with a bit of slower pace only.

Now the global development trend of EAF is not the capacity getting greater and greater, but the smelting cycle getting shorter and shorter. Therefore, the majority of EAFs producing long products are with a tonnage of 60 ~ 100 t, while the EAFs matching with thin slab continuous casting-rolling process are with a tonnage of 150~180 t. EAFs with 300 t capacity once developed in the past, but represent the trend no longer.

13. Layout rationalizing in a steelmaking workshop.

The layout is the basis of coordinated, fluent mass flow and high efficiency production in a steelmaking workshop. The progressive analysis-integration of functions of procedures and devices in a steel plant will inevitably lead to the coordination-optimization of time-space-function relations among various procedures, which must improve the steelmaking workshop layout. Generally, the layout design of steelmaking workshop should follow the principle of steady, continuous and highly efficient operation of three elements: mass flow, temperature and time.

Since 1950 s to present, the layout of BOF steelmaking workshop has undergone great changes, mainly due to the widespread application of continuous casting, the elimination of mixer and ingot teaming, the advancement of hot metal pretreatment and secondary refining technologies, and the extension of BOF campaign. Now, what is extremely important is the suitable procedure and device location in various bays of a workshop and the selection of bay numbers. In the meantime, trains are not used to transport anything but hot metal cars and ladles. The 30 t BOF workshop layout once copied uneconomically the 300 t BOF workshop layout in China, which resulted in too many bays and large area. From a development perspective, in a large integrated steel workshop producing high quality plates/strips, the layout of BOF steelmaking workshop would further change with the development of total hot metal pretreatment. What is particularly worthy of investigation is location of dephosphorizing converter and decarbonizing BOF, that is to arrange dephosphorizing vessel and decarbonizing BOF in different bays, in order to avoid the ladle crane of the high-speed decarburizing BOF being influenced by the operating crane of a dephosphorizing vessel. The dephosphorizing and desulfurizing devices may be arranged in the same bay. Fig. 8.17 shows a layout of a steel plant (built in the 1990s) with total hot metal desulphurization-desiliconization-dephosphorization pretreatment.

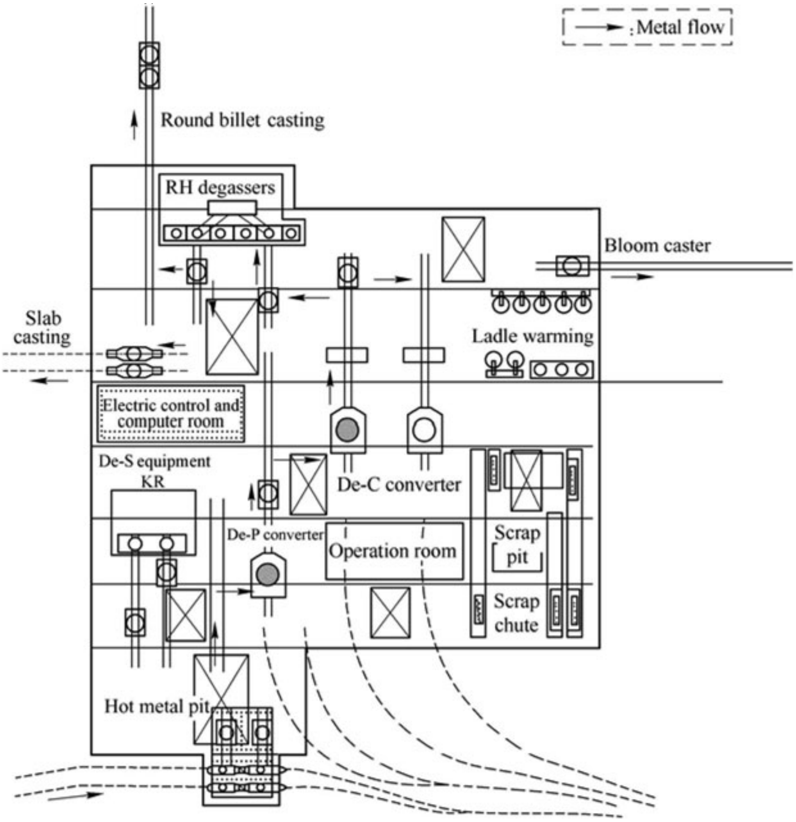


Fig. 8.17 Layout of a newly built steelmaking workshop (with total hot metal pretreatment) in a steel plant abroad

Great changes have also taken place in the layout of EAF steelmaking workshop. The layout of procedures and devices, previously parallel arrangement of several EAFs in one bay and parallel arrangement of numerous ingot teeming units in another, have evolved into the process of arrangement of UHP EAF×1+LF×1 (or plus VD×1) +CC×1. Now the layout of EAF-based steelmaking workshop has gradually evolved three models (Fig. 8.18), namely: one-bay layout

(EAF×1+LF×1+CC×1 are serial in one bay); T-shaped layout (EAF×1+LF×1 are laid out in one bay where continuous caster in transverse bay the same direction as the hot rolling); and double-bay layout (EAF×1 is laid out in one bay, LF ×1+CC×1 are laid out in another, the slab exit direction is vertical to the two bays.). The production capacities of these three models are different, even if the equipment capacities are the same (of course their quantities of transporting equipment are different, see Table 8.9). A steelmaking plant should not be laid out across too many bays, as it has only one EAF commonly. It is not necessary to have a special bay, just like in a BOF steelmaking workshop, for handling system of loose materials. As an EAF steelmaking workshop has less mass flow quantity and lower mass flow frequency than that a BOF steelmaking workshop has.

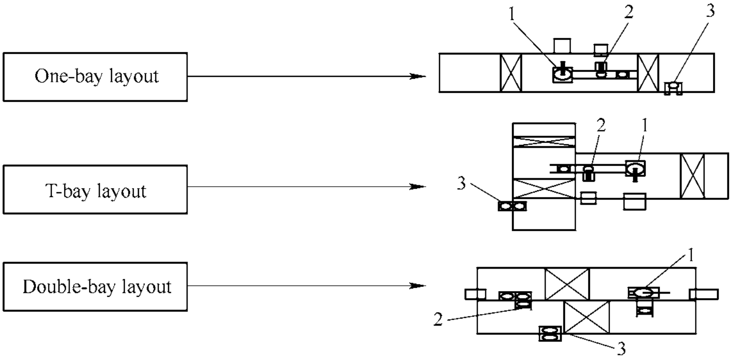


Fig. 8.18 Schematic layout of 3 sorts of EAF steelmaking workshops
1—EAF; 2—LF; 3—CC

Table 8.9 Transporting devices in 3 typical EAF steelmaking workshops

Workshop layout	Cranes	Ladle car	Ladle turret
Single bay	2	1	1
T-bay	3	1	1
Double bays	2	2	1

14. Rules and developing trend of steel workshop operation.

When discussing oncerating dynamics of manufacturing process in a steel plant in Chapter 7, it was mentioned that in an integrated steel complex, BF production is essentially continuous operation (though batch tapping), a continuous production not to be stopped, blast not to be standstill either. Therefore, from the perspective of mass flow, this is a continuous "push". To the essence of caster operation (where sequences casting is expected) in a steelmaking workshop, this is a kind of "pull" for the process mass flow. If the process mass flow "push" from the BF coordinates with process mass flow "pull" from caster, the steel plant would be synergic, coordinated, continuous and highly efficient in production, which is an attractive goal. But in fact it is difficult to be fully fulfilled. Therefore, some intermediate procedures or devices as buffers is necessary, particularly as "flexible loop" for mass flow, temperature, time, and chemical composition. As a matter of fact, the transportation of iron ladles, hot metal pretreatment, coverter, ladles, secondary metallurgical device, tundish and various transporting facilities might all have the function of coordinating-buffering. So, it can be considered that the production process in a steel plant as "elastic chain/semi-elastic chain" composed of rigid components and flexible components. Its operating way is syntonization. The developing trend is quasi-continuous or even continuous operation.

D. Analysis on the technical progress of ironmaking

In the foreseeable future, BF will remain the backbone of ironmaking technologies. BF functions were discussed in Chapte 8: 8.1.2. Currently, the trend of BF ironmaking technology progress mainly concentrates in the following:

- To further intensify the smelting in order to accelerate the synerg etic-optimization of cost, quality, efficiency;
- To effectively organize energy exchange, strengthen the functions of energy conversion;
- To promote continuation of operations, enhance comprehensive benefit.

1. Further intensification of smelting, improvement on cost, quality and efficiency coordinately.

BF smelting intensifying, efficiency enhancing, costs reducing and ensuring hot metal quality are all reflected in increasing BF's utilization; BF's utilization coefficient depends on smelting intensity and fuel ratio, namely:

$$U=\frac{i_\Sigma}{J_\Sigma}$$

where U is BF utilization coefficient, t/ (m^3·d) ; i_Σ is smelting intensity (amount of fuels burned by 1m^3 BF volume per day), t/ (m^3·d) ; J_Σ is fuel ratio(fuel consumption per tonne hot metal), t/t.

It is obvious that attention should be paid to both reducing fuel ratio and increasing smelting intensity in order to enhance BF utilization coefficient.

Decreasing fuel ratio benefits not only to improving the utilization coefficient, but also to reducing costs, which should be the optimal selection for BF smelting intensifying. Practices have proved that using beneficiated materials is a determinant factor for decreasing fuel ratio, which is one of the main approaches to achieve high quality, high production, low consumption and high efficiency for modern advanced BF. This has become the consensus in domestic and international BF ironmaking world.

Beneficiated materials are primarily reflected in raising the grade of ores charged into furnace, improving burden structure and improving coke quality.

1) To raise the grades of ores burden. Currently, iron content in the sinter used by most BFs can be up to over 58%, while iron content in pellets can be up to 65% or even higher.

Raising the grades of ores charged into BFs helps to reduce slag ratio. The slag ratio of some advanced BFs in the world has been reduced to 150~280 kg/t. Since 1990s, with the increasing share of imported ores, the grades of ores charged into BFs in China have been raised gradually, which promote the intensified smelting of BF (Table 8.10). However, as far as the grade of ores is concerned, the iron content in the ores for many BFs in China is still lower, compared with international level (Table 8.11, Fig. 8.19).

Table 8.10 Changes of BF utilization coefficient and grades of ores burden in China during 1990~2006

Year	BF utilization coefficient/t • $(m^3 \cdot d)^{-1}$	Grade of ores burden①/%
1990	1.73	53.31
1991	1.75	53.20
1992	1.81	53.40
1993	1.83	55.89
1994	1.81	58.77
1995	1.79	54.85
1996	1.75	
1997	1.83	55.08
1998	2.02	55.66
1999	2.14	56.25
2000	2.15	56.88
2001	2.34②	57.91
2002	2.46②	58.14
2003	2.47②	56.49
2004	2.52②	58.21
2005	2.62②	58.03
2006	2.675②	57.78

① Grade of ores burden: Fe content in the ores burden (%); ②Data from key steel plants.

Table 8.11 Composition of ores burden for some European BFs

Country	Company	Type of ore	Fe/%	Fe^{2+} /%	Oxidizing degree/%	SiO_2 /%	CaO /%	SiO_2/CaO	MgO /%	Al_2O_3 /%
Sweden	Lulea	Pellets	66.5			2.2			1.4	
		Sinters	49.2			3.4	23.1	6.8	3.2	1
Belgium	Sidmar	Sinters	59.8	4.56	97.46	4.98	7.16	1.44	1.82	1.14
Finland	Rautaruukki	Sinters	60.4	7.8	95.6	4.2	6.97	1.66	2.11	0.99
Holland	Hoogovens	Sinters	58.5	10.6	93.97	3.95	10.3	2.6	1.46	1.33
Germany	Schwelgen	Sinters	57.9	5.1	97.06	5.34	9.46	1.77	1.69	1.09
Germany	Dillingen	Sinters	58.2	5.92	96.6	5.61	8.37	1.49	1.52	1.23
Germany	Bremen	Sinters	58.8	6.48	96.32	4.97	8.34	1.68	1.62	1.22
Germany	Salzgitter	Sinters	58.8	4.8	97.26	4.77	9.78	2.05	0.33	1.3

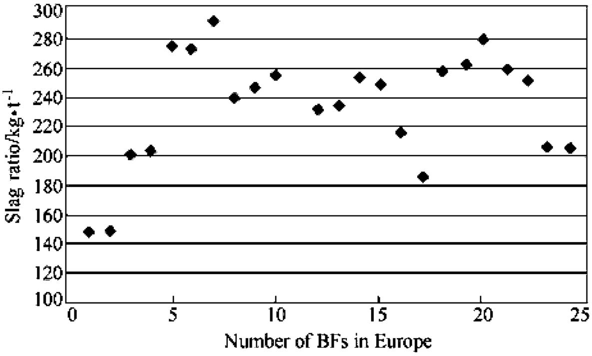


Fig. 8.19 Slag ratio of some European BFs

2) Improving the burden design of BFs. High-strength sinters are the burden for intensification of BF as one kind of bases. The strength and reducibility of sinters are related with basicity. The relation of sinter basicity vs its strength and reducibility was studied in a Chinese steel plant (Fig. 8.20) that the sinter basicity falls within 1.8~2.0, as well as its strength and reducibility are within a relatively optimized range under the conditions of this plant. It is rational that the high basicity sinters combinate with charge components of low basicity. Pellets is characterised as low basicity, high strength, regular size and good reducibility. The rational proportion of pellets with high basicity sinters would improve the burden design of BF to intensify BF smelting. At the same time, because the pellets are mainly consolidated by mineral crystallization, the pellets could be produced with less energy consumption and less pollution, as compared with producing sinters. Of course, fine iron ore concentrates, which are fitting for palletizing, must be available to produce pellets. Therefore, different BF should select the right burden according to their own resources, energy conditions and technical and economic factors. Table 8.12 shows burden and slag ratio of part of European BFs.

Table 8.12 Burden design and slag ratio of some European BFs

Country	Steel plant	Usage of pellets /kg • t^{1}	Usage of sinters /kg • t^{1}	Usage of raw lump_ores /kg • t^{1}	Slag/kg • t^{1}
Sweden	Lulea	1356	6	36（steel slag）	150
Finland	Rautaruukki	398	1115	0	203
Holland	Hoogovens	775	716	37	205
Germany	Schwelgen	296	1128	173	272
Germany	Dillingen	313	1182	103	262
Germany	Bremen	718	750	86	184
Germany	Salzgitter	599	581	336	232

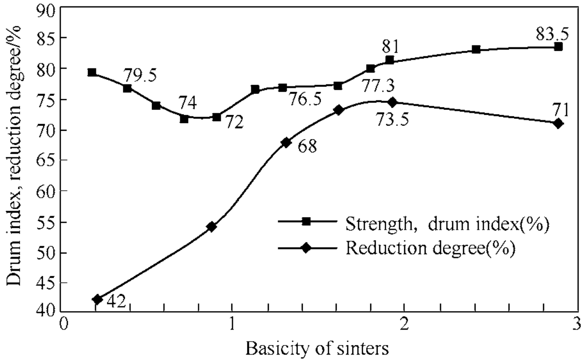


Fig. 8.20 Relation between the basicity of sinters and their strength and reduction degree

Table 8.12 shows that the burden design of BF varies wildly in different European BFs, but each burden structure is determined in accordance with respective conditions, based on the principles of optimized economic benefits. Meanwhile, a noticeable trend also could be observed that beneficiated burden is mainly used, with rational proportion with sinters and pellets, together with a portion of lump ores for adjustment.

3) Improvement of coke quality. In BF operation, main functions of coke include: reductant, supplying energy, bearing the pressure of burden column and improving the permeability of furnace burden column. If used as reductant and energy supplier, coke can be partially replaced by other fuels such as pulverized coals, natural gas and petroleum. But if used to bear the pressure and improving the permeability of furnace burden column, coke is hard to be replaced by other materials. Coke as a backbone of furnace determines, to a great degree, the permeability BF burden. Requirements on coke are conspicuously reflected in strength, ash and sulfur content. Without stable supply of high quality coke, BF would lose the basis for intensified smelting. For BFs with large volume (particularly over 3200 m^3), coke strength is especially important. Ash in coke has manifold impacts on BF smelting. The great proportion of SiO_2 in coke ash will cause the flux consumption to increase the slag ratio, and influence BF's heat efficiency, which is unfavorable for BF intensifying. The sulfur content in coke influences the load of metallurgy like de-sulfurizing inside BF. High sulfur content in coke would inevitably increase the basicity and amount of slag, thus increasing the fuel rate of BF.

Some large steel plants in China, Europe and Japan have strict regulation and management on coke quality. Quality indicators of metallurgical coke include:

- Strength indicators, including DI_{15}^{150} (blown crack resistance), M_{40} (crushing strength), M_{10} (wear strength);
- Thermal performance indicators, including CRI (lump coke reactivity), CSR (post-reaction strength).
- Coke composition indicators, including coke ash, coke sulfur content;

The indicators in some representative steel plants have been up to the levels shown in Table 8.13.

Table 8.13 Comparison of coke key figures

Indicators	Baosteel	China Steel	Kwangyang	Fukuyama	Mizushima Kawasaki	Usinor Dunkerque
DI_{15}^{150} /%	88.84	84.53	87.52	94.81②		
M_{40}/%	89.58	83.83	87.71①			51.3 (I40)
M_{10}/%	5.46	6.7	6.06①			18.4 (I10)
CRI/%	23.69	18.25		29.62		23.0
CSR/%	70.84	70.45	68.3	56.72		66.0
Coke ash/%	11.06	11.16	11.05	12.06	11.3	11.0
S content in coke /%	0.48	0.47	0.53	0.52	0.48	0.6

① Calculated data ($M_{40}=-63.7+1.73\ DI_{15}^{150}$; $M_{10}=66.45-0.69\ DI_{15}^{150}$); ② Value of DI_{15}^{130}.

4) Enhance smelting intensity. In the course of BF intensitive smelting, when the fuel ratio is decreased to below 500 kg/t, it would be more difficult to further reduce fuel ratio. But there are still many measures and great potentials to increase combustion intensity. The following points are to be used for analyzing how to increase smelting intensity:

(1) The relation between BF volume and combustion intensity. BF volume has direct related to the blast furnace hearth area and BF effective height. With the expansion of BF volume, the furnace hearth area is basically increased proportionally; When BF volume is increased to a certain level, the increase of BF effective height slows down (Liu, 1997). According to statistics, the changes in BF volume, hearth area and effective height are shown in Fig. 8.21.

Such relation would affect the ways of BF smelting intensity and its horizon.

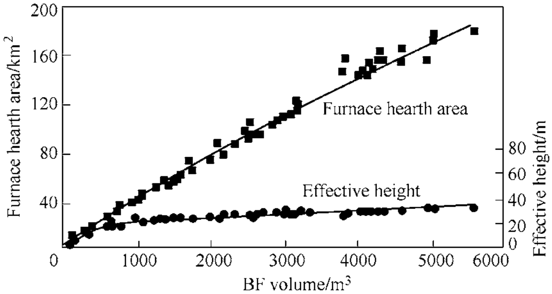


Fig. 8.21 Relation of BF hearth area, effective height with volume

(2) The function of BF hearth. BF hearth is the starting point of combustion and smelting, and also the falling end point of the main products (hot metal and slag). However, fuels and reductants like cokes mainly burn in the tuyere raceways, but not burn equivalently along the BF hearth surface. The tuyere raceway is a near ellipsoid

space. Viewed along the BF hearth cross section, it is a ring-like zone, which is an active zone of combustion before tuyere. Fig. 8.22 shows the proportion tendency of active BF hearth zones (Liu, 2001a). The statistic relation between BF volume and BF hearth diameter is shown in Fig. 8.23.

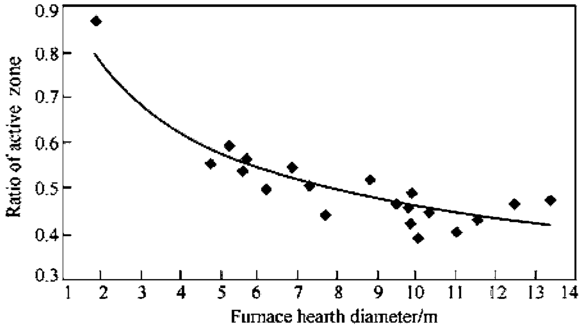


Fig. 8.22 Ratio of active zone of with different BFs

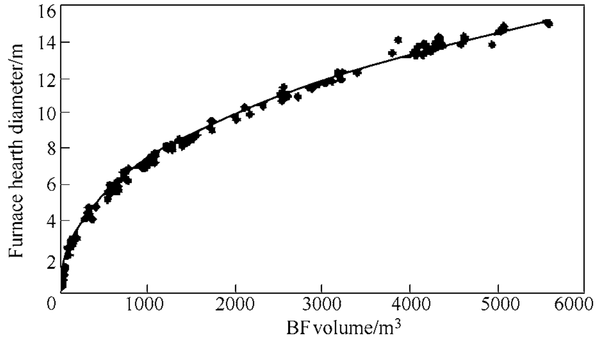


Fig. 8.23 Relation between BF volume and furnace hearth diameter

Table 8.14 Proportion of hearth active zone and smelting intensilg

BF volume/m^3	23	100	300	500	1000	2000	3000	4000	5000	5500
Furnace hearth diameter /m	1.8	2.9	4.5	5.6	7.5	9.8	11.8	13.3	14.6	15.1
Proportion of furnace hearth active zone	0.81	0.69	0.59	0.56	0.51	0.46	0.44	0.42	0.40	0.39
Index of smelting intensity /t·(m^2·h) ^{1}	1.37	1.17	1	0.95	0.86	0.78	0.75	0.71	0.68	0.66
BF utilization coefficient/ t·(m^3 • d) ^{1}	4.11	3.51	3	2.85	2.58	2.34	2.25	2.13	2.04	1.98

As the fuels and cokes mainly burn in the active zone of hearth, it could be measured for the capacity of BF burning cokes with the proportion of active zone of the BF hearth. Therefore, with the same burden, the active zones of BF hearths relatively reflect to the level of combustion intensity of BFs with different volumes. The capacity of BF hearth burning coke could be considered as the smelting intensity index (unit: t/(m^2·h) or t/(m^2·min)). In the reference (Liu Yuncai, 2001a), the relation between smelting intensity index and the utilization coefficient of BFs with different volumes has been calculated out (Table 8.14).

Yuncai Liu (2001b) further analyzed the influence of the BF height with the intensitive smelting of BFs with different volumes, while the effective height of a 300 m^3 BF was defined as "1". Comparing with the effective heights of BFs with different volumes, the height factors had been obtained. Then the reciprocal of height factor square root as the height index is defined, and the height indexes and smelting intensity of BFs with different volumes had been calculated. Their relation is shown in Fig. 8.24.

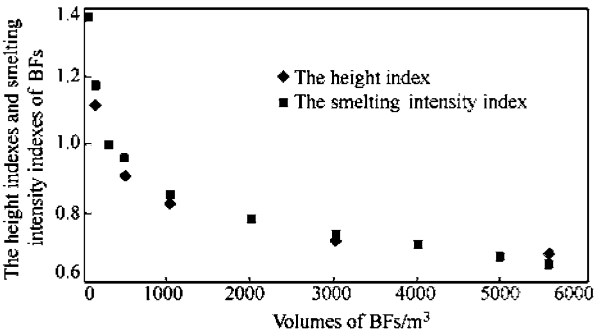


Fig. 8.24 The height indexes and smelting intensity with different BF volumes

In summary, the measures and limitative links for the smelting intensity of BFs with different volumes could be observed. For small BFs (with volume less 1000 m^3), it is easy to intensify by increasing blast flowrate and enhancing coke combustion. Practices have proved that for BFs with about 350 m^3 volume, 1 m^3 BF volume often matches with about 4 m^3 blasting capacity, while for large BFs, 1 m^3 BF volume matches with about 2 m^3 blasting capacity. The measures of intensifying large BF's smelting mainly include higher blast temperature (for instance, temperature above 1200℃), oxygen enrichment (for instance, 2% to 4%), top elevated-pressure, and using beneficiated ores to reduce slag ratio. Fig. 8.24 shows that BF's effective height varies very small for large BF but relatively larger for small BF.

In recent years, the volume utilization coefficients of many BFs with about 350 m^3 in China have been up to 3.5 t/(m^3·d). However, it should be noticed that under the same smelting conditions, the utilization coefficients of BFs with different volumes are incomparable (Table 8.15). Table 8.15 shows that 3.5 utilization coefficients of a 300 m^3 BF is only equivalent to 2.49 utilization coefficients of a 4000 m^3 BF.

Table 8.15 Calculation of intensified smelting of BFs with different volumes

BF volumes/m^3	100	300	500	1000	2000	3000	4000	5000	5580
Smelting intensing index	1.13	1	0.91	0.84	0.78	0.75	0.71	0.68	0.66
Corresponding utilization coefficient/t·(m^3·d) ^{1}	3.96	3.50	3.19	2.94	2.73	2.63	2.49	2.38	2.31

Thus, it would be possible to further calculate the expected annual production of BFs with different volumes after intensifying (Table 8.16), then determine the rational BF volume and rational BF numbers, based on which, to obtain the coordinated solutions of cost, quality and production efficiency problems.

Table 8.16 Expected annual production of BFs with different volumes after smelting intensifying

BF volumes/m^3	350	380	400	420	1260	1800	2000	2200	2500	3200	4065	4350	5000	5550
Selected utilization coefficient /t·(m^3·d) ^{1}	3.6	3.6	3.6	3.6	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.3	2.3	2.3
Operation days/d	350	350	350	350	350	350	350	350	350	355	355	355	355	355
Expected annual production/kt·a ^{1}	441	479	504	529	1058	1512	1680	1848	2100	2688	3463	3552	4083	4532

Recently, some Chinese scholars have taken their new cognizance (Zhang and Yin, 2002) of assessing method of BF intensification. The method of BF utilization coefficient should be further studied. Currently, there are at least two categories of assessing indicators for BF smelting intensifying: BF volume and BF hearth area to assess the intensity of BF smelting. The formulas are as follows:

Assessing BF utilization coefficients of BF volume:

$$\eta_V = \frac{P}{V_W}$$

where η_V is BF volume utilization coefficient, t/(m^3·d); P is BF daily production, t/d; V_W is BF working volume (effective volume), m^3.

Assessing BF utilization coefficient of BF hearth section area:

$$\eta_h = \frac{P}{A}$$

where η_h is utilization coefficient of BF hearth area, t/(m^2·d); P is BF daily production, t/d; A is BF hearth cross area at the centerline of tuyeres, m^2.

Table 8.17 shows the calculation results from the above formulas with the actual production data of different volume BFs domestically and abroad. Fig. 8.25 shows that the smaller the volume, the higher the η_V is, while the larger the volume, the higher the η_h is. The inconsistent calculation results of η_V and η_h are due to the difference in BF profile design. It is obvious that, the overall consideration of η_V and η_h is necessary for evaluating the intensity of BF smelting.

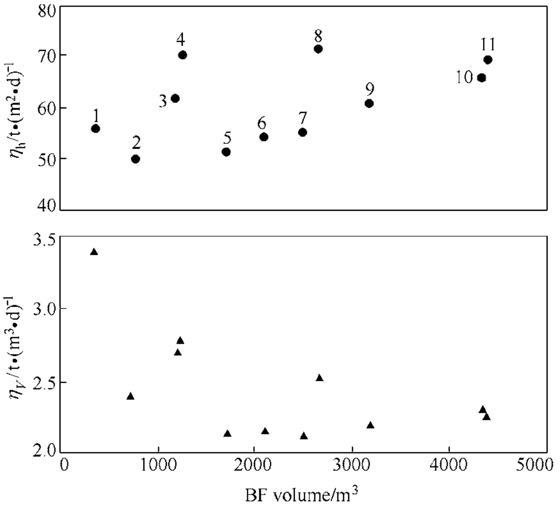


Fig. 8.25 Calculation ways comparison between two kinds of utilization coefficient of BFs with different volumes

1—Sanming Steel No.2; 2—Laiwu Steel No.2; 3—Pangang No.3; 4—Raahe No.2;
5，6—Shougang Nos. 2,4; 7，9—Wuhan Steel Nos. 4,5; 8—Hoogovens No.6;
10—Baosteel No.3; 11—Schwelgen No.7

Table 8.17 Comparisons of volume utilization coefficient η_V, furnace hearth area utilization coefficient η_h, smelting intensity I_s, combustion intensity I_c and V/A of BFs with different volumes

Item	Sanming Steel (2000) No.2	Laiwu Steel (2000) No.2	Pangang (2000) No.3	Raahe (2000) No.2	Shou-gang (2000) No.2	Shou-gang (2000) No.4	Wuhan Steel (2000) No.4	Hoogovens (Jan.~Sept., 1998) No.6	Wuhan Steel (2000) No.5	Baosteel (2000) No.3	Schwelgen (Jan.~Aug., 1999) No.1
BF volume/m^3	350	750	1200	1255	1726	2100	2516	2678	3200	4350	4416
Furnace hearth diameter/m	5.2	6.8	8.2	8.0	9.6	10.4	11.2	11.0	12.2	4.0	13.6
A/m^2	21.24	36.32	52.81	50.27	72.38	84.95	98.52	95.03	116.9	153.9	145.27
η_V /t·(m^3·d)$^{-1}$	3.40	2.42	2.69	2.78	2.13	2.15	2.12	2.51	2.19	2.29	2.24
η_h /t·(m^2·d)$^{-1}$	56.00	49.97	61.12	69.50	50.70	53.15	54.14	70.73	59.80	64.80	68.10
V/A	16.48	20.65	22.79	24.97	23.85	24.72	25.45	28.18	27.37	28.26	30.40
I_s /t·(m^3·d)$^{-1}$	1.73	1.28	1.33	1.24	1.04	1.11	1.09	1.24	1.13	1.05	1.12
I_c /t·(m^2·d)$^{-1}$	28.50	26.43	30.22	30.90	24.85	27.32	27.84	35.01	30.96	29.76	34.10

2. Effective arrangement of energy exchange, enhancing of energy conversion function.

Ironmaking process is a major procedure of energy consumption in steel manufacturing process. Taking some advanced integrated steel plants as example, ironmaking procedure consumes 68.5% of the total energy of the whole steel plant consumption including about 10.1% for the sintering, about 7.1% for coking, and the balance about 51.4% for BF itself.

Energy saving is very important for BF. Based on optimizing the burden of coals and ores, the high blast temperature, oxygen enriched blast, pulverized coal injection, high top pressure, reducing slag ratio, and intensifying smelting should be applied comphensively, in order to save energy. However, BF functions should be further broadened to the area of effective energy conversion.

BF is a counter-current bed reactor. Cold ferruginous matter with carbon are continuously charged into the BF from the top. The descending burdens are heated up and reduced gradually by the ascending gas, and descend to the softening zone, the slag has to separate with iron. In the course of BF smelting, the combustion of such fuels as cokes, pulverized coals generates a great amount of gases, almost more 2t BF gases are produced per tonne hot metal. Apart from the portion of gases (about 35% of all the gases produced by BF) consumed for hot blast stove, there are still a large quantity of BF gases to be utilized. It might be said that the biggest output of BF is the gas, instead of hot metal reflecting BF's fundamental attribute of mass-energy conversion. BF gases have chemical energy, thermal energy as well as kinetic energy. The BF gas kinetic energy comes from the kinetics of blast and fuel combustion. Therefore, the usage of BF gas should include thermal, chemical (for instance, steams generating, electricity) and kinetic energy (like electricity generating by top pressure recovery turbine), so as to make full use of the energy.

Actually, the hot metal produced by BF is also one of the modes of mass-energy conversion. The temperature and [C], [Si], [S] contents of hot metal will all have an impact on the efficiencies of mass-energy conversion in the following steelmaking process, such as the scrap usage efficiency, amount and recovery rate of BOF gas, the consumption of flux materials in steelmaking and slag quantity. Meanwhile, the slag ratio of BF smelting also reflects the process of mass-energy conversion. Producing cements with BF granulating slag is favorable for reducing energy consumption and environmental load of the whole society as compared with common cement manufacturing process. Slag thermal energy may also be utilized. Of course, this does not mean encouraging BF to increase slag quantity, but on a whole, to make use of beneficiated materials should be encouraged to reduce slag ratio.

Great attentions must be given to how to give full play to mass-energy conversion functions, particularly function of energy conversion. For instance, the issues about TRT power generation with BF top pressure, generating power by BF gas-stream boiler-steam turbine, by BF gas-gas turbine, and by waste heat boiler-steam turbine must all be considered. These are worthy to investigate under conditions both of large integrated steel plants and many smaller BF steel plants in China.

3. Continuous operation and process continuation of BF ironmaking.

In the discussion of the basic characteristics of BF operation, it was mentioned that the BF process has the natures of continuous production process (countercurrent, continuous moving reaction bed operation) and the batch iron tapping (or batch iron ladle transporting). Therefore, the essence and core of BF natures are its continuity. This is very much noteworthy. If the time- space scale enlarged, people would have a new and in-depth cognition of operation continuity and process continuation for BF ironmaking.

From the perspective of time scale of BF process, the continuity of BF smelting is first reflected in smooth running of BF and corresponding delay ratio (particularly the unscheduled delay ratio) or calendar operation rate, the annual BF calendar operation time should reach 255~360 days by the aid of a series of technical and managing measures. So, the BF delay ratio should not be higher than 1.3%~1.5%, which would deal with a series of related measures for smooth running, particularly the equipment reliability and BF operation expert system. While the time scale of BF operation further broadens, it would surely deal with the BF campaign of a generation. In the 21st century, the target of the generation campaign of a new large BF should be set at 20~25 years, the small or medium BF should be 12~15 years. So, technical measures, like usage of soft water, water treatment technique, copper cooling stave, top charging system, wall gunning technologies, refractory for furnace hearth and bottom, must be strengthened accordingly.

If the space scale of BF process continuation enlarged, it would be certainly thought of the related continuation of BF—BOF—CC—Hot rolling, particularly the long route of BF—hot metal pretreatment—BOF—secondary metallurgy – continuous casting. This would lead to a topic about BF's influence on optimizing interface techiques between ironmaking and steelmaking as well as steelmaking and continuous casting. The trend of further restructuring of steel manufacturing process should be taking full advantages of the continuity of BF operation to elevate the continuation degree of chemical metallurgical processes and even to solidification. Thus, the"one after another" matches of BF-BOF production capacities, the matching and optimization of BF iron ladle and the BOF hot metal charging ladle, including the capacity matching of BF iron ladle, BOF hot metal charging ladle and BOF (for a BOF with more than 150 t, BF iron ladle and the BOF hot metal amount charging ladle should preferably have the same capacity as the hot metal charged into the BOF) should be seriously studied. And also attentions to increase of turnover speed of BF iron ladle, particularly the shortening of turnover time of empty ladle, as well as rational selection of hot metal pre-treatment and its layout must be paid. It appears that the matching "one after another" for of BF—BOF capacities should be based on the minutes scale of flow rate but not scale of annual production. In the meantime, the drawbacks of mixer, the irrationality of hot metal pretreatment and transporting with torpedo car, even the unnecessity of individual pre-treating station between the BF and BOF would be further judged. In order to enhance the continuation degree of BF—BOF—CC section, the integrated technologies including, matching up one BF with one or two BOFs (depending on BOF tonnage), using one ladle both for BF iron receiving and BOF hot charging, hot metal pretreating in the steelmaking workshop by simple way without ladle shifting, hot metal series pretreatment (desulphurization in ladle, desiliconization and dephosphorization in coverter and then slag cut-off), as well as rapid blowing in steelmaking BOF should be practised orderly. These operations are reflected in a rational layout and the time scheduling diagram in rhythm and harmony. Such engineering design would certainly raise the level of continuation quasi-continuation and compactness to realize the integration of cost, quality, efficiency and benefits.

8.5.3 *Principles about engineering design in optimizing steel plant process structure*

Since the 1980s, the restructuring of most steel plants in the international steel industry has used continuous casting to connect-coordinate the chemical metallurgical processes with physical processes of metallurgy, and generally they tried their best to use fully continuous casting system to coordinate the production process of the entire steel plant. Therefore, to process optimization of steel plant structure special attentions should be given to the following aspects:

1. To determine the outline of product mix of each steel plant (not steel company group) by requirment from the market distribution, market demands and investment benefit assessment, and then analyzing the rational capacity range of modern rolling mills related with producing these products. It is necessary to pay attention to the rational scale size of every hot rolling mill and the compatibility of different types of mills (for instance, bar mill and wire mill have better compatibility, thin strip mills of different widths have better compatibility, but no compatibility between hot strip mill and bar/wire mill, and no compatibility of strip mill with seamless tube mill too). The compatibility of different kinds of mills should deal with the rational selection for BF, BOF or EAF, hot metal treatment, secondary metallurgy and caster, then it influences the product mix and process structure and rational economic scale.

2. To analyze the capacity of caster (including caster type, strand section, strand numbers) and select the connecting-matching relation of continuous caster with hot rolling mills. The coordinating-buffering relations of temperature, of time (rhythm) and of mass flow, and transporting pattern and ways must be considered to realize the optimum layout of steelmaking plant—rolling plant by making full use of energy and time based on the principle of convenience and rapidity. Generally, to strive for directly link the slab run-out rolling table or cooling bed run-out line with entry rolling table of reheating furnace in the rolling workshop will take the cranes or other transporting devices away as possible.

3. To analyze and select optimized-coordinated interface techniques among steelmaking furnace—secondary metallurgy—continuous caster to realize quasi-continuous and compact linkage. The coordinating-buffering of procedures and devices, and the tramsversely exchanging of running slabs with coordination among different types of casters should be noticed. To optimize the layout (particularly the locations of steelmaking furnace-main refining devices-continuous casters) in order to improve the optimization, smoothness and coordination of steelmaking workshop mass flows is necessary condition.

4. To determine the volumes and sets of BFs based on the rational scale and process structure of the steel workshop. (Generally 2~3 is the target, sometimes 1 BF running). Interface technique between BF and BOF based on product mix, and the layout of BF—hot metal pretreatment—BOF would be fixed to promote the dynamic-orderliness, quasi-continuation and compactness of high temperature mass flow.

5. On the base of above thoughts, to analyze and calculate the longitudinal coordination and transverse compatibility among BF—hot metal pretreatment—steelmaking — secondary metallurgy — continuous casting — reheating — continuous rolling in one steel complex. The process rationalization of different types of steel products, and the effective production of different but compatible steel products in the same plant would be organized in a structural system with comprehensive competitiveness. This is a complex design system integrating market demands, technical progress, economic benefits and environmental benefits.

This proposition, if implemented as the technical guidance in manufactaring-process design, would form the following strategic principles for optimizing:

1) Matching principle of mass flow rate in minute scale among procedures or devices;

2) Stability principle ("convergence") for temperature-time of mass flow in the process;

3) Continuation/quasi-continuation principle of mass flow in the process;

4) Principle of high efficient conversion and full recovery of materials and en-

ergy in the process;

5) Compactness principle of time and space in the process;

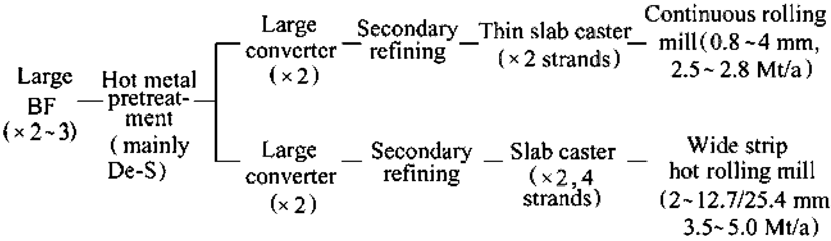
6) Principle of compact and simple for process network structure (general layout).

8.6 Modern Steel Plant Models

By studying the control on multi-factor mass flow in a steel plant, discussing the operation dynamics of steel plant and analyzing the steel plant structure, particularly in consideration of the behavior and phenomena of dissipation in steel manufacturing process, to minimize matter dissipation, energy dissipation and time-space dissipation by optimizing multi-factor mass flow in time-space and efficiency, with observing the characters of restructuring of different types of steel plant in various countries, in addition, to enhance the market competitiveness of steel plant and sustainability in the foreseeable future, the following steel plant models should be considered or recommended.

8.6.1 *Large integrated steel plants*

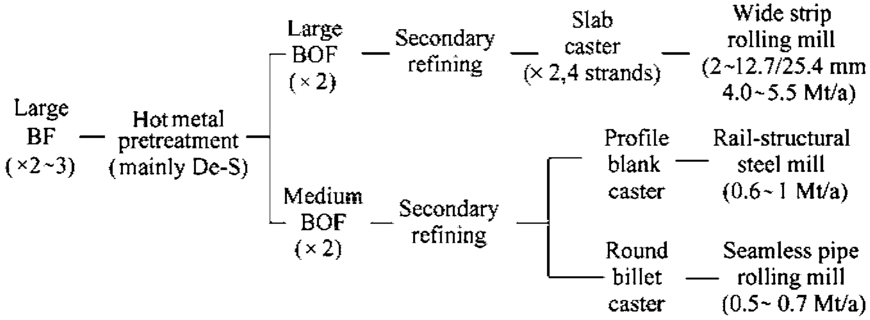
A. Plant producing plate and strip totally



Rational capacity: 6~8 Mt/a.

Extension products: Cold-rolled sheets, galvanized plates, tin-coated plates, color-coated plates, electrical sheets, welded pipes, etc.

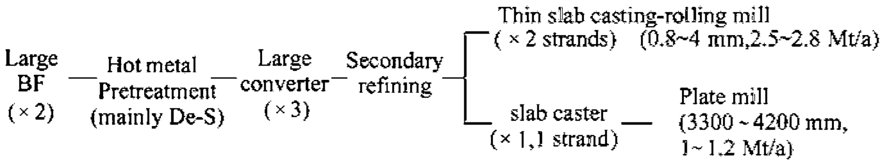
B. The comprehensive products type



Rational capacity: 6~8 Mt/a.

Extension Products: welded pipe, cold rolled sheets, galvanized plates, colored plates, etc.

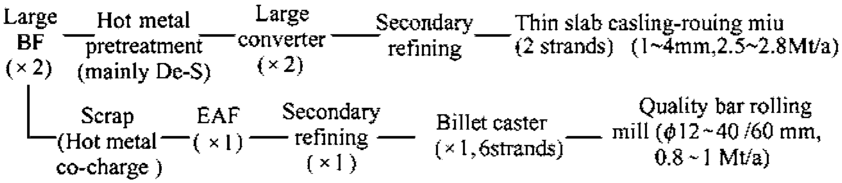
C. Flat products and their extension products type



Rational capacity: 3.5~4 Mt/a.

Extension products: welded pipe, cold rolled plates, galvanized plates, colored plates, UOE pipes, etc.

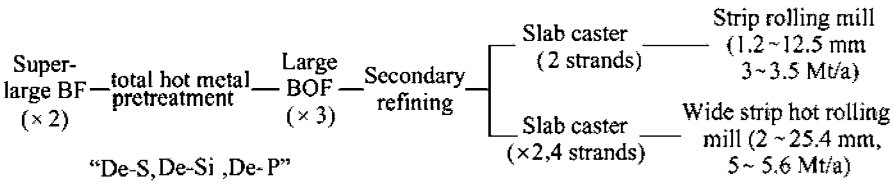
D. Mixed type



Rational capacity: 3.5~3.8 Mt/a.

Extension products: welded pipes, cold-rolled plates, galvanized plate, color-coated plates, etc.

E. Super-large type of strips (expandable type in the future, and possible for producing medium or heavy plates is reserved)

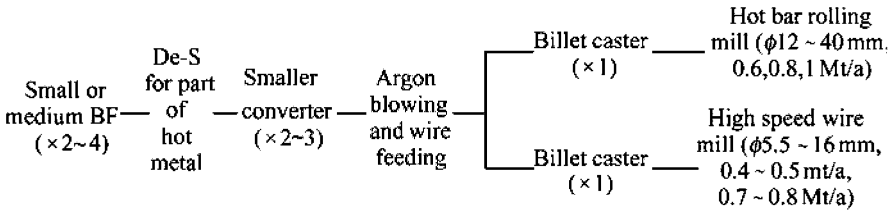


Rational capacity: 8~9 Mt/a.

Extension products: cold-rolled sheets, galvanized plates, color-coated plates, welded pipes, electrical sheets, large welded H-section steel.

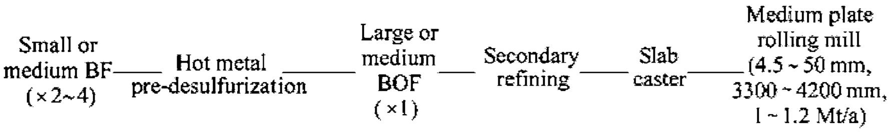
8.6.2 *Steel plants with small or medium BF*

A. Specializing long products type



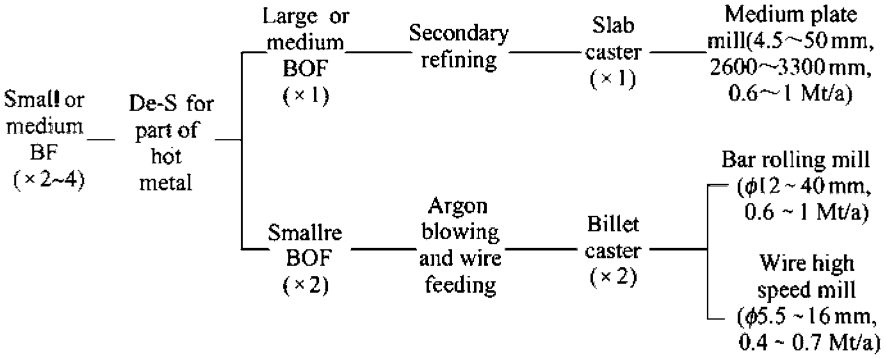
Rational capacity: 1.2~1.8 Mt/a.

B. Specializing medium plate type



Rational capacity: 1~1.2 Mt/a.

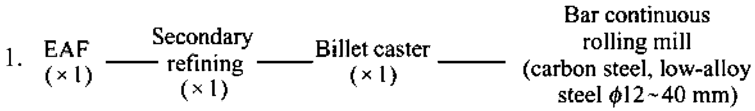
C. Comprehensive products type



Rational capacity:2.1~2.7 Mt/a.

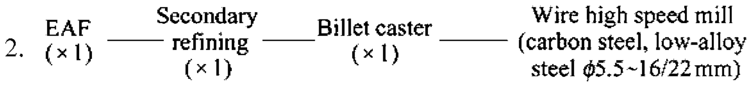
8.6.3 *EAF process steel plants*

A. Long products type



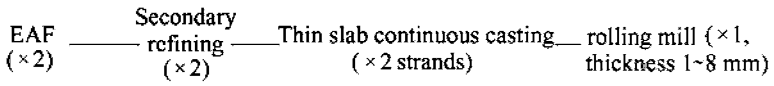
Rational capacity: 0.8~1.0 Mt/a.

2.



Rational capacity: 0.4~0.7 Mt/a.

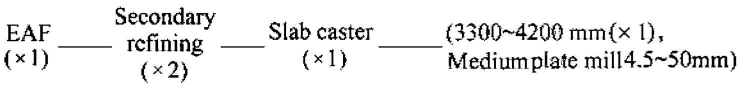
B. Strip type



Rational capacity: 1.6~2.2 Mt/a.

Extension products: cold-rolled sheets, galvanized plates, color-coated plates, welded pipes, etc.

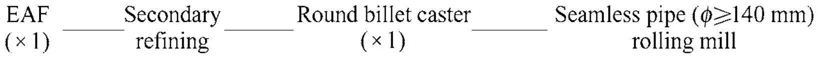
C. Medium plate type



Rational capacity: 0.8~1 Mt/a.

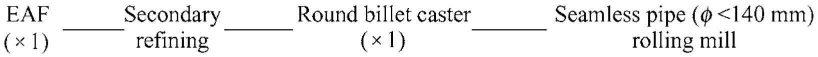
D. Seamless pipe type

1.



Rational capacity: 0.5~0.7 Mt/a.

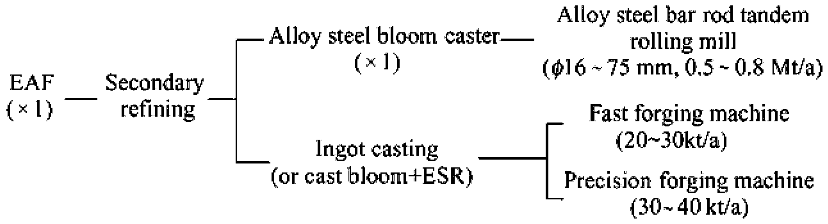
2.



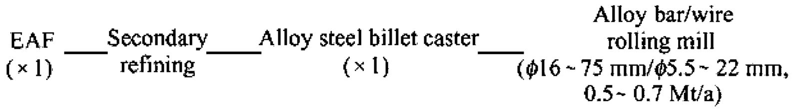
Rational capacity: 0.12~0.20 Mt/a.

E. Alloy steel long products type

1.



2.



F. Stainless steel plate type

1. EAF (×1) — Converter (×1) — Vacuum refining — Slab caster (×1) — Steckel mill (thickness 2~8/12.7 mm)

Rational capacity: 0.8~1 Mt/a.

Extension products: cold-rolled stainless thin sheets and their deep processing products

2. EAF (×1) — Converter (×1) — Vacuum refining — Slab caster (×1) — Hot strip rolling mill (thickness 2~12.7 mm)

Rational capacity: 1~1.5 Mt/a.

Extension products: cold-rolled stainless sheets and deep processing metals.

In conclussion, steel plant restructuring should be guided by the following aspects:

- Market orientation; product mix should be determined according to market demands (particularly for the regional markets);
- The region, where the plant is situated, should have comparable and location advantages in market, transportation, resources, energy, etc.;
- The steel plant should be well equipped with rational scales and advanced manufacturing processes for different kinds of steel products;
- Coordination-optimization among procedures and devices inside the mass flow of the manufacturing process;
- For different types of steel products, consideration should be given to the compatibility of the transverse flow between casters and mills;
- Optimizing the match numbers of caster and mill to each other;
- The number of BF should not be too many (normally, 2 to 3 is suitable), the number of steel making workshops should not be more than 2, which would facilitate the optimization of railway transporting network;
- To give play to the energy conversion function of a steel manufacturing process in order to make full use of energy;
- To give play to the environment friendly function of steel plants, so as to build up eco-industrial chains based on the local conditions.

8.6.4 *Steel plant and consolidated steel corporation (group)*

Steel plants have entered a restructuring and industrial upgrading era. As far as an individual steel plant is concerned, there should be a rational economic scale. If a steel plant's scale is smaller than that scale, it would never be able to produce quality, and low-cost products with modern technologies and equipment, nor to gain profit. However, for the scale of an individual steel plant, it is not always the bigger, the better. In an ultra-large-scale steel plant with irrational process structure, the production would fall into disarray and the general layout would be unfavourable. As a result, the excessively higher investment, the higher transportation cost, the higher energy consumption, the lower production efficiency and the lower capital return would happen.

The cost of steel products is composed of investment cost, production cost, transportation and sales costs. Too long sales radius (weighted mean) would lower the profit margin of unit product. Therefore, considering different steel products and different regional conditions, the production scale of an individual steel plant should fall into a rational range. Modern steel plants are following the developing trend of specialized production, regionalized sales and deep processing products. However, market demands for steels are diversified, and the technical progress leads to specialized production in a steel plant. Solution to this contradiction should not be building omnipotent ultra-large-scale steel plant, as it would cause problem like difficulties in raising funds and low capital return. Developing trend should be forming regional steel corporation or even trans-national steel corporation or specialized steel corporation. It may be a merger of steel enterprises with integrated financing operations; also be market-allocated, investment-divided strategic alliance of steel enterprises with partial dependent capitals and managements for each other. As for a steel plant which would be a link of an eco-industrial band (zone) in the future, it may form a consolidated corporation with enterprises of other sectors, such as power plant, cement plant, etc.

8.6.5 *Issues about investment*

To gain market competitiveness, steel plants need to rely on strategic investment for sustainable development. However, the investment strategy has to be carefully arranged, as the steel industry is now an industry with low investment return. In investing for a steel plant, considerations should be given how to implement innovations in structure and mode by best using existing knowledge and achievements. In Fig. 8.9, strategic investment issues like investment direction, investment order, investment strength, investment opportunity, capital make-up, capital raising and risk assessment are shown from the perspective of multi-target thinking.

It should be noted that steel plant restructuring is a process of technological progress; it is also a process involving more and more investment decision-making knowledge. Much creativity is also involved in the course of investment decision-making. For instance, it has been pointed out in chapter 1 that the main reason of Chinese steel industry, which had risen high emerged in the 1990s, is that the application and integration of 6 key/common technologies had smoothed out the manufacturing processes in Chinese steel plants, particularly the processes for long product manufacturing. At the same time, attentions had been given to strengthen the dynamic orderly investment to make the input – output efficiency higher, techno-economic profits noticeable and the investment reduced accordingly as the sinicization of technologies and equipment.

From the worldwide point of view, the investment experiences of international iron and steel industry since the 1973 oil crisis show that, with the technologies progressing and steel plant restructuring, the investment of unit steel product has been decreasing gradually. And the higher-level technologies, the lower the unit investment. Specifically speaking, the investment per tonne of steel products produced by EAF—thin slab continuous casting and rolling process would be reduced to around 300 USD, while by BF—BOF—thin slab continuous casting and rolling process to 600~800 USD even lower (Wiesinger, 1997) (Fig. 8.26). What should be vigilant about in the course of the development of a steel plant is that too high unit investment would weaken the competitiveness in the market.

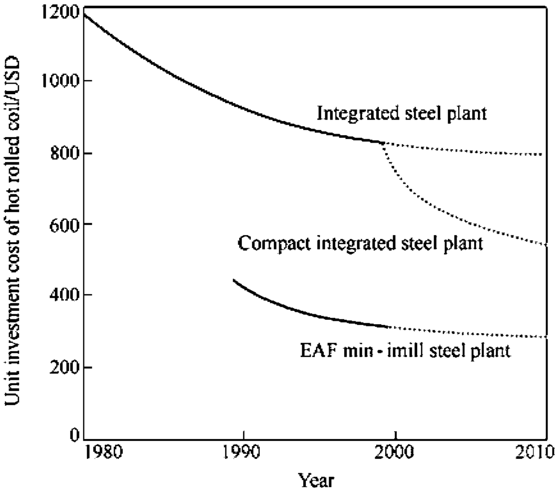


Fig. 8.26 Comparison of unit investment cost for integrated steel plant, compact integrated plant and EAF mini-mill

References

Chu M D (1995) Initial understanding of the position and role of transportation in a steel plant general layout, Engineering of Iron and Steel Works(5):34-36 (in Chinese)

Chu M D (1997) Again on transportation and layout, Metallurgical Transportation (4):3-5 (in Chinese)

Hubbard M A (1990) Process economics of desulfurization from blast furnace to steel ladle.

Steelmaking Conference Proceedings, AIME 73:357-365

Liu Y C (1997) Production practice of blast furnace profile evolution, Iron and Steel, 34 (supplement edition): 279-282(in Chinese)

Liu Y C (2001a) Analyzing the influence of BF volume on intensified smelting with smelting intensity index, Iron and Steel 36 (5): 9-13(in Chinese)

Liu Y C (2001b) Analyzing the influence of BF volume on intensified smelting with BF BF height index, Iron and Steel 36 (10): 14-16 (in Chinese)

Umezawa K (1992) Scrap Melting Process-Current Status and Future Prospect, Tetsu-to Hagane 78(4): 12-18 (in Japanese)

Wiesinger H (1997) Development of new technology opportunities and pitfalls, Iron & Steelmaker 24(12):33

Yin R Y (1993) The evolution of metallurgical process functions and the optimization of steel plant structure, Acta Metallurgica Sinica 29(7): 289-315 (in Chinese)

Yin R Y (1994) Engineering evaluation on structural optimization of steel industry and steel plants, Iron and Steel 29 (3): 1-22 (in Chinese)

Yin R Y (2001a) Understanding of several issues in the development of steelmaking technologies at the beginning of 21st Century, Steelmaking 17 (1): 1-6 (in Chinese)

Yin R Y (2001b) On the structure and developing mode of steel industry, Engineering Sciences 3 (6): 24-32 (in Chinese)

Yu Z X(2002) Development of computer controlled LD blowing process at No.3 steelmaking plant of WISCO, presented in the 2nd branch meeting (Oxygen Steelmaking, Secondary Metallurgy), the 23rd International Iron and Steel Annual Conference, Paris

Zhang S R, Yin H (2002) Ways of evaluating BF's smelting intensification, Ironmaking (2): 1-6 (in Chinese)

Chapter 9

Steel Plants and the Environment Issues

Resources, environment, and eco-friendliness are issues that steel plants must face in contemporary times. Since the 1960s, international steel industries exerted great efforts in terms of environmental protections, have gone through periods of public hazard and pollution controls, energy conservations and emission reductions, and are now undergoing a period of cleaner production and green manufacturing. They are also step-by-step developing and expanding eco-industrial chains, and in the more advanced countries, promoting the construction of regional circular economic systems.

As part of a future sustainable development strategy, the functions of the steel manufacturing process will be extended to:

- *The function of steel product manufacturing;*
- *The function of energy conversion;*
- *The function of waste treatment and recycling.*

The future mode of steel plants development will gradually take, in the main, two forms: steel plants of suburb type, and steel plants at harbor eco-industrial parks.

In the course of one and a half century development, especially the quick development at late part of the 20th century, steel industry had already reached a gigantic large scale and a high technological level. Reviewing the development of late 50~60 years, it can be seen that steel plant gained economy scale benefit mainly by enlarging production scales before 1970s. After the oil crisis, steel plant gradually optimized structure by doing a profound manufacturing process reform, and then formed quasi- continuous/continuous manufacturing process, finally realized optimization of technology and economy. As a steel plant consumes a great deal of resource and energy, furthermore, brings lots of emissions, it will inevitably conflict with the environment of the earth if without recycling and reusing.As the published report by Rome Club *The Limit to Growth*, people have gradually realized that the earth is the only home base which human can live on. In order to actualize the harmonious relationship between human and environment, we must insist on the sustainable development, and form "3R" (reduce, reuse and recyce)

R. Yin, *Metallurgical Process Engineering*

type circular economy society. The problem of ecosystem has already become the fundamental problem in the end of 20th century which affecting the development the steel industry.

9.1 Issues on Sustainable Development

Topics of sustainable development,manufacture linkage and evolution of the values of goods, features and multi-levels of the influence of steel plants on environment were discussed in this section.

9.1.1 *Put forward of the topic*

In the 20th century, the progress of the science and technology greatly improved the social economy's development and quickened the process of industrialization and urbanization all over the world. At the same time, lacking of comprehensive understanding of earth environment, the ecosystem has been sharply worsened. The main reason is to carry on large scale production without limiting the use of resource and energy. At the same time the problems aroused by large consumption and the thrown wastes after consumption are not considered well. These all bring a series pollution problems aroused by destroying the ecological self-cleaning ability (they include public hazard pollution problem, industrial pollution problem, daily life pollution problem and earth environment problem etc., Fig.9.1). Thus the environmental problems became more and more visible. Environment protection attracts the attention of the entire world. From then on, humans start to consider the fundamental problems such as earth environment, eco-balance, then raise the strategy of sustainable development.

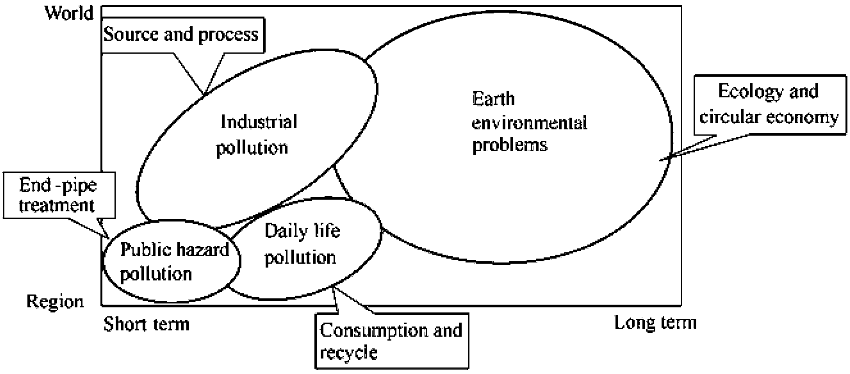


Fig.9.1 Connotation of environmental problems and relationships among different types of environmental problems

Through practice, people begin to understand that to solve the environmental problems successful, only doing the end-pipe treatment is insufficient. And too much end-pipe treatment will aggravate enterprise and society's economic burden; even affect the developing power of enterprise and society. Therefore, if we want to change the disadvantage factors of environment, we must set about the root, which brings out the problem (so called source treatment). That's mean it covers all steps including the raw material supply-manufacture of products—consumption of products—waste abandon/recycling. Only adopt the strategy considering the full life cycle, can we solve the problem thoroughly.

Therewith, people start to think about a series of topics, concept, connotation and countermeasure of sustainable development from different levels. Such as: innocuous treatment of pollutant and poisonous substance; energy saving, cleaner production-green manufacturing, eco-industrial chain, circular economy society and so on (Yin, 2002).

9.1.2 *Manufacture linkage and evolution of the values of commodity*

The existence and development of human's society can't survive without manufacturing industry. Of course, the concept and connotation of manufacturing industry are developing progressively with time. Now, manufacturing industry can be defined as: by relevant manufacture process the useful resources and energy are transformed into industrial goods and consuming goods .The connotation of modern manufacture process not only covers steps from raw materials and energy to finished goods but also the concept expansion from processing to manufacture chains. The manufacture chains include the full life cycle of the products from product design, manufacture process design, manufacturing process to finished product, emission controlling with its innocuous treatment, product use phase, abandoning and recycling.

With the time passes, the manufacture chains have developed from "river model" to "lake model" (Stahel, 2007) little by little. The"river model" is refered to the linear structure of the industrial economy, while the "lake model"is refered to the closing-loop material circulation of the industrial economy.

Steelmaking process belongs to the process manufacturing industry. The life cycle of steel products will involve such a cause-effect linkage inclusive of exploitation of resources and energy, transportation, processing, assembling, use phase, abandoning, classification and recycling (See manufacture chains Fig. 9.2).

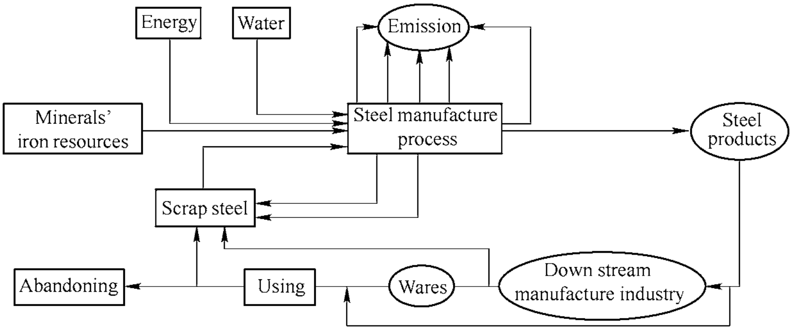


Fig. 9.2 Connotation of Steel Products' Life Cycle

With the effect of sustainable development strategy spread increasingly, people's value view to commodity is changing. At the same time, people's definition to quality is also profound quickly. It is concluded that the quality not only relates to optimization of technology and an optimal usage, but also to the system optimization of debt, such as investment cost, and fund recovery rate (Walter, 2007). On conception of function and time, the quality should be defined as a long-term system function optimization. As comes to value view to commodity, the fundamental meanings should include both the strong market competitiveness, and the sustainability of development.

9.1.3 *Features and multi-levels of the influence of steel plants on environment*

All kinds of emissions that caused by steel production have a multi-level effect on environment (Yin, 1997). Generally speaking, industrial exhaust emission will affect the regions even to the worldwide, such as CO_2, SO_x, and NO_x and so on. These substances, to large extent, have a cumulative effect on the green house gas emission and the acid rains. Wastes such as sewage, waste liquid, waste slurry caused in manufacture process will have a great effect on drainage basin, underground water, even oceans. While various slag, sludge, dust, steel scrap, noise, vibration, and scintillation, at large extent, will influence living and healthy of the operators and the related community residents, even to a regional system. To pollution of different type and emission from different level, their zones affected are different so their countermeasures are different, too.

9.2 Progress of Environment Protection in Steel Enterprises Worldwide

From the development progress of environment protection around the steel enterprises, it can be seen that this is a gradually improved cognition. The related countermeasure changed from the end-pipe treatment to relatively initiative precaution, dispose, assimilation and recycling (Fig. 9.3). In the whole, it experienced four stages as following (Yin, Zhang, Lu, et al, 2002):

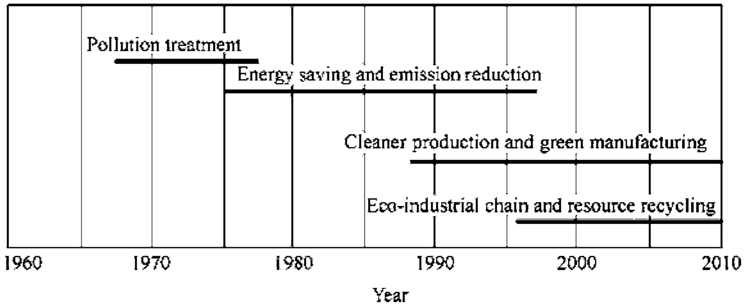


Fig. 9.3 The Sketch of progress of environmental protection around steel enterprises worldwide

1. From 1960s to1970s: pollution treatment stage. Because developed countries had a long history of steel industry, the problem of public hazard pollution was exposed early. So their cognition to protect environment was earlier, too. At that stage, they adopted measures such as dilution discharge and end-pipe treatment. Therein, the purpose of use end-pipe treatment is to lower the concentration of contamination to meet the need of emission regulation by using high efficient equipment and technology. But this method is only to transfer the contamination from here to there, or among different mediums .At the same time, overmuch end-pipe treatment would increase the economical burden in enterprise and society, even affect their self-developing motivity.

2. From 1970s to 1990s: energy saving stage (the stage of sources treatment of emission). The oil crisis which broke out in 1973 made western countries realized the importance of energy, so they started to adopt various methods to reduce energy consumption. Decrease in specific energy consumption as well as small consumption, small emission and big productivity. may be realized through enevgy saving As a matter of fact, it can reduce all kinds of emissions from their sources. It should say that is an efficient, relative initiative strategy. Long-term practice indicated that energy saving is an active, economical measure to protect environment. It decreased the expenditures of environment protection; meantime, it also got economical and environmental benefit. Generally speaking, energy saving is the key point of environmental protection that promoting with environment protection, they are closely related.

3. From late 1980s to 1990s: the stage of cleaner production and green manufacturing (active source treatment). Cleaner production is the strategy given by generalization of the experiences and the lessons of industrial pollution and its

treatment. Cleaner production advocates high efficiency of resource using to reduce or prevent the emission of pollutant and poisonous substance from the source. So it can realize the purpose of environmental protection while guaranteeing the economical benefit. Obviously, cleaner production puts entirety, precautionary and sustainable environment strategy into the manufacture process, products and their service. Compared with the end-pipe treatment, cleaner production is changed from simplex, passive pollution control phase to the stage of overall, initiative precaution and reduction of the pollution. The connotation of green manufacturing is more extensive than cleaner production; it includes the improvement of products' using efficiency, the prolongation of life span, the waste management for recovery and recycling. It also related to products' full life cycle assessment of environmental burden.

4. Later 1990s: the stage of studying eco-type reforming of steel plant and entering into circular economy society. The aim is forming the eco-industrial chain through the combination of the steel enterprise with the processes of related production, the products' consumption, abandoning, decomposition, reuse and recycle. This is an important thought and symbol that indicates the steel industry eco-type reforming and entering into the circular economy society.

9.3 Green Manufacturing in Steel Plants

With the demands of sustainable development, environmental protection has new progress in the field of research and practice. The "eco-label" is applied to express the environmental information and the environmental burden of products. The life cycle assessment is also used to compare the environmental performance among products. The cleaner production becomes mainstream technologies. The green manufacturing process, even the eco-industrial chains are developing. The environmental performance in enterprise is improved with establishment of the environmental management system and the environmental management standards of ISO14000 are established to promote the sustainable development in the future all over the world.

9.3.1 *Concept and connotation of green manufacture*

We should pay great attention to green manufacturing. Nowadays, people all over the world have recognized the concept of "large manufacture". It almost includes all manufacturing industries such as metallurgical, chemical, architectural and mechanical industry etc.. Therefore, green manufacturing will certainly involve in the operation, development, reforming and breakthrough of all manufacturing industries.

Because of the short history of growth of the green manufacturing, today there is still no unitary definition about it. The concept and connotation are still in the exploratory stage. According to the viewpoint in the blue book from the *Society of Manufacturing Engineers, USA* (Mclogk, et al, 1996) it can be seen that green manufacturing is a modern manufacturing pattern with comprehensively thinking about the resource and energy consumption and the environmental impact. It aims to make least negative effect and highest resource utilization on the full product life cycle from design, processing, package, transportation, using, abandoning to recycling. It will also optimize the economic efficiency, the environmental and the social benefits of the enterprises.

The main concepts of green manufacturing:

1. We should take measures to control the origin of pollution in the manufacture process from source and pay great attention to the green life cycle of products.
2. The pollutant should be eliminated inside the process of manufacture and the economic efficiency and environmental benefits should be coordinated.
3. The eco-industrial chain should be formed among different types and related enterprises to promote the "zero" emission system (also named as minimum emission system).
4. The so-called pollution refers to the exogenous pollution that is above the acceptance ability of the system eco-balance in different scales.
5. The incessant integration prevention strategy about environmental pollution is stressed, and the optimum mode of sustainable development strategy is pursued.

There are different standpoint even incomplete uniform concept between the green manufacturing and the end-pipe treatment. The end-pipe treatment is related to the treatment of environment that has already been polluted. The aim is to recovery or near to recovery the environment back to the original that is not polluted. This always leads to the higher business cost; even weaken the market competitiveness. However, the green manufacturing lays emphasis on strategy preventing the pollution from the source, but it not negates the end-pipe treatment. Attention to the green manufacturing should be paid from the fundamental rules, the process technology and engineering to developing the environment-friendly process (including selection of raw materials and energy, their alternative and substitute etc.), technical equipment, manufacturing process, eco-products and their use phase etc. Based on these breakthrough technologies the paradox between environmental pollution and sustainable development would be solved.

9.3.2 *Philosophy and technical route for green manufacture*

A. The consideration of green manufacturing

Green manufacturing certainly has multi-scale and multi-level connotation because the formation and solution of environmental problems are developed in multi-level and multi-scale from local, regional and even global area. It requires general methods such as sustainable development view and systematology to do the entire study. The theories and technologies at different level and multi-scale should be integrated. At the microcosmic level, the method such as product design, choose or substitute of raw materials and energy options, technique, equipment and management improvement should be used. At the mesoscopic level, eco-industrial chain strategy such as the mass flow cycle inside region and the symbiotic coexistence among the industries are adopted. At the macro level, policies and regulations as the administrative-economic levers are used as guide.

When we are studying and developing the green manufacturing process and green production technology, the entire premeditation method by artist should be used for reference. Firstly, we should grasp the concept and connotation of "perfect" as a whole (including both microcosmic and macroscopic), and they are used as a method of solving environment-friendly green manufacturing system. The holistic view and method of solving environmental problem are required. Thus people should observe the problems as a general designer that is thinking from general and macroscopic at first, and then gradually to mesoscopic and microcosmic. The methods of "white box", "gray box" and "black box" can be used for studying linkage from the macroscopic to the mesoscopic and microscopic.

B. The technological route of green manufacturing

According to the object concerned and the problems observed, green manufacturing could bring various types of technologies. Cleaner production design including consideration about the flow and composition of waste in the manufacture process is adopted. Life cycle assessment is used to analyze the energy consumption and raw material usage and the environmental burden of the products. Industrial ecology is formed to study the interaction of these substances and its ultimate destination through a series of related substance groups such as raw materials, energy, products, by-products and emission etc. The opportunities and feasibility of pollution prevention are evaluated by these methods and technologies comprehensively from different point of views, scales and levels. At the same time these are also processes of integrated research and development to the pollution prevention technology.

The general framework of green manufacturing technology is including the strategic choice for raw materials/energy, the analysis-integration and reconstruction-optimization strategy for manufacture process, the life cycle assessment study for product use, abandon and recycling, and the eco-industrial chain formation strategy for substance/energy fully utilizing (recycling) etc.

As an engineering technology, the green manufacturing technology has to go through the course of research and development. This both include the route from microcosmic and mesoscopic to macroscopic, such as from unit/procedure to the whole works, and also from macroscopic meditation to microcosmic or mesoscopic design. To solve the environmental problem, the countermeasures of green manufacturing technology are:

1. Unit process should be optimized. The function-structure-efficiency of unit process should be improved. The unnecessary input and output should be cut down as possible. The resources and energy load of unit process should be minimized.
2. The optimization among different unit processes should be considered. The discharges, wastes, and surplus energy of different processes should be best used and the systematic design of interprocess linkage may be completed.
3. Technological breakthrough to reuse the discharges and wastes that can't be used at present should be sought for.
4. The end-pipe treatment technique or ecological self-cleaning ability should be adopted.

9.3.3 *Key role of manufacturing process in the course of greenization of steel plants*

The optimization of steel manufacturing process system plays a key role to the green steel industry. Manufacturing process is the core of the structure optimization and the cardinal points of the greenization of the steel plants. What's more, the manufacturing process not only influences the selection, substitution and using efficiency of materials and energy, but also influences the conversion of materials and energy as well as the production efficiency. The manufacture process also influences the discharging process and the type, the composition and the quantity of emission.

After the development of about 150-years the modern steel plants take two basic routes:

1. The integrated steel enterprise, a chain of BF—BOF—CC—Hot rolling—Deep processing route, based on iron ore and coal;
2. The mini-mill, a chain of EAF—Refining—Continuous Casting—Hot rolling route, based on steel scrap and power.

These two routes have their own characters, but both them are the subject relating with environment. The fitness of the manufacturing process structure will affect the environment strongly. Certainly the environmental burden and impact factor of the two manufacturing process routes are also different.

9.3.4 *Technologies of green manufacture of steel plants*

To become the green manufacturing industry, the new technologies and the process optimization are adopted step by step to guarantee the development into ordering, coordination, high-efficiency and continuation. To realize the greening of steel production its self, the followed should be paid attention to.

1. The orderliness of the manufacturing process. Based on the thermodynamic analysis of processes, the analysis-optimization of set of procedure's functions can be achieved. Then the dynamic orderliness of the manufacturing process is realized. The productive power of adjacent processes is matched by enlargement of technical facilities.

2. The coordination of manufacturing process. By stabilization and qualification of raw materials and energy and applying the information technology widely, we can hold the reliability of the facilities and achieve the steadiness of the production. Based on it, a series of interface techniques are developed to achieve the coordination of the whole manufacturing process.

3. The high-efficiency of manufacturing process. By adopting technologies such as near-net-shape casting, high speed continuous casting, high temperature connection of steelmaking with rolling, endless rolling, hot metal pretreatment, and second metallurgy, meantimes, by realization of the plan layout compacting the process performance precision and the campaign enlargement of reactors (BF, BOF, etc.), the high-efficiency of the manufacturing process can be achieved.

4. The continuation of manufacturing process. Based on the ordering, synergy, high-efficiency of manufacturing process, the continuation/quasi-continuation of the whole process can be achieved with the information integration technology. The manufacturing process continuation incarnates the continuous mass flow, steady process temperature and compact space (especially the minimum slab and/or bloom storage and the compact layout of casting- rolling), ultimately is expressed in the minimized processing time and a speedy operating rhythm.

The steel manufacturing process should follow these technical guidelines to achieve the higher goal in the future, and gradually satisfies the greening request:

1. Process temperature. For strip production the operating temperature in full manufacturing process is not lower than 950℃, better higher than 1000℃. But for long products, the operating temperature in full manufacturing process shouldn't be lower than 900℃.

2. Process running time. About the blast furnace—converter—hot rolling manufacturing process, the running time should be less than 1000 min. As to the electric arc furnace—hot rolling manufacturing process, the running time should be less than 180min.

3. Green house gas emission per tonne steel. Blast furnace—converter—hot rolling process shouldn't be more than 1400 kg. Electric arc furnace-hot rolling manufacturing process shouldn't be more than 160 kg.It can make a reference to

Fig.9.9 and 9.11 (Yin and Cai, 1999).

According to the steel industry greening countermeasure, the environment-friendly techniques should be separately developed to realize in every concrete measure to promote the greenization of the steel industry and the greening countermeasure goal would be achieved gradually.

The green technology certainly doesn't conflict with the effective end-pipe treatment. The greenization must guide the environment policy of the steel plants that includes source abatement, process control, recovery, recycling and end-pipe treatment. Certainly, from the viewpoint of the source treatment, the method of pollution prevention is more initiative and effective than the end-pipe treatment. The following three aspects should be thought to develop the key green techniques for the steel plants.

1. Promoting reliable energy saving and environmental protection technologies, such as power generation with BF gas, coke dry quenching (CDQ), BF top pressure recovery turbine (TRT), converter gas recovery, regenerative combustion (HTAC), slab hot charge direct rolling, high speed casting, near-net-shape casting, pulverized coal injection into BF, long BF campaign, BOF slag splashing and slag recovery.

2. Investing on efficient green techniques: Waste plastics injection into BF or waste plastics reuse in coke oven, sinter plant gas desulphurization, coal based grate-kiln for pellet firing and tailings disposal.

3. Researching on new green techniques: Smelting reduction, new energy source, strip casting, new coke making and carbonization processes, recycle of waste tyre, garbage cineration or refuse melting and other society friendly waste treatment technology.

9.4 Steel Plants and Industrial Ecology

Industrial ecology is a new integrated science that attends to the sustainable development of the ecosystem in recent years (Wang and Yang, 2002a). It systematically designs, projects and controls the framework, manufacturing process, information feedback and control mechanism of the artificial ecosystem according to the holistic, harmonious, recycle and autogenetic principles of eco-cybernetics. The high economy benefit and ecology efficiency can be achieved in the system.

Relationship between steel plants and industrial ecology, and the eco-type modification of steel plants will be discussed in this section.

9.4.1 *About industrial ecology*

Industrial ecology is different from the environment engineering, which based on the end-pipe treatment. Industrial ecology emphasizes the resources comprehensive utilization, systematic integration of technology, the intersection of disciplines and the interprocess linkage. Industrial ecology also emphasizes the quantity and quality of the production should combine with the effect and the order of the community service. It focuses on increasing the employment opportunity rather than decreasing. It even more focuses on the consummation of the functionality rather than the structural increasing.

Industrial ecology is also a science of sustainable development that leads the industry extension, enterprise reforming and inspirits the new industrial revolution. The sustainable development will be lip service only if it have not supported by the industrial ecology. Industrial ecology is an applied science not only to improve the economy but also to improve the environment.

Industrial ecology is the economic ecology, which reveals the metabolism of material and energy flow of the enterprise, the life cycle of the products and even the industry evolution. It's the nature ecology which studies the stress effect to life supporting system and the response mechanism of the exploitation of resources about the industry and the environmental impact activity. It's the human ecology, which studies the relationship of human activity about production and consumption with the natural, economic and social environment. It's also the engineering ecology, which studies about eco-design and ecosystem coordination on the level of time, space, quantity, structure and order of the production and its unit procedures.

Transforming conventional industry to ecological industry, the essential is that the environment protection input becomes ecological effective output. It promotes the balance and harmonious development of the eco-capital with the economic capital, the ecological establishment with the production establishment, the eco-service function with the social service function. There are two innovations:

The first one is the increment in eco-efficiency. The improved production process leads to the best rational use of the resources both for ecosystem and economy.

The second is the extension of eco-effectiveness. More rational products suitable for ecology and economy should be designed to satisfy the needs of society and environment.

The eco-product development strategy contains improving the quality of the raw material and energy, reducing the material and energy consumption, optimizing the production manufacturing process, rationalizing the product circulation, extending life cycle of the products, reducing the environment burden of the production, effecting the waste utilization, optimizing the system function and so on.

Industry eco-type reforming is a complex ecosystem engineering that based on the large space-time scale. It needs the ideas change on strategies. It involves conception of eco-philosophy, view of eco-ethics, view of eco-value and view of eco-culture. It needs the corresponding regime reform, which involves coupling mechanism, production system, life style and coordinate evolution and so on. It also needs the technical breakthrough that involves the knowledge innovation, the measure innovation, the function innovation, the structure innovation and the products innovation and so on. As to the detailed technology, the skills and tools on eco-assessment, eco-layout, eco-design and eco-management are needed to develop and apply.

9.4.2 *Research view of industrial ecology*

Industrial ecology studies the relationship between the industrial activities and the global environment. It provides a new concept of environment management to the development of human industrial society. Industrial ecology was produced on the foundation of the sensation and rational cognition on the overload about industry activity exceeding environment capacity. Thomas Graedel thinks that the industrial ecology is a new concept that makes the industry correspond with the environment system from analysis of the interaction between human activity and environment. This discipline aims at finding out the theory and the method of the industrial material's optimal cycling (Graedel, 1994) applying ecology into industry.

In industrial ecology, consideration of the activity of industry system was developed under the background of social and economic system. Industry cannot disengage the economic and natural system where it depends on. Industrial ecology directs the industry practice using assessment with multi-value measure (embodied multi targets group), one important scale is the material recycling ratio. Using this concept to direct the industry practice and fulfill it in the whole industrial process: from the raw material (i.e. resource like ores) to the prepared material, from semi-products, products or parts to entire machine or facility and so on, from the recoverable wastes to the final garbages and so on. The ecologic optimization and the closed circle of industrial substances should be implemented.

The principle of industrial ecology comes from the theory of bioecology. Comparing with the bioecology, its mechanism has arisen. During the industrial ecology system, each of the manufacturing processes should be treated as an interdependent, inter-connective with larger industrial processes and as a compositive part. Though there are differences between the concepts of industrial ecology and bioecology, but we will gain a lot if we make an imitation based on the analogy character of industry system with the biologic system (Frosch and Gallopooallos, 1989).

Industrial ecology emphasizes that the cooperation among industrial departments has to exist for the closed inter-process recycling. These industrial departments have four types:

1. The department to obtain the inorganic or organic raw materials.
2. The department of manufacture and processing the materials.
3. The department to manufacture final products and equipment.
4. The department responsible for the waste collection and disposal.

By industrial ecology it requires controlling the linkage and operation among these departments according to the closed material-recycling mode or encouraging the material circulation flow among the whole industrial system. An efficient operation mode will be developed gradually and then the harm to the external supporting system will be reduced in large scale. An ecologic industrial mode such as the "semi-opening" or "close-loop" will be constructed.

As a whole, there are more than 20 kinds of definition about the industrial ecology (CÔté, 1995), among them at least three basic elements are common to all (Erkman, 1999):

1. Industrial ecology is a comprehensive and integrated conception that is about all the composing of the industry system and the connection with ecosphere.

2. The biophysical fundamentals of the industry system, i.e. the whole about the material and energy flow and the deposition, related with human activity, is the research scope of the industrial ecology. The viewpoint of the industrial ecology is to use non-materialize criterion to value the economy, that is different from the usual theory.

3. The technological motivation, i.e. the long-term development of key technologies is a decisive (not the only one) factor of the industry system .It promotes to gain knowledge from the cycle of biology system and to transfer the present industrial system to the sustainable development system.

9.4.3 *Steel plants and eco-industrial chain*

A. Specifics of steel plant

According to the technological feature of the steel manufacturing process and the request of economy benefit, the steel plants usually have the following specifics:

1. Large production scale and large throughput of the material flow: The basic modes of modern steel plants can be classified according to the annual steel output as class of 6~8 Mt, class of 3~5 Mt and class of 1~2 Mt. The related material throughput is about 5t per tonne steel. In China, aboat 37% commodity are transported by railway and the average distance is about 1050 kilometer.

2. High resources and energy concentrated: In an advanced integrated steel en-

terprise, the consumption rates are around as 0.6~0.7 t coal equivalent, 1.5~1.6 t iron ore, 3~6 t fresh water and 0.15~0.25 t steel scrap and so on.

3. Long manufacturing process, numerous procedures and complicated structure: The steel manufacturing process is a multi-procedure in series and integrated processing system. The structure of its processing flow is very complex. The steel plant requires processing without intermittence because of its high temperature operation.

4. Along with the large amount and multi types of emission in matter and energy, the steel manufacturing process forms a complex environmental and ecologic interface with the external environment.

5. Because of large production scale and concentrated resources and energy, the large flux of capital and current funds as well as the frequent economic balance of payments must be aroused.

The mentioned above indicate that the heavy environment burden of the steel plants and the arduous task of environment protection. At the same time, it also contains the opportunity of the function extension of the steel plants and the importance of eco-type reforming of the steel plants in the future.

B. The historic topic of steel plant facing in the new century

The whole 20th century is a period of fully developed industry and technology. However, the uncontrolled using of resources and energy for the mass production, the massive consumption without considering the result and the disorderly mass abandon caused the deterioration of environment and ecosphere and lacking of the energy and resources day by day. These conditions are very harmful to the global ecologic and sustainable development which including the steel industry. So people recognize that the international steel industry (including the steel plants in China) is facing the same historic topic—to get the ability of market competition with sustainable development together. Both of them contain the factors and objects that usually are complex or contradictious. This is a preferential multi targets under the specifically boundary. For example, the topic of market competition ability contains the factors of production cost, products' quality, specification, the delivery time, yield and the capital turnover and so on. The ability of sustainable development contains the supply of resources and energy, the efficiency of material and energy, the specific environment burden and environment-friendliness of unit production (or unit production value), the possibility to make ecological industry (especially the factors of time and economy). These historic topics must be faced and solved. It will arouse a serial of rich and colorful scientific research, technical innovation and the integration of engineering optimum. The fields of engineering ecology and economic engineering are also involved in.

C. The eco-type modification and engineering ecology of steel plants

Over a long period of time, it is considered that steel plants are of high resource and energy consumption, high emission, high waste forming and high pollution superficially. Now these problems about the manufacturing process modification of production unit and process flowchart by adjusting and optimizing in time, space, quantity, structure and order to minimize emission and wastes, the reestablishment of steel plants of position in social economy by widening the process functions, constructing the eco-industrial chains and implementing eco-type reforming must be solved. It's worth to research the topic that how to made the steel plants to be a linkage centre of the material and energy flow in the industrial ecologic chains of the circular economy society.

From the viewpoints of knowledge chain of process engineering, ecologic engineering and circular economy, the consumed amount of resource and energy and also the relevant demand of funds are increasing with the enlargement of material-energy-time-space in different border, such as the research of science, the technical development and innovation, the integration and optimization of engineering, the industrial forming and development and the harmony and sustainable development of whole economy and society (Yin, 2003) (Fig.9.4).

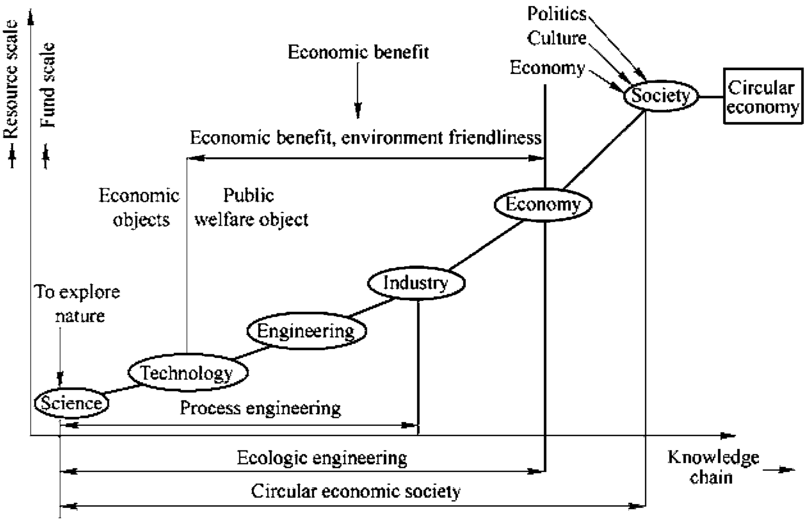


Fig. 9.4 The relationship between expanding scale of resources and funds with knowledge chain

To construct the eco-industrial chains and then form an eco-type industry park, up to grow into a circular economic society, we must pay more attention to these aspects:

1. The extension and closed loop (or semi-closed) of material recycling and

improvement of their efficiency.

2. The coordination-optimization of the time-space factors (the efficiency of applied energy and funds, the geographical allocation).
3. The maximum of the cycle flux of materials and energy.
4. The used funds turnover and the economic rationality.

Industrial ecology is the knowledge that refers to the industrial ecologic design and the coupling of ecosystem among industries related to units of matter production or each section of the system in the level of time, space, quantity, structure and order. During the steel plants' eco-type reforming, the research of industrial ecology must be aroused. It can be studied from these aspects:

1. The closed materials, circulation of the eco-industrial chains (or an eco-type industry park) including the research of quantity index of matter.
2. The cascade utilization of energy and its efficiency in the industrial ecologic chains including the way of energy saving and new energy source.
3. Harmonious system structure of eco-industrial chains in respect of economy and environment and the efficient operation rules. That means the reasonable steel manufacturing process and the industrial ecological chains, even an eco-type industry park will be formed over the steel and the other industry. At the same time, the matter and energy flow, life cycle assessment of the products, the collocation of time and space factors, the efficiency of resource material flow and funds circulation and general environment burden should be studied.

The target of eco-type reforming of steel plants essentially is to reform the relationship between the developing objectives and thes structure of industry. It represents the harmonious and sustainable development of physical world in ecosphere.

In a word, the goal of steel plants eco-type reforming is to implement the optimization of economic benefit and ecosystem. Its function can be described by the following two aspects:

1. The increment of ecologic efficiency. The eco-efficiency may be enhanced by exploiting the new functions of the steel manufacturing process. It is the steel manufacturing process in a new era. It is programmed for the better economic benefit, the full new products, the friendliness with environment, the resources and its recycling, the energy and its cascade utilization. The design of this manufacturing process must fully consider its functions and position in the industrial ecologic chains also.
2. The optimization of eco-effectiveness. It contains the eco-design and the eco- assessment of the products and so on.

In the future economic society, the eco-type factory will be the standard mode of eco-industry and circular economy. It differs far from the traditional factory in value orientation and the assessment standard. The Table 9.1 lists the differences between the eco-type factory and the traditional factory.

Table 9.1 Comparison between the eco-type factory and the traditional factory

Item	Traditional factory	Eco-type factory
Enterprise object	Product-oriented, high profit-oriented	Function-oriented, economic and ecologic benefit adjusted
Enterprise structure	Chain type, rigidity	Network type, adapt each other
Scale trend	Unitary production, large-scale	Multiserial producing, reasonable scale of self-adaption net
Resources and energy consumption	High resource consumption, low energy efficiency	Low resource consumption in entirety, high energy efficiency
Relationship of economic system	Lengthways, department economy	Transverse, multiplex ecologic economy
Environment protection	End-pipe treatment, large input but low output	Whole cycle complex control, pay equal attention to input-output
Waste, emission	Emission disorder, negative benefit	Recycling utilization in ecosystem factories, benefit positive
Economic benefit	High partial benefit of unit factory, low in whole	High comparative benefit of unit factory, high in whole
Social benefit	Reduce job chance	Increase job chance

On the view of technical progress and innovation, the eco-type reforming of enterprise will come through steps of the improvement of technology, the innovation of product (especially to the equipment manufacturing industry), the innovation of manufacturing process integration (especially to the process manufacturing industry), the function extension and the macro system revolution. It proceeds in a long period (historical age) and also develops from low-level production system to high-level gradually. Wang Rusong shows/that the improvement of technology, the innovation of product or/and the innovation of manufacturing process integration, the function extension and the macro system revolution will improve the economic-ecologic benefit in 2 times, 5 times, 10times and 20 times respectively (Fig.9.5).

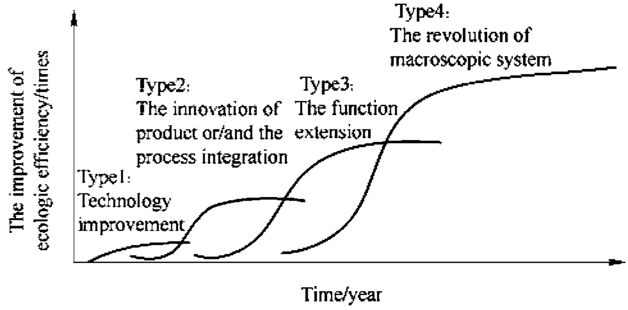


Fig. 9.5 The ecologic development of enterprise grading picture (Wang and Yang, 2002b)

9.5 Function Extension of Steel Plants and Circular Economy Society

Through the incessant technological development and integration optimization, the functions of steel manufacturing process are broadening. Relationships between function extension of manufacturing process and eco-oriented transforming of steel plants will be dissussed in this section.

9.5.1 *Function extension of manufacturing process and eco-oriented transforming of steel plants*

The processing procedures of steel manufacturing process are so many and each procedure has its own different functions. The collections of input and output of materials/and energy for each procedure are different but interdependent on adjacent procedures. They construct several kinds of complex ecological interface with external environment. Fig.9.6 shows the material/energy input and output corresponding to producing 1000 kg of hot metal in blast furnace. It can be seen from the Fig.9.6 that the input materials include raw ores, sinter (pellets), recycling converter slag, etc.; the input energy include coke, pulverized coal and electricity, as well as water, air (blast, oxygen enriched) etc. The output include the materials such as hot metal, BF slag and dust, the energy such as BFG , steam, electricity, hot water and warm water.

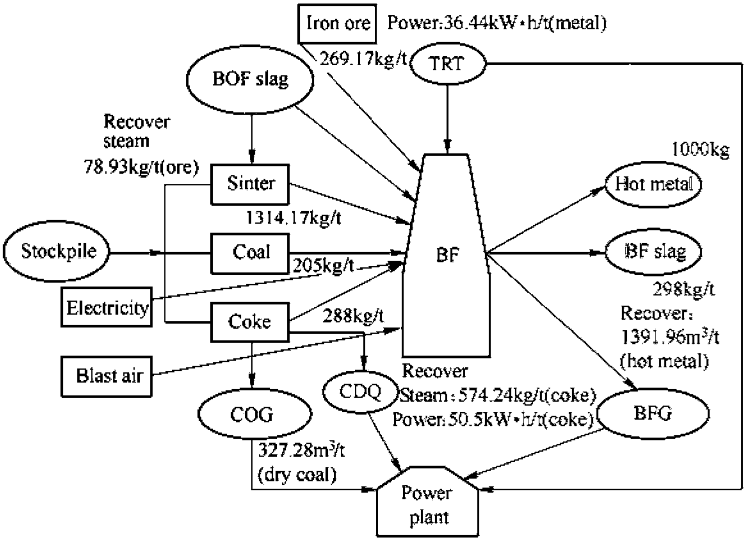


Fig. 9.6 Material and energy input and output of the blast furnace

The input and output of materials and energy per tonne liquid steel of BOF are shown in Fig.9.7. The input materials include hot metal, scrap, flux agents, ferroalloys, etc.; the energy input includes electricity, coke oven gas, oxygen, nitrogen, argon, steam, as well as water, air etc., and the output include the materials such as liquid steel, BOF slag, dust and the energy such as converter gas, steam, hot water, also some drained cooling water.

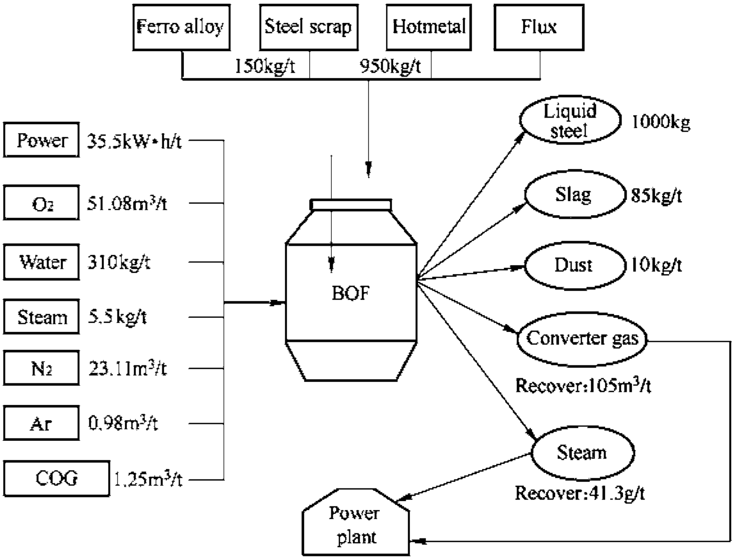


Fig. 9.7 Material and energy input and output of BOF steelmaking

Similarly, we can list the input-output collections of coking oven, sinter machine, electric arc furnace, secondary metallurgy, continuous casting, reheating furnace, hot rolling, cold rolling etc. Apparently, either for the BF—BOF integrated steel plant or for the EAF mini-mill, the manufacturing process's function should not be limited itself to the metallurgy-material production. The necessity and possibility of the function extension are shown from the input-output collections of operating and processing procedures.

During the beginning of the 21st century, to recognize deeply as well as to exploit fully the functions of steel manufacturing process become a topic of epochal significance. If only from the point of view of metallurgy and material science, the function of steelmaking is just to produce steel products. But if from the view of engineering, industry/ and society, that is to say, expanding our view to resources, energy, environment, ecology, circular economy etc., the function of steelmaking is not only limited in the material production. Therefore, we should be by broadened viewing field and more positive attitude to think about the functions of steel manufacturing process and the problems of iron and steel enterprises eco-type reforming.

According to above discussion, it can be seen clearly that the modern steel-manufacturing process (especially BF—BOF integrated plant) adaptable to sustainable development will mainly have three functions:

- The function of steel product manufacturing;
- The function of energy conversion;
- The function of waste treatment and recycling.

A. The function of steel product manufacturing

The main function of steel manufacturing is to produce the qualified steel products with low-cost, less emissions on the basis of the minimum consumption of resources and energy. The steel products ought to meet the users' changing requirements and must be supplied for the social production and the private consumption.

Such steel product manufacturing process is the life cycle system of green steel products, which embodies the concept of product life cycle assessment (LCA). The life cycle system of green steel products will relate to the cause-effect linkage resource and energy exploitation, transportation, manufacturing process, machining and assembling, using phase, abandoning, and recycling processes. The following indicators can assess green degree for steel products:

1. The specific consumption of resources, energy and the emissions (including greenhouse gases);
2. The use efficiency and service life of products;
3. The environment load of steel and its products;
4. The regeneration of steel and its products.

Fig.9.8~Fig.9.11 show the calculated data of material, energy and environmental burden for two advanced steel manufacturing processes.

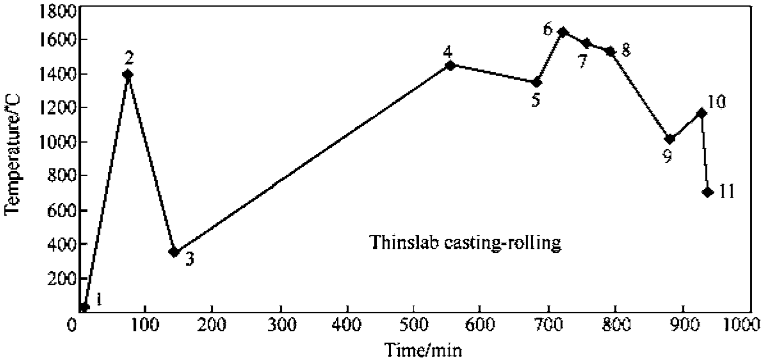


Fig. 9.8 The temperature- time track of mass flow in BF—BOF process

1—Iron ore; 2—Sinter; 3—Ore bin; 4—BF tapping; 5—Converter charging; 6—Converter tapping; 7—Refining; 8—Continuous casting; 9—Slab conveying; 10—Reheating furnace; 11—Rolling

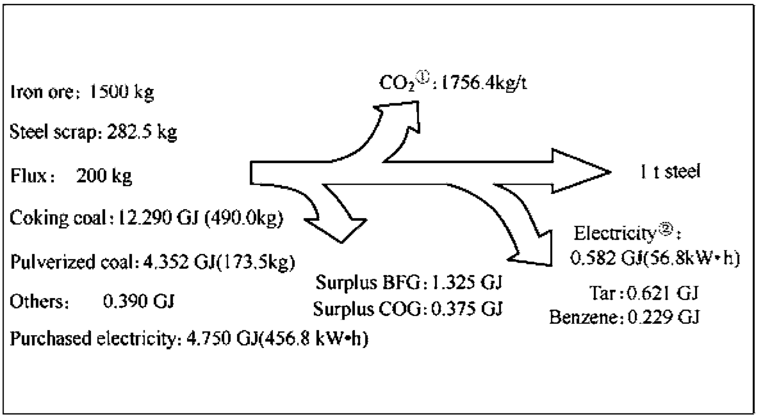


Fig. 9.9 Diagram of material, energy and environmental burden in BF—BOF—thin slab casting-rolling process (Enterprises without their own power plant)

① BF—BOF—thin slab casting-rolling process, with the annual slab production of 2.8 Mt. The specific energy consumption is 18.650 GJ/t, i.e. 637.3 kgce/t. While calculated by 1 tslab, the CO_2 emission is about 1756.4 kg/t, among which 1376.4 kg(CO_2)/t belongs to the emission of manufacture procedures, while 380 kg(CO_2)/t belongs to the emission of power plant outside. The CO_2 emission factor of electricity is 0.95 kg(CO_2)/(kW · h).

② Recovered electricity per tonne of steel from CDQ and TRT is about 56.8 kW • h/t.

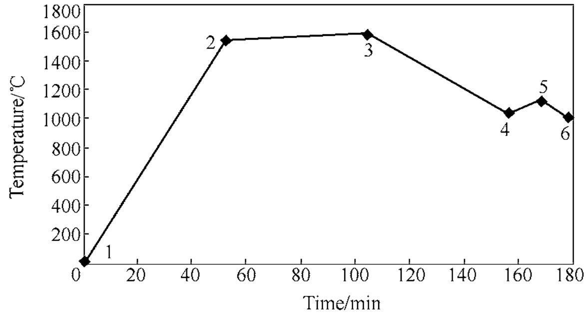


Fig.9.10 The temperature- time track of mass flow in EAF—thin slab casting-rolling process

1—Charging; 2—EAF tapping; 3—Refining; 4—Continuous casting; 5—Reheating; 6—Rolling

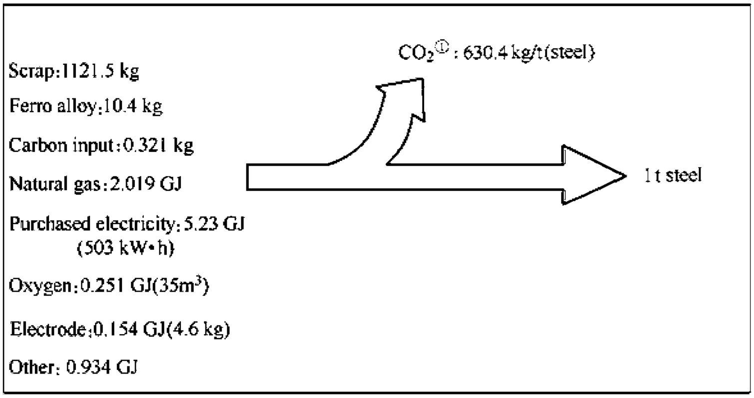


Fig.9.11 Diagram of material, energy and environmental burden in EAF—thin slab casting-rolling process

① EAF—thin slab casting—rolling process, with the annual slab production of 2 Mt. The specific energy consumption is 8.91 GJ/t, i.e.304.2 kgce/t. While calculated by 1 tslab, the CO_2 emission is about 630.5 kg/t, among which 152.5 kg(CO_2)/t belongs to the emission of manufacture procedures, while 478 kg(CO_2)/t belongs to the emission of power plant outside. The CO_2 emission factor of electricity is 0.95 kg-(CO_2)/(kW · h)

B. The function of energy conversion

The steel manufacturing process usually accompanies energy conversion. As an example of the integrated steel enterprise, the BF—BOF—hot rolling process is actually an iron-coal chemical industry. This process may be taken itself for a reactor to convert coal into energy such as gas, heat, electricity, steam, even hydrogen, dimethyl ether etc.

In the integrated steel enterprise, a large quantity of combustible gases and high temperature products (such as red coke, etc.) are co-produced from various reactions in the metallurgical devices. Especially a large amount of BF gas with low sulfur content, a large amount of converter gas with high CO content, a lot of hydrogen-rich coke oven gas, and the off gas of smelting reduction are already co-produced together with smelting processes. These are all the symbols of the energy conversion function of the steel plants. Meanwhile, a lot of high-temperature waste, steam and hot water are come into being during the steel production. Integrating the above energy forms the self-sustained power generation is risen in the steel plant. Many large integrated steel complexes are developing to purchase only coal but no electricity and oil. In China, the steel plants with an annual production capacity of 10 Mt have been equipped with 1.2 million kW • h power plant that generating about 7 billion kW • h per year. 1 kW • h only needs 260~270 g coal equivalent. The economic-environmental benefit is significant. As to a large number of existing integrated steel enterprises, the production of hot metal in blast furnace is often associated 250~350 kg/t of BF slag supplying to cement industry. Compared with cement produced by limestone, the cement produced by BF slag can save limestone about 45% and reduce CO_2 emissions about 44% (Nobate and Ueki, 2002), as shown in Table 9.2.

Table 9.2 Energy and CO_2 emission comparsion of cement produced by BF slag and by limestone

Index \ Item		Limestone cement (*A*)	BF slag cement (*B*)	Reduction (*A-B*) /*A*
Limestone consumption/kg		1092.0	600.6	45%
Energy consumption	Coal/kg	103.6	57.8	44%
	Power/kW • h	99.2	72.56	27%
CO_2 emission/kg		775.6	437.0	44%

According to the assessment based on calculation (Scaife, Nunn, Cotterll, et al., 2002)using the life cycle analysis, if the BF slag used in the production of cement and the BF gas used in power plant are considered, the greenhouse gas emissions of the coal-based steel manufacturing and of the gas reduction process has little difference. From the point of view of greenhouse gas emissions, power generation and cement production together with integrated steel manufacturing have obvious profits. This is a very good example about fully bring into play the energy conversion function of the steel manufacturing process.

In fact, EAF mini-mill process is also an iron- coal processing. The coal is just converted into electricity through external power plant, and ferruginous matter mainly comes from prompt scrap and obsolete scrap in society. Some EAF plant recovered the hot electric furnace gas to preheat the scrap charge, which can save 100 kW • h/t. It is another type of energy conversion.

Development of hydrogen, a new clean energy, is a worthwhile frontal research project in steel manufacturing process. Steel plant can use adsorption and separation method to produce hydrogen from coke oven gas. More noteworthy is using $CO\text{-}H_2O$ reaction from the converter gas with rich CO, or from the smelting reduction off gas with rich CO & H_2. The hydrogen can be further processed to a liquid energy dimethyl ether (CH_3OCH_3).

The low exerge waste heat and residual energy in the steel plants can be transferred into the hot water to provide nearby community residents to use.

C. The function of waste treatment and recycling

Many procedures or devices in the steel manufacture possess the capability to treat and recycle many urban wastes. The resources and energy can be reused. It should be emphasized that the waste that the steel plants handled is the bulky municipal waste, such as:

- Re-melting a variety of iron and steel scrap for recovery of ferruginous matter.
- Handling the bulk of waste plastics by injecting plastics into blast furnace (Fig.9.12) or charging into coke oven.
- Recycling waste tires (using liquid nitrogen produced in air separation stations for the cryogenic treatment).
- Dealing with the social garbage (using combustible gases from steel plants in special incinerator).
- Treating urban wastewater and sewage (using large water treatment devices in steel plants), and so on.

In the coming years of new century, the social-economic functions of steel plants should be evolved. Steel plants can form eco-industrial chains in different area, and gradually realize the different eco-type reforming.

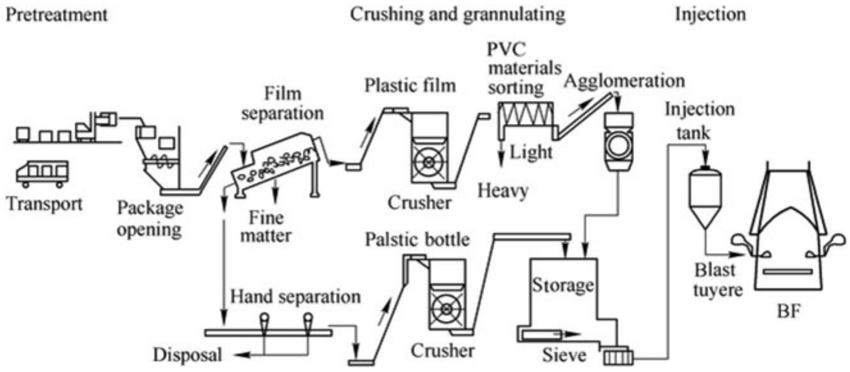


Fig. 9.12 Injecting waste plastics into BF (recycled plastic containers and package materials can be injected into BF)

9.5.2 *Steel plants in circular economy society*

A. Circular economy mode and connotation

Down till the beginning of 21^{st} century, with the marked rise in scientific and technological level, the social production scale is unprecedented expanding. Human society seems so powerful and self-satisfied to face the future development. But people have to face the survive crisis and severe challenge, such as the explosive population growth, the rapid depletion of mineral resources and fossil energy, lack of water resource and heavy water pollution, atmospheric pollution and soil desertification, acid rain area extension, decrease of forests and arable land area. More deep-seated problems are that endangered biodiversity, global warming, and ozonosphere hollow area and so on. Most of them are affecting the people's health and life and severely restricting the economic development. Even the earth ecosystem that evolved over 40 million years would be brought to a crisis. In 1972 the United Nations conference on Human Environment in Stockholm, adopted the *Declaration of United Nations Conference on Human Environment*, which thought-provoking pointed out that "only one Earth" for today's people to live, "this Earth is not ours from the previous generation inherited, but borrowed from future generations". This is such a shocking word! Since then, the reports of *the World Commission on Environment and Development* in 1987, the declaration of United Nations summit on *Environment and Development* in Rio de Janeiro, Brazil in 1992, the new declaration and speeches on *the United Nations Summit on Sustainable Development*, in Johannesburg, South Africa and *Assembly of Global Environment Facility*, in Beijing, China in 2002 constantly repeatedly emphasized one idea: Mankind must abide by the principle of "development that meets the needs of the present without comprising the ability of future generations to meet their own needs".

China is in the transition period that is shifting from pre-industrial to industrial-development, and the contradiction of economy to environment is very prominent. National leaders have clearly pointed out: "Only take the road of circular economy based on most effective using the resources and protection the environment, the sustainable development can be achieved."

Circular economy can be regarded as the resources closed-circuit utilization oriented economy(Jin, Li and Feng, 2003). That is to say, with production expansion and economic growth, the "win-win" goal of the survival and development of human society can be achieved by building the social economy pattern of resource-producing-products-consumption-waste recycling, clean closed circulation. "Circular economy" was first stated in *Economics of Natural Resources and the Environment, Harvester wheat-sheaf, 1990* by British environment economist D. Pearce and R. K. Turner. Circular economy is a new production mode, based on a closed-cycle mass flow system, and is also a new development method. From an economic point of view, circular economy changes the "environment" from the economic constraints of external factors into a new economic internal production essentials (Xu, 2004).

Circular economy is the patterns that integrate the cleaner production, comprehensive utilization of resources, renewable energy development, eco-design of products and the ecological consumption, and apply ecological rules to guide the economic activities of society. In accordance with their depth and extent of matter recycling, circular economy can be divided into the following categories:

1. Primary waste recycling. This means that wastes are recycled simply, which have been industrialized in the early of the 20th century. For example, steel scrap recycling, waste paper recycling, glass recycling, which were already in large

scale. Recently that Ricoh in Japan utilizes used Coca-Cola PET bottles for spinning to make dress. In this period substances have not been changed at the molecular level, limited in the aggregate transformation.

2. Recycling constituted of "Producer—decomposer". At the end of 20th century, as the development of the home appliances industry and the auto industry, the waste appliance dismantling appeared. For example, thermoplastic was granulated as resource. Thermosetting plastic were smashed as filler. Copper, silver, mercury and other metals recovered with leaching method respectively. So, the used appliances were decomposited and transformed into raw materials. End-of-life vehicles could be treated in similar way. This material recycling had been a step forward.

3. Recycling resources consisted of the eco-industrial chains. For example, it has successfully been developed in China the "Sulfuric Acid Plant—Phosphate Fertilizer Plant—Cement Plant" eco-industrial chain. Sulfuric acid is supplied to phosphate fertilizer plant for fertilizer production; its by-product gypsum changes with pyrolysis position into sulfur dioxide and lime; the lime is used in the production of cement; and the sulfur dioxide returns into the production of sulfuric acid. Sulfuric acid is used for the production of phosphate fertilizer again. The pollution problems caused by large amount of gypsum piling up have been vanished, and the element sulfur recycled. This pattern achieves a deep-level matter recycling where the molecular conversion occurs.

4. Recycling resources with the coupling of "Eco-industrial system" and "natural ecosystems". This is the further advanced mode. For example, as the carbon dioxide emission in current industrial production is tremendous, some fast-growing trees and oil phytoplankton are going to develop by biological transgenic technology. Carbon dioxide in the air will be fixed by them into biomass, and biomass will be further processed into bio-oil as an energy source. Such use of biomass energy will not increase industrial carbon dioxide net emission.

B. Steel plant functions and modes in circular economy society

1. Ecologic requirement and economics of industry. The function extension of the iron and steel manufacturing process will gradually guide the steel plants to implement ecological modification in the future development. Steel plant eco-restructuring is one of industrial ecology.

The essence of Industrial Ecology is a march that with the development of eco-industry and construction of eco-industrial park, the input & output of industrial economic activities of human society can gradually be balanced, harmonious, smooth and sustained into metabolism of natural ecosystem. To grasp the essence, we must distinguish the similarities and differences between metabolism of natural and industrial processes. Both of them consist of mass circulation, energy conversion and message transfer. All are the same and obey the natural laws. The difference is that the artificial metabolism in the industrial process is driven, controlled and adjusted by human and is subordinated to the needs of people, but the natural metabolism of ecosystems is evolved spontaneously. The former case has a short-cycle and a fast circulating rate but the latter a long-cycle and a slow rate. The former energy consumption is large and more than the solar energy that mankind can capture and convert, so the stored solar energy in lithosphere (coal, oil, gas etc.) and other energy (hydropower etc.) are needed. But the latter only spend a part of its energy captured and converted, and have some excess energy stored into the lithosphere. On the whole planet, the former case causes the relative imbalance, instability, disharmony and unsustainable results but the latter keeps the balance, stability, harmony and sustainability.

The way to solve the above difficulties is to find the roadmap of industrial ecosystem and firmly to develop the ecological industry.

Ecological industry not only plays a role of scientific, technical, environmental, ecological aspects, but also include connotation of economics. Industrial ecology means that the operative internal relations between the economic system (including the industrial system) and the ecosystem must be established. That is to say the eco-industrial processes are not only to follow the laws of ecology, but also practicable in the economic operation.

In the mid-1960s, K.E. Boulding published the article *The economics of the coming spaceship earth* (Boulding, 1992). He raised a fundamental economic issue according to the laws of thermodynamics. He pointed out that, first of all, according to the first law of thermodynamics, the wastes produced in production and consumption do not vanish, the substance aggregate conserves in the matter system. Therefore, the environmental capacity to receive the wastes must be considered when design and plan of economic activities. Secondly, although recycling can reduce the environment burden, but according to the second law of thermodynamics, entropy increase means that the whole recovery is impossible.

In early 1970s, Allen V. Kneese, Robert U. Agres and Ralph C. d' Arge published a book *Economics and the Environment*. They re-demarcated the economic system based on the mass balance of the first law of thermodynamics, and proposed the famous mass balance model. The main theories include:

Firstly, a modern economic system is composed of four parts: material production, energy conversion, remnants processing and final consumption. The mass flow relations exist among these four parts, and between the economic system composed of the four parts and the natural environment system.

Secondly, if the economy system is a closed system (no inlet or outlet) without net mass accumulation, the quantity of matter surplus from the economic system into the natural environment within a period, is roughly equivalent to the quantity of materials from the natural into the system. The inference from this theory is that the quantity of residues emitted from economic system exceeds the quantity of raw materials used in production, as many inputs (e.g. water and air) in both production and consumption are usually not considered as a raw material.

Thirdly, the above thinking also applies to an open, modern economic system having material accumulated, but the analysis and calculation is more complicated.

Fourthly, although more and more of pollution control techniques are used in the modern economic system. It should be clearly aware that, controlling environmental pollution only changes the forms of special pollutants, but never to be eliminated the pollutants substantial entities. For example, for treatment of polluted gases, the gases become cleaner, but dusts and other solid pollutants remain in the ground. It shows that mutual conversion exists among various remnants.

Fifthly, in order to reduce the pollution from the economic system to the natural environment, the fundamental way is to enhance the matter and energy efficiency and to broaden the recycling accompanied with economic development. Only this way can reduce the exploitation and consumption of the natural resources and reduce the pollutant emissions.

The works of Ecological Economy researchers have also important directive significance on eco-industry and industrial ecology. The Earth Policy Institute USA director, L.R. Brown clearly pointed out in the book Eco-economy: Building an Economy for the Earth (Brown, 2001) published in 2001: In the natural world, one kind of bio's self or excreta is another kind of bio's vegetativeness. Nutrition are constantly in circulation. This campaign approach is feasible, our duty is to apply this pattern to economic modes successfully.

2. The future modes and the social economic functions of the steel plants. With the social and the economic development, urbanization will be further accelerated, especially, in the developing countries such as rapid developing China. From the points of view of production and consumption, city, especially industrial and commercial city is often the high-centralized areas of production, consumption and waste treatment. Therefore, for the basic materials' consumption and discarding such as of steel, plastic, glass, aluminum, copper, lead, zinc the recycling must be considered. Moreover, urban consumption of energy such as electricity, gas, water, hot water is enormous and growing. Obviously, the eco-type reforming of the steel plants of suburb type around a number of cities with the necessary situation has many favorable conditions for the economic and ecological values. Scrap, waste plastic, garbage and other wastes from city, can be used nearly and effectively by a large

steel plant. In addition to the needed steel supply for the city and its surrounding areas, steel plants can also supply hot water even power to the community residents. Therefore, a number of suburb type and eco-industrial steel plants around cities are likely to develop in the future. These steel plants of suburb zone type will grow up with developing philosophy as show in Fig.9.13.

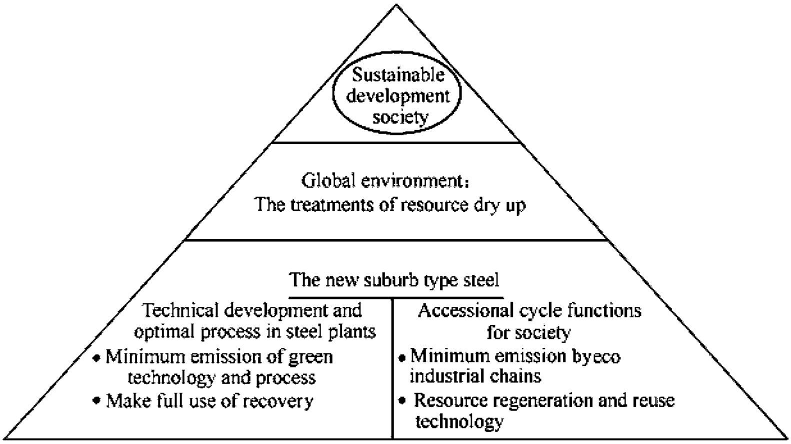


Fig. 9.13 The development philosophy of environmental friendly and suburb type steel plants

With the rapid economy globalization, the international trade capacity of bulk resources in minerals and energy are expanding. The basic material steel and principal energy source oil expand their trade capacity remarkably in the course. For example: global seaborne iron ore of trade has reached 450~500 million tons/year. In 2002, China's iron ore imports reached 111.49 Mt, and crude oil imports reached around 70 Mt. The development of harbor type large integrated steel complex will lead some harbor cities with excellent comprehensive conditions gradually to become an eco-industrial zone. In such conditions, the large integrated steel complex can rely on predominant situation in mass flow, funds, technology and talent to extend its manufacturing chain and management chain. The eco-industrial chains for example combined with shipbuilding, containers making, cement manufacturing, and even the architectural structure industry may be constructed. Besides, in the large integrated steel plant, lots of carbon monoxide-rich gas and hydrogen-rich gas were gained simultaneously. After deep research and gradual development, plentiful supply of hydrogen may be gained with them. If this hydrogen is used among the adjacent petrochemical enterprises, the competitiveness of these enterprises must be increased. In these eco-industrial zones, the resources, energy and funds can be used full effectively, and the relative environmental burden per unit output will decrease. It is a heavy-chemical category of industrial eco-type-trading zone. In the industrial-trading ecosystem of steel plant and its relations among other industries in nearby areas are shown in Fig. 9.14.

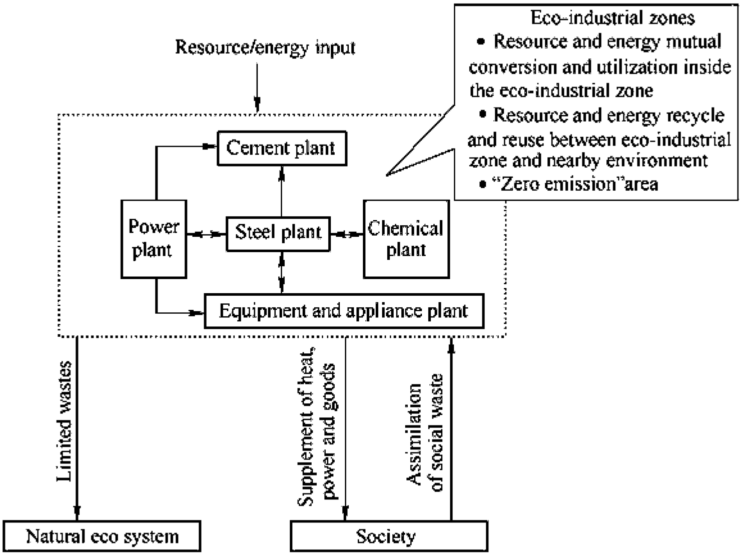


Fig. 9.14 The role of a steel plant in eco-industrial zone

As forming the eco-industrial chains, iron resources become an important thing in circular economy (Fig.9.15). Meanwhile, the social economic functions of steel plants are expanded through ecological transforming.

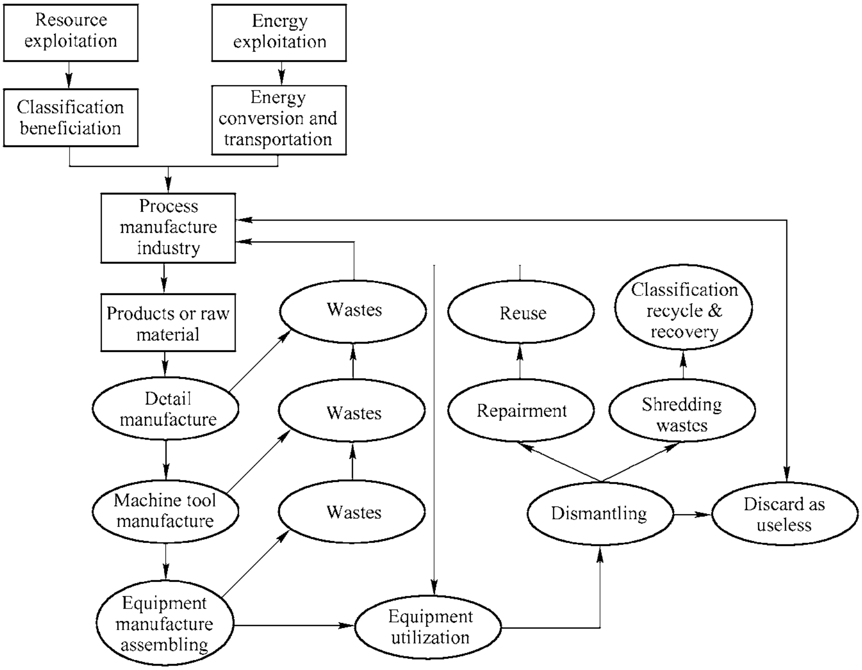


Fig.9.15 Eco-industrial chains and circular economy

In summary, it can be seen that the future developing mode of the steel plants will follow the eco-type reforming through the green manufacturing process, and gradually form two main alternative modes: the type of suburb zone and the type of harbor eco-industrial park.

In the future, the social economy functions that the steel plants may undertake are listed as below:

1. Steel plants take the start of the iron-coal chemistry. It is necessary to produce the better and cheaper steels, but also to develop of new clean energy.
2. Steel plants can be one of the cores of the harbor eco-industrial park in the future.
3. Steel plants can be a kind of municipal waste treatment and recycling and the heat supply station to community residents nearby.
4. Steel plants can be the coordination points of industrial wastes recycling, and harmless treatment as well as energy cascade reutilization.

To the new development of process industry in China, we should deliberate on the social-economic functions of steel plants with new conception of development. We should think about the iron and steel enterprises' social roles and the opportunities of various businesses in transition under different conditions in future.

References

Boulding K E (1992) The economics of the coming spaceship earth. In: Markandya A,Richardson J ed.Earthscan Reader in Environmental Economics. Earthscan Publications Ltd. London

Brown L R (2001) Eco-economy: Building an Economy for the Earth. Norton, W.W.& Company, Inc

CÔté R P (1995) The Industrial Ecology Seminar: Principles, Topics for Discussion and Dictionary, Industrial Park as an Ecosystem Project. Faculty of Management, Dalhousie University. Halifax

Erkman S (1999) Industrial Ecology. Xu Yingyuan translated.The Economic Daily Press, Beijing, 14-15 (in Chinese)

Frosch R A, Gallopooallos N (1989) Strategies for Manufacturing. Scientific American, 261(3)

Graedel T E (1994) Industrial Ecology: Definetion and Implementation. In: Industrial Ecology and Global Change. The Press Syndicate of the University of Cambrige, 23

Jin Y, Li L Y, Feng J T (2003) Eco industry: principle and application. Tsinghua University Press, Beijing, 3-5 (in Chinese)

Mclogk S A, et al (1996) Green Manufacturing. Society of Manufacturing Engineers, USA.

Nobata K, Ueki Y (2002) Basic property and the method of effective use on Portland blast-furnace slag cement and ground granulated blast furnace slag. Nippon Steel Technical Report 86(7):44-47

Stahel W R(2000) Creation of New Environmental Business Models. In: Commemorative Symposium in Eco-Products 2000. Tokyo, Japan, 15-38

Scaife P, Nunn J, Cotterll A, et al (2002) Towards Sustainable Steelmaking——an LCA perspective.ISIJ International, 42, supplement,S5-S9

Walter R S. Sustainable Development and Strategic Thinking, Chinese Journal of Population, Resources and Environment. 2007(5),4:3~19

Wang R S, Yang J X (2002b) From heavy industry to green civilization. Shanghai Science and Technology Press, Shanghai, 51 (in Chinese)

Wang R S，Yang J X (2002a) From heavy industry to green civilization. Shanghai Science and Technology Press, Shanghai, 4-6 (in Chinese)

Xu S L (2004) Guangming Daily，6th,Jan,2004 B4 (in Chinese)

Yin R Y (1997) The Development trend of steel industry. Iron and Steel, 32(supplement): 22 (in Chinese)

Yin R Y (2002) Energy-saving. Clean production, green manufacturing and sustainable development of steel industry. Iron and Steel 37（8）：1-8 (in Chinese)

Yin R Y (2003) Steel plant modes vs. industrial ecological chain. In: Jin Yong, Li Yourun, Feng Jiutian ed. Proceedings "Eco industry". Tsinghua University Press, Beijing, 218 (in Chinese)

Yin R Y, Zhang S R，Lu Z W, et al (2002) Green manufacturing vs steel industry.Report for consultive project of Chinese Academy Engineering：10-11 (in Chinese)

Yin R Y，Cai J J (1999) Steel production process vs emission atmosphere. Iron and Steel 34（5）：61-65(in Chinese)

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