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# Metallurgical Process Design

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# Handbook of
## Metallurgical Process Design

edited by

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# Preface

In addition to material selection and component design, there are other equally important considerations that must be addressed in the overall process of design selection. One of these is process design, which not only affects cost and ease of production, but may also impact the final microstructure and mechanical properties of the component being produced. While there are various texts which address a particular process design such as forging, casting, and rolling, there is a need for a single text that will provide an overview of these processes as they relate to metallurgical component design. The objective of this text is to provide a thorough overview of the more important processes from the standpoint of the effect of design.

There are an extensive array of process designs discussed in this book. In Part One, Chapters 1 and 2 provide an overview of hot and cold forming process design, which includes forging process design. Chapter 3 details the effect of steel rolling process on microstructure and properties. Chapter 4 provides the most thorough and current overview on aluminum rolling process design available anywhere. Chapter 5 discusses semisolid metal-forming design. Chapter 6 provides a rigorous overview of the principles of aluminum extrusion process design and Chapter 7 is a comprehensive review of superplastic forming design.

Part Two focuses on casting process design for steel and aluminum, including continuous process designs in addition to a summary of various foundry casting process designs. Extensive guidelines for die casting process design are also included.

Various heat treatment practices are conducted to achieve the desired microstructural and mechanical properties of a particular material. Proper design is vital to the end-use properties of the component being produced. Part Three deals with various heat-treatment topics including: an overview of the effect of heat-treatment process design on hardening, tempering, annealing and other properties, carburizing and carbonitriding, nitriding, induction heating, and laser hardening. Chapter 17 discusses the use of quench factor analysis for selection of appropriate quench media for aluminum processing. Chapter 18 covers the use of intensive quenching methodology to provide superior compressive stresses and fatigue properties and/or the replacement of more expensive steel alloys with less expensive plain-carbon steels.

Part Four deals with a topic of ever-increasing importance—surface engineering. This section includes topics on ion implantation, physical vapor deposition (PVD), chemical vapor deposition (CVD), and thermal spray process design. Coating process design for surface endurance is also discussed.

In Part Five, Chapter 22 provides information on designing for machining processes, which is a key topic in metallurgical process design.

This book is an invaluable reference for persons involved in any aspect of product design including metallurgists, material scientists, product and process engineers, and component designers. It is also appropriate for use in an advanced undergraduate or graduate class on material design.

We are indebted to the persistence and thorough work of the contributors to this book. We are also especially grateful for the patience and invaluable assistance provided by the staff at Marcel Dekker, Inc. throughout the preparation of this text.

*George E.Totten*
*Kiyoshi Funatani*
*Lin Xie*

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# Handbook of
## Metallurgical Process Design

# 1

# Design of Forming Processes: Bulk Forming

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## I. BULK DEFORMATION

Bulk deformation is a metal-forming process where the deformation is three-dimensional in nature. The primary use of the term *bulk deformation* is to distinguish it from sheet-forming processes. In sheet-forming operations, the deformation stresses are usually in the plane of the sheet metal, whereas in bulk deformation, the deformation stresses possess components in all three coordinate directions. Bulk deformation includes metal working processes such as forging, extrusion, rolling, and drawing.

## II. CLASSIFICATION OF DEFORMATION PROCESSES

The classification of deformation processes can be done in one of several ways. The more common classification schemes are based on temperature, flow behavior, and stress state. The temperature of the deformation process is under direct control of the operator and has a profound effect on the viability of the process and the resulting shape and microstructure of the finished product. The flow behavior and the stress state differ from temperature in that they are a result of the actual deformation process that one chooses.

### A. Temperature Classification

The temperature classification scheme is normally divided into two primary regions—cold working and hot working. Cold working occurs at relatively low temperatures relative to the melting point of the metal. Hot working occurs at temperatures above the recrystallization temperature of the metal. There is a third temperature range, warm working, which is being critically examined due to energy savings and is, in some cases, used by industries.

#### *1. Cold Working Temperatures*

Cold working usually refers to metal deformation that is carried out at room temperature. The phenomenon associated with cold work occurs when the metal is deformed at temperatures that are about 30% or less of its melting temperature on an absolute temperature scale. During cold work, the metal experiences an increased number of dislocations and entanglement of these dislocations, causing strain hardening. With strain hardening, the strength of the metal increases with deformation. To recrystallize the metal, a thermal treatment, called an anneal, is often needed. During annealing, the strength of the metal can be drastically reduced with a significant increase in ductility. The ductility increase often allows further deformation to occur before fracture. The final surface finish and dimensional tolerances can be well controlled in a cold work process.

#### *2. Hot Working Temperatures*

Hot working occurs at temperatures of 60% or above of the melting temperature of the metal on an absolute scale. At elevated temperatures, the metal has decreased strength, hence the forces needed for deformation are reduced. Recrystallization occurs readily, causing new grains to continually form during deformation. The continual formation of new grains causes the ductility of the metal to remain high, allowing large amounts of deformation to be imparted without fracture. Control of final dimensions is more difficult in a hot-worked metal due to scale formation and volumetrical changes in the part during subsequent cooling.

### *3. Warm Working Temperatures*

Warm working occurs between hot working and cold working. It occurs in the approximate temperature range of 30–60% of the melting temperature of the metal on an absolute scale. The forces required to deform metal in the warm working regime are higher than during hot working. The final finish and dimensional tolerances are better than hot working but not nearly as good as a cold working process. Although warm work seems to have drawbacks, the primary driver for warm working is economic. There is significant cost in heating a metal up to hot working temperatures. If the working temperature is lowered, there can be major cost savings in the process.

## B. Flow Behavior Classification

The flow behavior of a metal or alloy during bulk deformation processes falls into one of two categories—continuous flow or quasi-static. The easiest way to distinguish between these two types of flow is to imagine a movie being made of the deformation region during processing. If the shape of the deformation region changes during each frame of the movie, the process is a continuous-flow process. If in each frame of the movie the shape of the deformation region remains the same, even though a different material is in the region, it is a quasi-static-flow process. The bulk deformation process of forging is an example of a continuous-flow process. As the metal is being shaped in the forging die cavity, the deforming region, which is often the entire amount of metal, is continuously undergoing change. Processes such as rolling, wire drawing, and extrusion are examples of quasi-static flow. For example, in rolling, the deformation region is the metal being squeezed between two rolls. The shape of the deformation region does not vary, aside from initial startup and final finish, although different material flows into and out of the region.

The classification based on flow is useful in determining what type of modeling scheme can be used to simulate the bulk deformation process. For a quasi-static-flow process, the deformation region can often be handled as a single region and a steady-state type of analysis can be applied. For a continuous-flow process, a more complex analysis needs to be used to simulate the process accurately. The complex analysis needs to account for the continually changing shape of the deformation region.

## C. Stress State Classification

In all bulk deformation processes, the primary deformation stress is compressive in nature. This is in contrast to sheet metal forming where tensile stresses are often used. Stress state classification consists of two categories for bulk deformation—direct compression and indirect compression. In direct compression, the tools or dies directly squeeze the workpiece. Forging, extrusion, and rolling are examples of direct compression processes. In indirect compression, the deformation region of the workpiece is in a compressive stress state but the application of these compressive stresses occurs by indirect means. Wire drawing is an example of an indirect compression process, where the wire is pulled through a die. The workpiece contacts the converging surfaces of the dies, creating high forces normal to the die surface. The dies react to these forces by pushing back on the workpiece, causing a compressive stress state to exist in the deforming region of the metal. Thus although the equipment action is of a tensile (pulling) nature, the plastic deforming region is being squeezed.

It should be noted that although the stress state for bulk deformation is compressive, there are situations where tensile stress components may be present within the workpiece and fracture may occur. The metal-forming engineer needs to be aware of these types of situations and to properly design the process to avoid the potential fracturing that can occur on the workpiece due to the tensile stress components. For example, in the forging of a right circular cylinder between two flat dies in the axial direction, if friction on the top and bottom surfaces is high, the sides of the cylinder will bulge and some tensile hoop stress may occur on the outside surface of the workpiece. A more insidious example is an extrusion process where a small reduction is performed through a die with a high die angle. For this situation, the deformation region may be limited to the surface region of the workpiece, causing some internal tensile stress components along the centerline of the workpiece. If the internal tensile stress components become excessively high, they can cause an internal fracture in the workpiece. This fracture is referred to as central burst. The worst aspect of central burst is that it cannot be detected via visual methods.

## III. TYPES OF BULK DEFORMATION PROCESSES

### A. Forging

Forging is a metalworking process where a workpiece is shaped by compressive forces using various dies and tools. The forging process produces discrete parts. Some finishing operations are usually required. Similarly shaped parts can often be produced by casting or powder metallurgy operations, but the mechanical properties of a forged component are usually superior compared to other processing methods. Forging can be done hot or cold. Warm forging is a process that is growing in popularity due primarily to thermal energy costs. Typical forged parts are shown in Fig. 1.

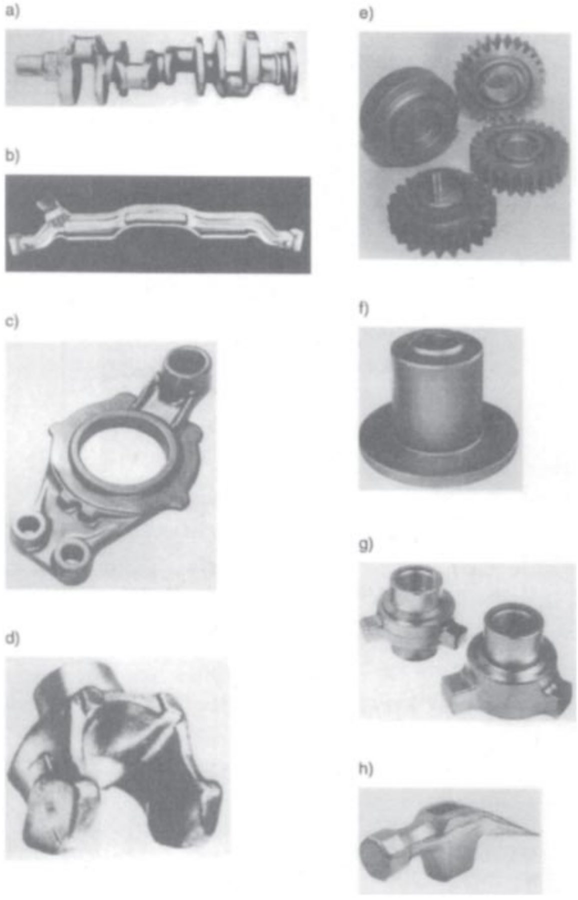

**Figure 1** Examples of forged parts: (a) automotive crankshaft; (b) truck axle; (c) truck bracket; (d) universal joint; (e) automotive gears; (f) truck assembly part; (g) coupling fittings; and (h) hammer head. (From Ref. 1.)

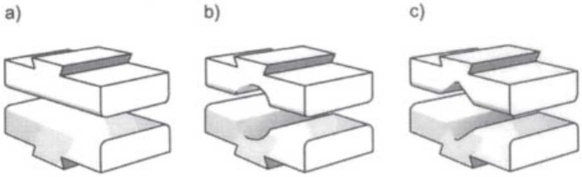

**Figure 2** Open die forging tools: (a) flat dies; (b) U-shaped dies; and (c) V-shaped dies. (From Ref. 2.)

Open die forging consists of dies with very simple geometry. The dies are usually flat, U-shaped, or V-shaped, as seen in Fig. 2. The shaping of the metal occurs through manipulation of the workpiece and skill of the operator. It is a process that is useful in producing a small number of pieces. It is difficult to hold to close tolerance in this type of forging. Open die forging between two flat dies is often called upsetting. Cogging or drawing out is an open die forging process where the thickness of the workpiece is reduced by successive small strikes along the length of the metal. Open die forging is closely related to blacksmithing.

Closed die or impression die forging consists of a die set with a machined impression, as shown in Fig. 3. There is good use of metal in this operation as compared to open die forging. Excess metal beyond the size needed for forging is used and flows into the gutter portion of the die set to produce flash. The excess metal helps to insure that the cavities are completely filled at the end of the press stroke. Good tolerances and accuracy of the final forging are attainable. The die costs for closed die forging are fairly high due to their property requirements and machining costs.

Closed die forging often occurs in a sequence of steps. Each step of the operation usually has its own impression in the die block. The first step distributes metals into regions where extra volume is required in the final component. This step often involves edging, where extra metal is gathered, or fullering, where metal is moved away from the local region. In hot forging, the first step is referred to as busting because the scale on the surface of the workpiece is busted off. The second step is blocking, where the part is formed into a rough shape. The third step is finishing, where the final shape of the component is imparted to the workpiece. The fourth step is trimming, where the excess metal in the flash region is trimmed from the component. Figure 3 illustrates these various steps.

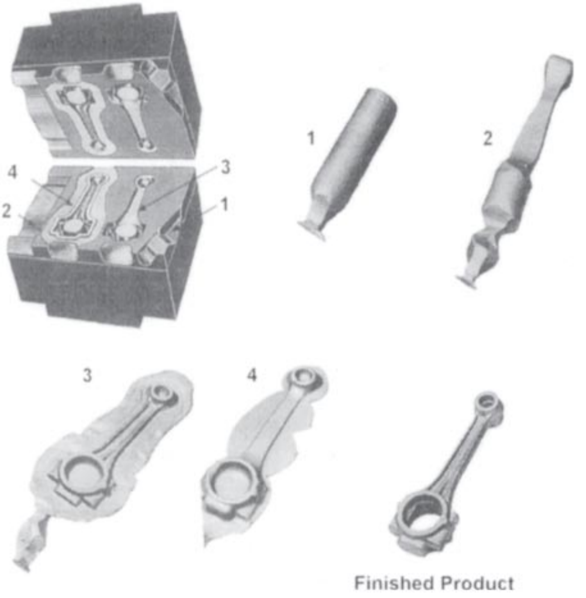

**Figure 3** Impression forging dies with forging sequence. (From Ref. 3.)

The machines used for forging are hammers and presses. Hammers are energy-limited equipment and can be a simple gravity drop machine where a free-falling ram strikes the workpiece. Augmentation of the energy supplied to the hammer can be done in the form of pressured air, steam or hydraulic fluid. In a hot closed die operation, multiple blows are usually needed during each step, especially the blocking and finishing steps, when using a hammer to forge metal. Table 1 provides some numerical details about hammers for a typical gear blank forging.

For forging, there are three types of presses used—mechanical press, hydraulic press, and screw press. Mechanical presses are stroke-limited equipment with a large flywheel powered by an electrical motor. The up-and-down motion of the ram is handled via a connecting rod attached to a crank shaft. The travel distance during each press stroke is controlled by machine design and operation. Hydraulic presses are load-limited equipment where the press will stop once its load capacity is reached. The power comes from pressurized hydraulic fluid. Screw presses, similar to hammers, are energy-limited equipment. A large flywheel transmits power through a vertical screw, which causes the ram to move. The ram movement stops when all the energy from the flywheel has dissipated. Table 2 provides some numerical details about hydraulic presses to produce the same gear blank as in Table 1.

In order to be successful in forging a metal, the formability of the metal needs to be understood, especially with regard to temperature and speed. The impression die shape needs to be carefully designed and machined to allow a good flow of metal without seams or laps developing. The die material needs to be carefully chosen to match the metal being shaped and the temperature of the operation.

## B. Extrusion

Extrusion is a bulk deformation process where a billet, generally cylindrical, is placed in a chamber and forced through a die. The die opening can be round to produce a cylindrical product, or the opening can have a variety of shapes. Typical extrusion products are shown in Fig. 4. Because of the large reductions imparted during the extrusion process, most extrusion processes are performed hot in order to reduce the flow strength of the metal. Cold extrusion can occur but it is usually one step in a multistep cold forging operation.

Forward or direct extrusion is where the billet is pushed from the backside and the front side flows

**Table 1** Characteristics of Hammers for Forging a 4.45-lb Steel Gear Blank

| Hammer size | Process time (sec) | Minimum part temperature (°F) | Maximum part temperature (°F) | Die temperature (°F) | Load (tons) |
|---|---|---|---|---|---|
| 4000 lb, 1 blow | 0.003 | 2143 | 2359 | 502 | 850 |
| 2500 lb, 3 blows | 2 | 2110 | 2219 | 418 | 874 |
| 1500 lb, 6 blows | 5 | 2031 | 2158 | 506 | 818 |
| 1000 lb, 12 blows | 11 | 1970 | 2117 | 553 | 389 |

Temperature buildup in dies is lower than press systems.
A 4000-lb hammer had 40% of initial energy available.
Good uniformity of temperature in part.
*Source:* Ref. 4.

**Table 2** Characteristics of Hydraulic Presses for Forging a 4.45-lb Steel Gear Blank

| Press size | Process time (sec) | Minimum part temperature (°F) | Maximum part temperature (°F) | Die temperature (°F) | Load (tons) |
|---|---|---|---|---|---|
| 250 tons, slow | 1.6 | 1458 | 2159 | 1233 | 250 |
| 500 tons | 0.75 | 1533 | 2181 | 1164 | 500 |
| 1000 tons | 0.33 | 1639 | 2194 | 1072 | 676 |
| 2000 tons, fast | 0.18 | 1721 | 2198 | 996 | 705 |

Two-hundred-fifty-ton press stalled and left underfilled on outer diameter.
Fast 2000-ton press is similar to mechanical or screw press.
Smaller presses resulted in increased die temperature.
*Source:* Ref. 4.

through the die. Indirect or inverse or backward extrusion is where the die, which imparts shape, moves into the billet. The equipment used to perform an indirect extrusion is more complex than for a forward extrusion. To overcome the significant friction resistance between the billet and the chamber in a forward extrusion, hydrostatic extrusion has been developed. In hydrostatic extrusion, the billet is smaller than the chamber and is surrounded by hydraulic fluid. The hydraulic fluid is pressurized, which squeezes the billet through the die opening. Caution with both the sealing of the fluid and at the end of the process, where the final part of the billet could become a high-velocity projectile, needs to be exerted. Impact extrusion is similar to indirect extrusion and is often performed cold. The tooling, usually a solid punch, moves rapidly into the workpiece, causing it to flow backward and around the face of the punch. This produces a tubular-shaped type of product. These types of extrusions are schematically shown in Fig. 5.

The equipment for extrusion is normally a horizontal hydraulic press. A large shape change is imparted to the billet during a single stroke of the press. The shape change causes significant distortion in the metal during the deformation.

For success in extrusion, the temperature and speed of the process need to be determined based on the formability of the metal being deformed. Excessive temperature, speed, or friction can cause surface cracks to propagate along grain boundaries, which are referred to as fir tree cracking, due to hot shortness of the metal. Improper geometrical configuration of the tooling can cause central bursts if the angle of the die opening is too large, or the reduction is too small. Piping or cavitation at the end of the extrusion can be minimized by reducing the severity of the distortion in the product, or by reducing friction.

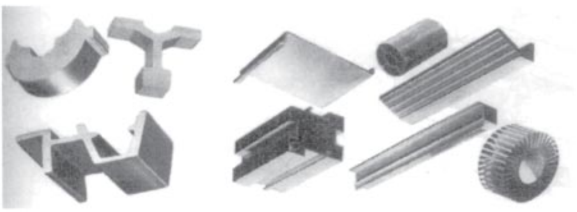

**Figure 4** Examples of extruded parts. (From Ref. 5.)

## C. Rolling

Rolling is a direct compression deformation process, which reduces the thickness or changes the cross section of a long workpiece. The process occurs through a set of rolls, which supply the compressive forces needed to plastically deform the metal. Flat rolled products are classified as plate, sheet, or foil, depending on the thickness of the product. A plate has thickness greater than 6 mm, whereas a foil has thickness less than 0.1 mm. A sheet has thickness between that of the plate and the foil. Rolling can be done hot or cold. In many products, initial reductions are performed hot, where the metal can experience large shape changes without fracturing, and the final reductions are performed cold, so that better surface finish and tolerances can be achieved.

Flat rolling reduces the thickness of the metal, producing a product with flat upper and lower surfaces. Shape rolling can also reduce the thickness of the metal but, more importantly, it imparts a more complex cross-section shape. Shape rolling can be used to produce bars, rods, I-beams, channels, rails, etc. Ring rolling can be used to produce a seamless product by reducing the wall thickness of a ring through the action of two rolls. Seamless pipes can be produced and sized by specialized rolling operations such as rotary tube piercing, tube

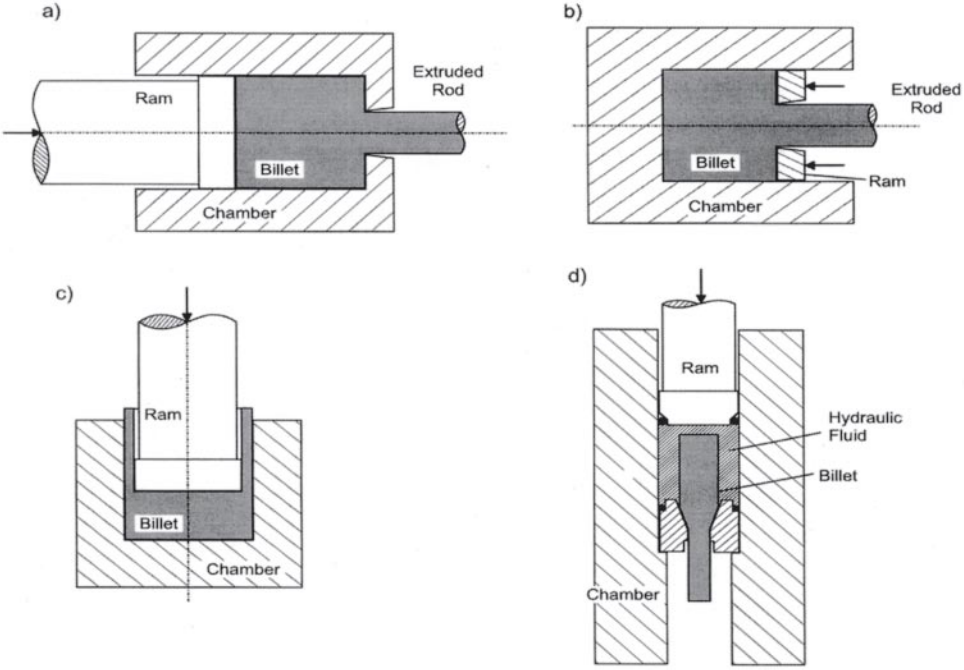

**Figure 5** Schematics of extrusion processes: (a) direct or forward extrusion; (b) indirect or reverse extrusion; (c) impact extrusion; and (d) hydrostatic extrusion. (From Ref. 6.)

rolling, and pilgering. A variety of rolling processes for steel are schematically shown in Fig. 6.

Although large, the rolling mill equipment is relatively simple. A two-high mill consists of two rolls, and a three-high mill consists of three rolls, which also allows reduction to occur on reverse directional flow of the metal. A four-high mill consists of two work rolls in contact with the metal and two back up rolls. A six-high mill is like a four-high mill, but has two additional rolls between the work roll and backup roll called intermediate rolls, which allow in essence some control over the crown and camber of the work rolls. Cluster mills exist usually for the production of thin foil products. A cluster mill will have a pair of small-diameter work rolls and a series of intermediate and backup rolls to support the work rolls. A tandem rolling mill will have a series of rolling stands where each stand imparts a specific amount of reduction. The operation of a tandem mill is challenging due to coupling effects between the stands.

Defects can be present in sheet and plate products if the rolling operation is not performed correctly. Wavy edges, waves along the centerline, zipper cracks along the centerline, or edge cracks can occur if the reduction is not uniform across the width of the metal. Crowned rolls, six-high mills, and sleeved rolls can be used to correct these types of defects by properly controlling the amount of roll bending that occurs. Small amount of waviness in a sheet product can be eliminated by a postdeformation leveling operation, where the sheet passes over a series of rollers while under tension. Alligatoring or fish tails can occur at the front end or back end of the workpiece. Proper alignment of the feed stock into roll gap, proper balancing of the friction between the top and bottom rolls, and proper choice of roll size for reduction can be used to minimize or to eliminate these two types of defects.

## D. Drawing

Drawing of a round rod or wire is an indirect compression process where the cross-sectional area of the metal is reduced by pulling it though a converging die. A schematic illustration of wire drawing is seen in Fig. 7. The process is normally done at ambient temperatures. The major factors that need to be controlled include: reduction, die angle, friction at the die-workpiece interface, and drawing speed. Tubes can also be drawn in a similar process. To control

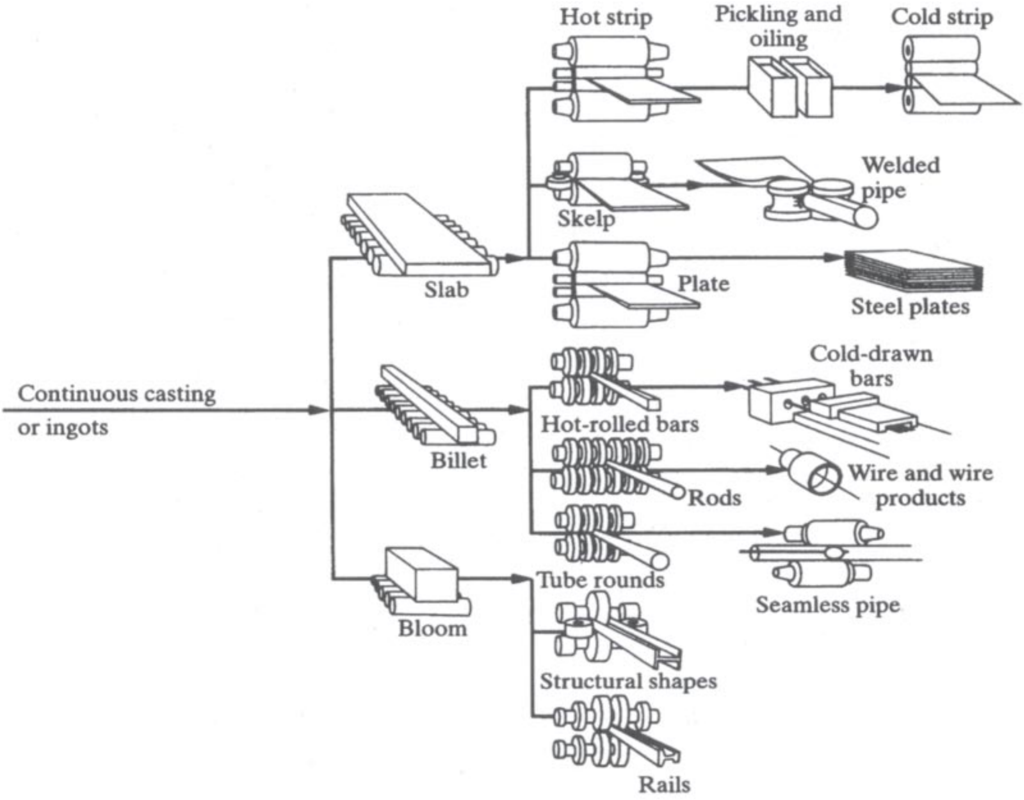

**Figure 6** Schematics of various rolling processes for steel. (From Ref. 7.)

the interior diameter of a tube, a mandrel, which can be fixed, moving, or floating, is used. Because the metal is pulled through the die, the final product, which has the reduced cross section, is subjected to tensile stresses. If these tensile stresses become excessive, then the wire would fracture in a mode similar to a tensile test. The limit on the value of the tensile stress that can be supported limits the amount of reduction that can be achieved in one pass. Multiple reduction passes with multiple dies are needed to achieve large reductions in cross-sectional areas. The approach is analogous to a tandem rolling mill with multiple stands. The theoretical maximum reduction for a frictionless, perfectly plastic material is 63%. In production processing, the reduction that is used is often limited to 35% or 40%. The ironing process, which is used to reduce the wall thickness of a sheet metal, is also a drawing-type operation.

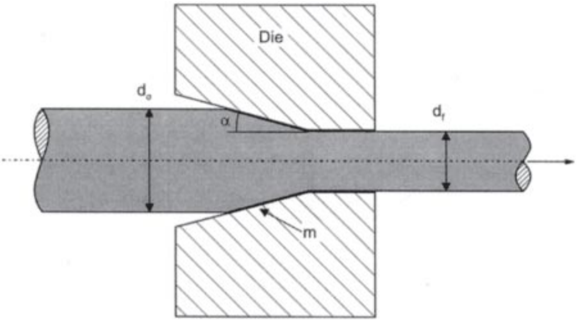

**Figure 7** Schematic of a wire drawing process.

The configuration of the opening in the final die will control the configuration of the product produced. Although a cylindrical shape is the most common, other shapes can be imparted to the wire in the process.

The metal is cold-worked during the wire drawing process and intermediate anneals may be needed to increase its ductility to sufficient levels in order to reach the final reduction desired. Internal fractures, called central busts, can occur if the die angle is too large, or the reduction is too small. For rods, tubular products, or high-strength wires, postdeformation straightening may be required.

## IV. PROCESSING ASPECTS

### A. Temperature

In bulk working operations, thermal energy is often supplied to the workpiece to increase its temperature. There are a number of methods used to heat up metal workpieces. Heating in a gas-fired furnace, induction heating, and electrical resistance heating are the most common methods that are used in industries. The operation and control of the heating process are critical features in controlling the deformation process. The workpiece needs to be at the proper working temperature in order to achieve the desired shape change and to have the proper microstructure for deformation.

The deformation in the workpiece is produced by mechanical work. Most of the mechanical work imparted into the workpiece during deformation is converted into heat. The heat causes the workpiece to increase in temperature. The maximum possible increase in temperature is often referred to as adiabatic heating and is calculated by assuming that the entire amount of mechanical work is converted in the temperature rise. The adiabatic temperature rise for a bulk deformation process can be calculated by:

$$\Delta T = \frac{W}{\rho C_{\mathrm{P}}} \tag{1}$$

where $W$ is the mechanical work per unit volume for the deformation process, $\rho$ is the density of the workpiece, and $C_{\mathrm{P}}$ is the heat capacity for the workpiece.

### B. Strain

During bulk plastic deformation, a shape change is imposed on the workpiece. Strain is the normal measure to quantify the amount of deformation. In operations such as rolling, extrusion, and wire drawing, the cross-sectional area $A$ of the workpiece normally decreases as the length $L$ increases. In forging, the opposite usually occurs where the cross-sectional area increases and the height $h$ of the workpiece decreases.

In most forming operations, the volume of the workpiece remains constant. The constancy of volume is expressed as:

$$A_0 L_0 = A_1 L_1 \tag{2}$$

Plastic deformation is often measured by the engineering strain:

$$e = \frac{L_1 - L_0}{L_0} = \frac{A_0 - A_1}{A_1} \tag{3}$$

or by the true strain:

$$\varepsilon = \ln\left(\frac{L_1}{L_0}\right) = \ln\left(\frac{A_0}{A_1}\right) = \ln(e + 1) \tag{4}$$

Often the measure of deformation for bulk deformation processes is expressed by the reduction in area:

$$R = \frac{A_0 - A_1}{A_0} \tag{5}$$

For forging, the equations will be similar:

$$A_0 h_0 = A_1 h_1 \tag{6}$$

$$e = \frac{h_0 - h_1}{h_0} = \frac{A_1 - A_0}{A_1} \tag{7}$$

$$\varepsilon = \ln\left(\frac{h_0}{h_1}\right) = \ln\left(\frac{A_1}{A_0}\right) = \ln(e + 1) \tag{8}$$

It should be noted that these equations are simplified measures for strain during the process. In bulk deformation, the strain in the workpiece will usually vary from point to point, and for a continuous-flow process, the strain will also vary at each time instant in the process. In its true form, strain is a second-order tensor, which, during deformation, has six unique components—three normal components and three shear components. In deformation operations, strain is often expressed by its three principal components $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$. For deformation processes, which have undergone proportional loading, the effective strain at a point in the workpiece is often given by the Mises equivalent strain:

$$\bar{\varepsilon} = \sqrt{\frac{2}{3}\left(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2\right)} \tag{9}$$

### C. Strain Rate

During deformation processes, the speed of the operation is usually measured by strain rate. Strain rate $\varepsilon$ is the time rate of the change of strain:

$$\dot{\varepsilon} = \frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \frac{1}{L}\frac{\mathrm{d}L}{\mathrm{d}t} = \frac{v}{L} \tag{10}$$

where $v$ is the velocity.

Strain rate is an important variable because the strength and microstructural response of many metals is dependent on the strain rate. Like strain, strain rate in its true form is also a second-order tensor. The effective strain rate at a point in the workpiece can be expressed as:

$$\dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}\left(\dot{\varepsilon}_1^2 + \dot{\varepsilon}_2^2 + \dot{\varepsilon}_3^2\right)} \tag{11}$$

where $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, and $\dot{\varepsilon}_3$, are the principal strain rate components of the strain rate tensor.

## D. Stress

In bulk deformation operations, stress has two meanings. The first meaning of stress is related to the equipment used to deform the workpiece. It is a measure of the load requirements necessary to get the workpiece to plastically deform. This is an important aspect that needs to be considered because the sizing of the equipment for bulk deformation is fundamentally dependent on the load requirements for plastic flow.

The second meaning of stress is related to the workpiece. During deformation, each point in the workpiece has a stress state, which is a measure of the materials' internal resistance to the externally supplied forces. These two meanings are interrelated.

In bulk metalworking operations, the external loads supplied are often compressive in nature. Wire drawing is an exception, where the supplied load is a tensile force. For compressive deformation processes, the pressure required for deformation usually describes the external stress. The pressure can vary from point to point along the tool-workpiece interface, often due to the friction resistance present. An average pressure for deformation to occur is:

$$p_{\mathrm{AVG}} = \frac{F}{A} \tag{12}$$

where $F$ is the force or load supplied by the equipment, and $A$ is the area over which the load is being supplied. For wire drawing, a similar equation can be used, but it determines the average drawing stress on the wire being pulled through the die:

$$\sigma_{\mathrm{AVG}} = \frac{F}{A} \tag{12}$$

The internal resistance within the workpiece to these external loads varies from point to point. The measure of this resistance is the internal stress that exists in the workpiece. If the specific point in the workpiece undergoes plastic deformation, then the internal stress is equal to the flow strength of the material at that point.

Internal stress, such as strain and strain rate, is a second-order tensor. This second-order tensor has six components—three normal components and three shear component. The stress tensor is often expressed in terms of the three principal components $\sigma_1$, $\sigma_2$, and $\sigma_3$.

The effective stress at a point within the workpiece is given by:

$$\bar{\sigma} = \sqrt{\frac{1}{2}\left((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right)} \tag{14}$$

If the effective stress at a point within the workpiece has reached the value of the flow strength of the material at that point, then plastic flow will occur.

If the effective stress and effective strain are known for the deformation process, then the work per unit volume of material for deformation $W$ can be determined by

$$W = \int \bar{\sigma}\,\mathrm{d}\bar{\varepsilon} \tag{15}$$

Another important stress measure is the mean stress component or hydrostatic stress component:

$$\sigma_{\mathrm{M}} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{16}$$

For deformation processes, the stress components must be of a sufficient deviation from the hydrostatic stress to cause plastic flow to occur. A pure hydrostatic stress cannot cause plastic flow to occur within a normal material.

## E. Friction

During bulk deformation processes, frictional resistance to sliding occurs at the interface between the workpiece and the tooling. The frictional resistance is due to the surface asperities that are present at the microscale on both the tools and the workpiece. These asperities impede the sliding motion that can occur during contact under pressure. Figure 8 schematically shows how the asperities interact to impede motion.

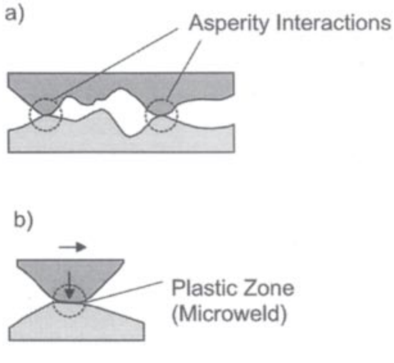

**Figure 8** Schematic of frictional resistance and wear on sliding metal surfaces: (a) interactions of asperities; and (b) localized plastic deformation. (From Ref. 8.)

Friction causes the required deformation loads to increase. Friction causes the flow of the material to be less homogeneous. High levels of friction can result in surface damage to the workpiece, or seizing of the workpiece to the tooling.

Frictional resistance is usually described by a shear stress component $\tau_F$. There are two basic models that are used describe the frictional stress component that occurs during metalworking operations. Both of these models are highly simplified and only capture the major aspect of the very complex interaction that occurs at the tool-workpiece interface.

The first model is referred to as Coulomb's law. The frictional stress component is directly proportional to the pressure that exists between the tool and the workpiece at the point of interest, or:

$$\tau_F = \mu p \tag{17}$$

where $\mu$ is the coefficient of friction. The value of $\mu$ can vary from 0 to $1/\sqrt{3}$ (i.e., 0.577). At low-pressure levels, this equation is a good description of the frictional stress component.

The second model is a better description at higher pressures at the interface. It is referred to as the constant friction factor equation. It assumes that the frictional stress component is some fraction of the flow strength $\sigma_o$ of the workpiece:

$$\tau_F = m\frac{\sigma_o}{\sqrt{3}} \tag{18}$$

where $m$ is the constant friction factor. The value of $m$ can vary from 0.0 for an ideal frictionless interface to 1.0 for an interface where full sticking between the workpiece and tool occurs.

Friction is controlled through lubrication. The role of the lubricant in metalworking is important in reducing frictional resistance. Lubrication can also play a vital role in cooling the tooling, preventing heat flow from a hot workpiece into the tooling and protecting the new surfaces created during the deformation from oxidation or chemical reactions.

## F. Yield Criteria

The ease with which a metal flows plastically is an important factor in deformation processes. The dominant factors that influence the flow (or yield) strength of a metal are the temperature and the amount of prior cold work. Yield criterion is the relationship between the stress state and the strength of the metal. When the criterion is met, then plastic deformation occurs. In uniaxial tensile tests, the yield criteria predict that flow will occur when the uniaxial tensile stress reaches the metals' yield strength. For bulk deformation processes, the stress state is not a simple uniaxial state, hence the criteria for yielding are more complex relationships.

The Tresca yield criterion or maximum shear stress criterion indicates that plastic flow will occur when:

$$\tau_{\max} = \frac{1}{2}(\sigma_1 - \sigma_3) = \sigma_o \tag{19}$$

where $\sigma_1$ is the largest principal component of the stress state, $\sigma_3$ is the smallest principal component of the stress state, and $\sigma_o$ is the flow strength of the metal. If Eq. (19) is satisfied, then plastic deformation will occur.

A more generally applicable criterion is the Mises criterion or maximum distortion energy criterion, which is:

$$\sqrt{\frac{1}{2}\left((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right)} = \sigma_o \tag{20}$$

Other criteria for the relationship between the applied stress state and the flow strength of the metal, which can cause plastic deformation, do exist, but the two equations given here are the ones most often used to describe bulk deformation processes.

In three-dimensional principal stress space, both yield criteria will plot as surfaces. Thus the yield criteria are often called the yield surface for the metal. The surface for the Tresca yield criterion is a hexagonal-shaped prism, whereas the surface for the Mises yield criterion is cylindrical. If $\sigma_3$=0, then the yield surface reduces to yield loci curves in the two-dimensional $\sigma_1$-$\sigma_2$ space. Figure 9 shows the relationship between the Tresca and Mises yield criteria in this reduced two-dimensional space.

## G. Hardening

During cold work, the metal increases in strength with increased deformation. This phenomenon is referred to

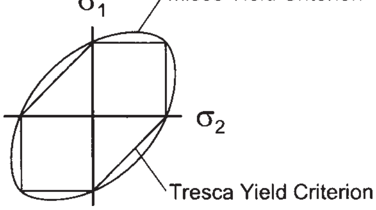

**Figure 9** Comparison of Tresca and Mises yield criteria in reduced principal component stress space.

as hardening. Plastic hardening in metals is often reasonably well characterized by a power law equation, where the strength is dependent on the amount of plastic strain imposed:

$$\sigma_o = K\bar{\varepsilon}^n \tag{21}$$

where $K$ is a strength coefficient for the hardening behavior and $n$ is the strain hardening exponent. These two material parameters are usually obtained via a tensile or a compression test. Equation (21) indicates that the metal strengthens as the strain increases, which is isotropic hardening. In isotropic hardening, the yield surface is continually expanding with strain. If the strain path imposed on the metal during deformation is changed (e.g., if it is reversed), the yield strength on reversal may be different than expected for the strain imposed before the change. This difference is a manifestation of kinematical hardening, where the center point of the yield surface moves with strain. Figure 10 shows the difference between the yield surface changes that occur for isotropic hardening as compared to kinematical hardening.

## V. DESIGN ISSUES TO PREVENT FAILURES

### A. Geometrical and Mechanics Issues

The shape of the tooling and the initial shape of the workpiece are important geometrical factors for bulk deformation processes. Incorrect choices of these geometrical factors can lead to problems during deformation, or lead to process-induced defects in the final product being produced.

In extrusion, rolling and drawing the size and shape of the deformation zone have a strong influence on a variety of forming parameters, such as friction work, redundant work, and deformation loads, as well as properties in the formed part, such as internal porosity, internal cracking, distortion, homogeneity of strength, and residual stresses. A common single parameter measure of the deformation zone geometry is the Δ parameter. The Δ parameter is defined as the ratio of the average thickness or diameter $h$ of the deformation region to the contact length $L$ between the tooling and the workpiece, or:

$$\Delta = \frac{h}{L} \tag{22}$$

It has been found that deformation under conditions of high Δ parameters can lead to microporosity along the center line of the workpiece, or, in extreme cases, can lead to internal cracks. Caution needs to be used when $\Delta > 2$ because it is this condition that can lead to problems. Figure 11 shows data from an extrusion process that exhibit both sound flow behavior and central burst.

Flow localization can occur in the workpiece during deformation. The common cause of flow localization is a dead metal zone between the workpiece and the tooling. Poor lubrication in forging can cause sticking friction

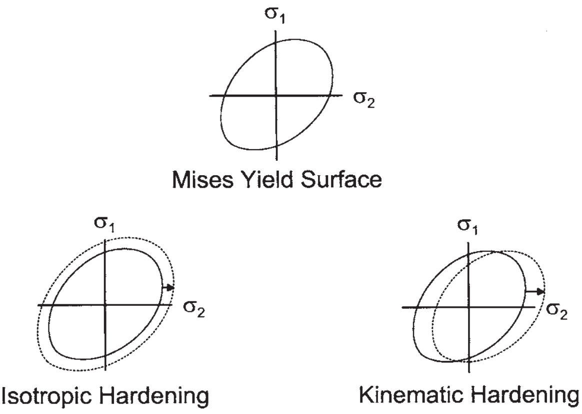

**Figure 10** Comparison of isotropic hardening to kinematical hardening for a Mises material in reduced principal component stress space.

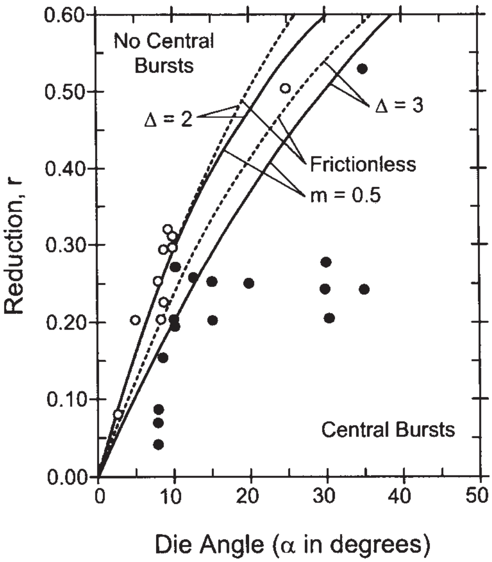

**Figure 11** Criteria of the prevention of central burst in extrusions. (From Ref. 9.)

between the die and the workpiece, and in the sticking region, a dead metal zone can occur. Forging dies, which are cooler than the workpiece, can extract heat from the metal, causing localized cooling. The metal at a lower temperature has higher flow strength and is more resistant to plastic deformation, which can lead to a dead region in the workpiece. In extrusion, dead metal zones can occur due to very large die angles and the metal will shear over itself, leaving a dead metal region adjacent to the die.

In closed die forging, the width and thickness of the land region are very important parameters. The land region is the choke point for metal flowing into the flash region of the forging. As multiple parts are forged, the land will wear away. The small thickness and large width of the land opening provide restrictive flow into the flash and cause increased pressure to occur in the die cavity. The increased pressure in the cavity allows for better filling of the impression, but at the cost of higher load requirements. If the flow of the metal inside of a cavity during forging is not properly controlled, a lap, a flow-through defect, or a suck-in defect may occur. A lap is where the metal folds back on itself. A flow-through defect occurs when the metal is forced to flow across a recess in the die that is already filled. A suck-in defect occurs when there is too much metal flow into a centrally located rib region. These types of defects can be avoided or minimized by proper redesign of the die cavity.

### B. Metallurgical and Microstructure Issues

The common failure modes that occur in cold work deformation processes include: free surface cracking, shear bands, shear cracks, central bursts, and galling. In hot work processes, the common failures are hot shortness, central bursts, triple-point cracks, grain boundary cavities, and shear bands. Metallurgical aspects and microstructure features can have a strong influence on the tendency of the workpiece to experience one of these failure modes.

Because of the segregation and cast microstructure in ingots, these types of workpieces need to be hot-worked. Due to chemical segregation and microstructural inhomogeneities, the properties of an ingot are not constant from one location to another. Care must be taken to provide enough deformation to break down the cast structure. Low melting point phases may also be present and can lead to hot shortness if the temperature during deformation is not carefully controlled.

Hot working can lead to creep-type fractures, especially at slower working speeds in metals with low workability. It is also important not to let the workpiece be locally chilled during hot working processes. Chilling can lead to strength variations in the metal and cause the promotion of shear banding.

Cold working causes the strength of the workpiece to increase during deformation. Thus regions where significant cold work has been imparted to the metal are regions of higher strength. These strength variations can lead to internal shear banding. The grain size of the workpiece also can have an influence on the final product produced. Working of large grained metals can lead to a surface roughening phenomenon called orange peel, which is usually undesirable.

## VI. WORKABILITY AND TESTING METHODS

### A. Definition

Workability is a characteristic that is usually attributed to the metal or alloy. It is a relative measure of how easily the metal can be plastically deformed without fracture. It should be noted that workability depends not only on the metal itself, but also on other external processing factors. The temperature and stress state imposed by the processing conditions will strongly influence workability. Most metals have high higher workabilities at higher temperatures. Workability is usually higher under compressive states of stress as compared to tensile states. Terms such as formability, forgeability, extrudability, and drawability are often used to describe the workability within a specific metal-forming process.

### B. Tests

A number of different mechanical tests are used to assess the workability of a metal or alloy. The best test is the one that most closely mimics the actual stress state that would exist in the metal during the bulk deformation operation. Unfortunately, the optimum is often not the easiest one to perform on the amount of material available, or is constrained by the type of laboratory testing equipment available for use.

#### *1. Tensile Tests*

The tensile test is the most common test used to evaluate the mechanical properties of a metal or alloy. The tensile test can be set at a variety of speeds to study strain rate effects and a variety of temperatures to study the properties of the metal as a function of temperature.

In a tensile test, a specimen of known initial geometry is placed in testing apparatus and pulled until fracture. The pulling load and the tensile elongation are measured throughout the test with a strip chart or computerized data acquisition. Load and elongation are converted into engineering stress-strain data. From the engineering stress-strain curve elastic modulus, the yield strength, ultimate tensile strength, fracture stress, and tensile elongation can be determined. Figure 12 shows a typical engineering stress-strain curve for a metal. After the test specimen is removed from the testing apparatus, the final cross-sectional area in the fracture region can be measured and the reduction in area can be calculated. The reduction in area and the tensile elongation are the two primary measures for the ductility of the metal. The ductility determined from a tensile test is for the tensile stress state, temperature, and strain rate imposed on the specimen during the testing.

The engineering stress-strain curve can be transformed into a true stress-true strain curve for the metal. The transformation is valid between the yield point and the ultimate point, where uniaxial plastic deformation occurs and localized necking has not occurred. The data from a true stress-true strain curve can be plotted on a log-log scale. From such a plot, the slope is the strain hardening exponent *n* and the intercept is the logarithm of the strength coefficient *K*.

## 2. Torsion Tests

The torsion test is a fairly straightforward process. The specimen is held fixed on one end and the other end is twisted at a constant angular velocity. The torque needed to twist the sample and the angle of twist are the measured parameters. The deformation is caused by pure shear and large strains can be achieved without flow localization and necking, which occurs in a tensile test, or barreling, which occurs during a compression test. The test is suitable in providing flow stress and ductility data for materials as a function of strain, strain rate, temperature, and prior processing. The test is frequently used to determine these material properties under hot working conditions. Because the strain rate imposed on the material is proportional to the rotational speed of the test, high strain rates (up to $10^3$ $\text{sec}^{-1}$) are obtainable in a torsion test.

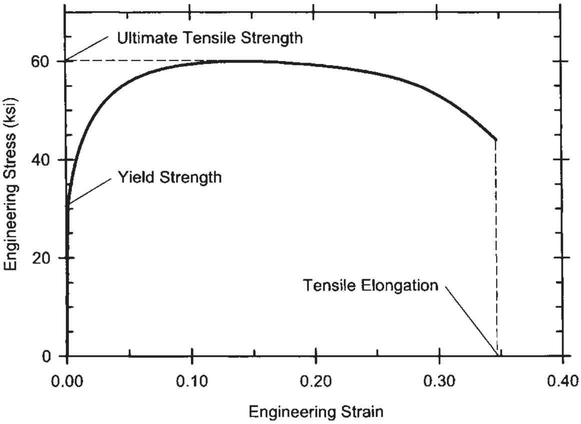

**Figure 12** Engineering stress-strain curve from a uniaxial tensile test with material properties indicated.

Because a torque is being applied to the specimen during the torsion test, the stress state in the material will vary from the centerline to the surface of the specimen. The variation in stress state in a torsion-tested specimen is in contrast to the tensile and compression tests where the stress state in the deforming region of the specimen is relatively uniform. The analysis of the torque twist data to produce stress-strain curves for the material needs to be done carefully, with an understanding of the test itself.

## 3. Compression Tests

Because most bulk deformation processes involve compressive states of stress, a compression test is often more desirable in assessing the workability of a metal that will be deformed by such a process. In theory, the compressive force imposed on the metal during a compression test creates a uniaxial stress state within the metal. If this were the case, then the analysis of the experiment would be handled in a manner similar to the data acquired via a tensile test. Unfortunately, the existence of a uniaxial stress state in a compression sample is not achieved because the specimen is compressed between two flat platens. The compression causes the cross-sectional area to increase and the friction that exists at the top and bottom surfaces, where the specimen is in contact with the platens, causes nonuniform flow. The unconstrained sides of the sample will show the nonuniform flow by bulging. A bulged sample is a clear indication that the stress state was not uniaxial.

To overcome this difficulty with friction, a variety of specimen geometries have been used, as shown in Fig. 13. Each specimen is compressed and the compressive strain in the axial direction and the diametrical strain are measured. Measurement is usually performed by imposing a grid onto the side surface of the specimen and periodically stopping the test to measure the change in dimensions of the grid pattern. When a cylindrical specimen is compressed, the strain path that it follows can be

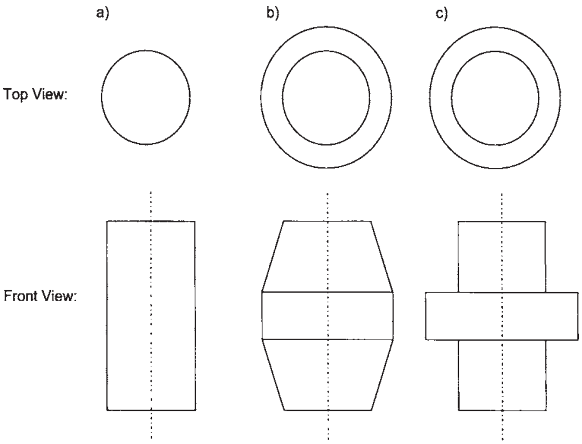

**Figure 13** Schematics of compression test specimen geometries: (a) cylindrical sample; (b) tapered sample; and (c) flanged sample. (From Ref. 10.)

different, as shown in Fig. 14. The specimens are compressed until fracture occurs to assess the metals' workability during compression and produce a forming limit curve. Typical fracture curves (or forming limit diagrams) for 1020 steel, 303 stainless steel, and 2024-T351 aluminum are shown in Fig. 15.

### 4. *Friction Tests*

The most common method used to determine the friction factor for a forging process is the ring compression test. The test can be conducted at varying temperature and speed, and with the lubricant and workpiece material of interest. The workpiece material is machined into a ring with dimensions usually in a 6:3:2 ratio of the outer diameter to the inner diameter to the thickness. The ring is compressed in the thickness direction to a given level of deformation and the new inside diameter is measured. Friction calibration curves can be used to determine the friction factor from the amount of deformation imparted to the ring and the change in inner diameter (Fig. 16). Rings of other dimensions can be used but the appropriate calibration curves must be used for the specific starting geometry.

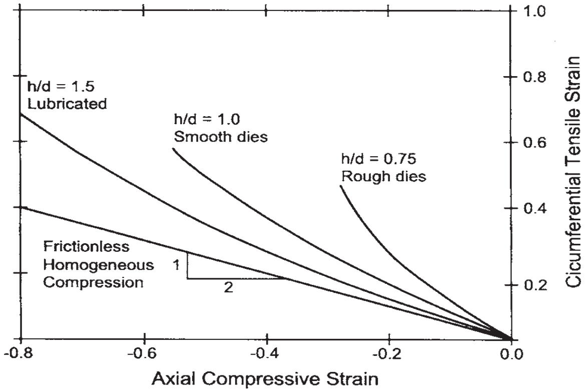

**Figure 14** Strain paths for compression tests of cylindrical specimens with various height *(h)*-to-diameter *(d)* ratios and various lubrication conditions. (From Ref. 11.)

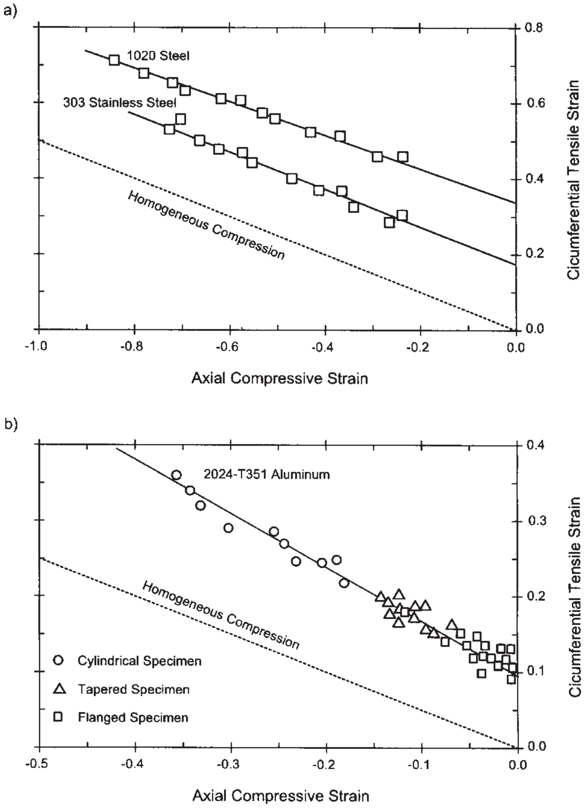

**Figure 15** Cold upset compression failure criteria: (a) 1020 steel and 303 stainless steel; and (b) 2024-T351 aluminum. (FromRef. 11.)

## VII. DEFORMATION MODELING METHODS

A diagram illustrating the input and output as well as the constraints, which must be considered when trying to model a bulk deformation process, is shown in Fig. 17.

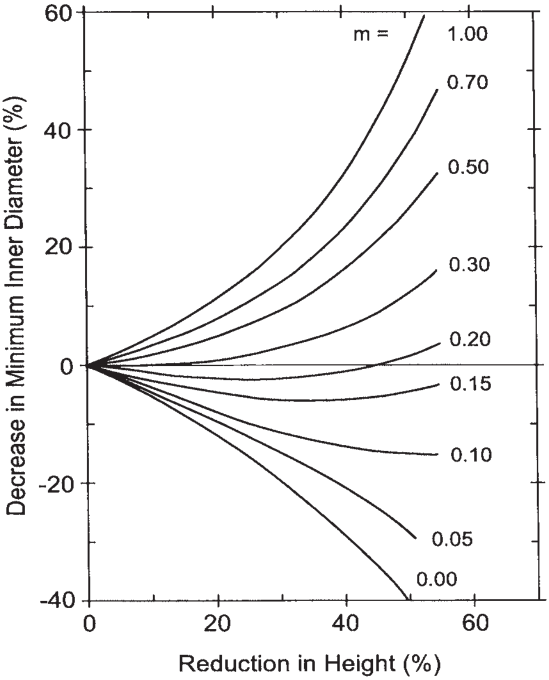

**Figure 16** Ring test calibration curve for the determination of constant friction factor for rings with a 6:3:2 geometrical ratio of outer diameter/inner diameter/height. (From Ref. 12.)

The input parameters fall into three major categories—geometrical parameters, process parameters, and material parameters. Constraints imposed by either the product requirements or by the equipment should also be considered and incorporated into the model. Often models flag situations where one of the constraints is exceeded, rather than directly imposing the constraints.

The result of the modeling effort is the determination of process geometry and process performance conditions. Models, especially if they are complex and account for the fine details of the process, can take a long time to run and often the results cannot be determined in "real time." The models are normally used to provide a more detailed understanding of the process, rather than in a control scheme. For control of a specific bulk deformation process, empirical models based on historical operating data are often best suited for the task.

What occurs within the core of a model is shown in Fig. 18. In essence, the model must adhere to the laws of deformation mechanics. The relationships between stress and strain both within the deforming metal as well as within the tooling and at the interface between the workpiece and the tooling must be obeyed.

The stresses that are generated within the workpiece and the tooling must satisfy the equilibrium equations, yield criteria, metal flow properties, and stress boundary conditions. Likewise, the strains generated from these stresses must satisfy compatibility equations as well as incompressibility requirements and any imposed displacement boundary conditions.

For a model to be exact and complete, all of the requirements in Fig. 18 must be met for a given set of input parameters. The complete and exact solution, except in very simple cases, cannot be obtained. Often it is necessary to simplify the model by allowing some of the deformation mechanics requirements to be relaxed. Although this simplification does not give an exact solution, the solution obtained is often quite reliable for many processing situations. Simplifications are often necessary to obtain solutions. The amount of time and effort one is willing to invest is often directly proportional to the closeness of the solution to the exact solution. To get extremely close, a large investment of time, personnel, and funds is often needed.

To describe each of the individual techniques, a specific example will be used. The sample problem will be the open die compression forging of a right circular cylinder between two flat parallel platens (Fig. 19). This simple example is used primarily for illustrative purposes. It is equivalent to the initial breakdown (or pancaking) of an ingot or bar in an open die press or forge. This problem will be examined via the slab equilibrium, slip line, upper bound, and finite element method (FEM) techniques. The methods describe herein can be applied to other bulk deformation processes.

## A. Slab Equilibrium

In the slab equilibrium technique, a small element (or slab) is extracted from the deforming workpiece (Fig. 20). A force balance is performed on this small slab. This balance of forces leads to a differential equation, which relates the stresses in the workpiece to the geometrical variables of the process. With the use of a yield criterion, an assumption of the principal stress directions, and some knowledge of the boundary conditions, a solution to the differential equation can be obtained. For simple geometrical shapes, an analytical solution is often achieved. For more complex shapes, the solution can only be obtained by numerically solving the differential equation. The solution relates the actual values of the pressure needed for deformation to the geometry, friction, and material properties.

For the forging of a cylindrical disk, an analytical solution can be obtained for pressure as a function of

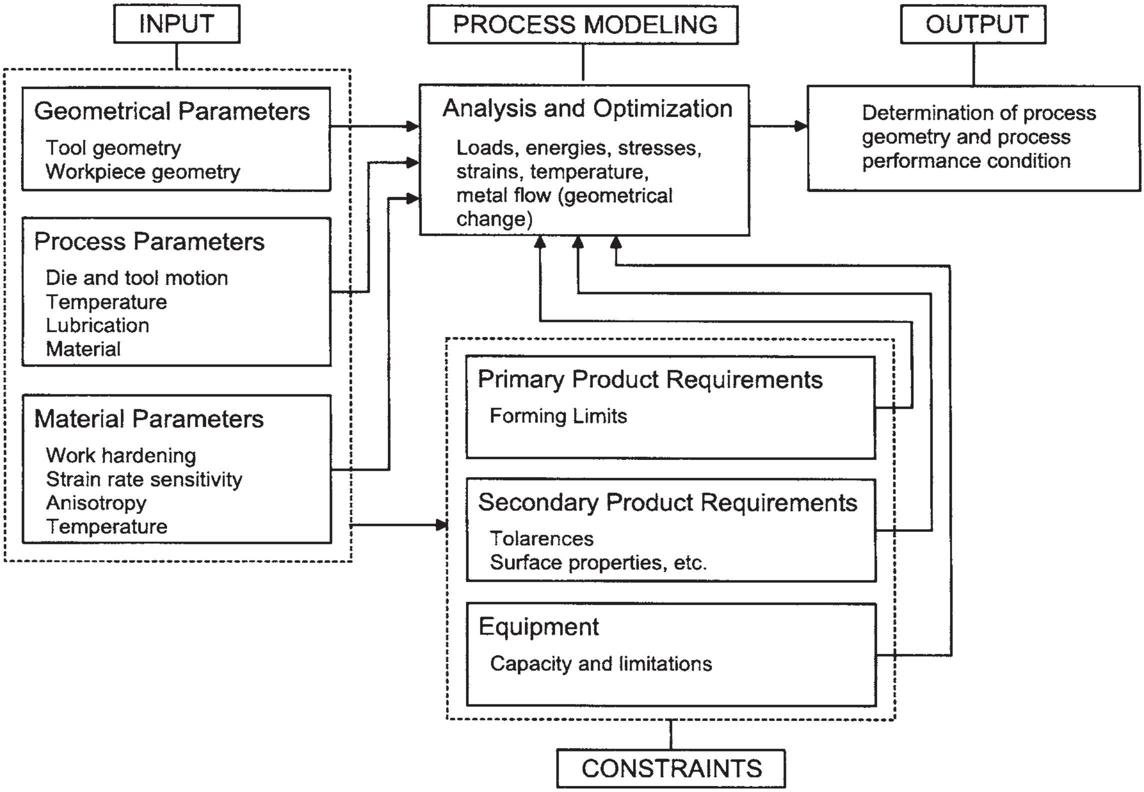

**Figure 17** Factors involved in modeling of bulk deformation processes. (From Ref. 13.)

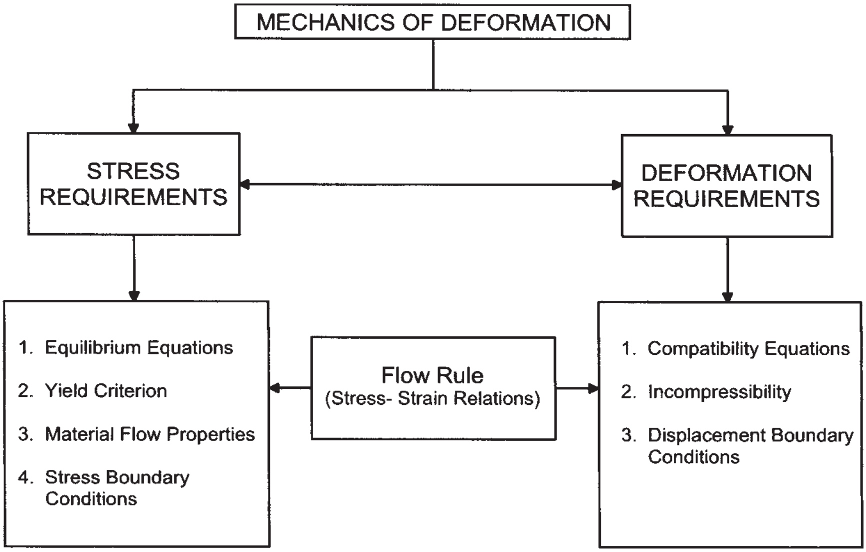

**Figure 18** Fundamental mechanics involved in the core of the modeling of metalworking processes. (From Ref. 14.)

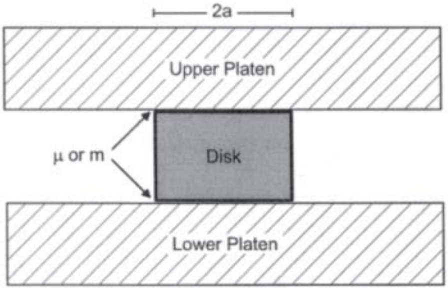

**Figure 19** Schematic of open die disk forging process.

the radial position along the disk. The solution is as follows:

$$p = \sigma_o e^{\frac{2\mu}{h}(a-r)} \tag{23}$$

$$p_{\mathrm{AVG}} = \frac{1}{2}\left(\frac{h}{\mu a}\right)^2 \sigma_o \left[e^{\frac{2\mu a}{h}} - \frac{2\mu}{a} - 1\right] \tag{24}$$

$$F = p_{\mathrm{AVG}} \pi a^2 \tag{25}$$

where $p$ is the pressure at any point, $\sigma_o$ is the material flow strength, $\mu$ is the coefficient of friction, $a$ is the radius of the disk, $r$ is the radial position, $h$ is the thickness of the disk, $p_{\mathrm{AVG}}$ is the average pressure, and $F$ is the load.

The slab equilibrium provides a solution at a discrete point in time. To determine how the load varies with displacement, an assumption of how the metal changes shape as a function of time must be used. If a uniform shape change is assumed (i.e., the disk remains as a right circular cylinder during the deformation—no bulge or foldover), then a load-displacement curved can be determined.

For an initial disk with the values for the parameters listed in Table 3, the load-displacement curve, up to a 75% reduction in thickness, is shown in Fig. 21. The pressure distribution across the top of the disk can also be obtained from this method by using Eq. (23). Figure 22 illustrates this distribution for three different reductions—25%, 50%, and 75%. The large increase in the center of the disk is due to friction and this shape is usually called the friction hill.

**Table 3** Properties and Dimensions for Open Die Disk Forging Example

| Variable | Description | Value | |
|---|---|---|---|
| $a$ | Radius of disk | 0.50 in. | |
| $h$ | Height of disk | 1.00 in. | |
| $m$ | Coefficient of friction | 0.25 | For slab and FEM |
| $m$ | Constant friction factor | 0.50 | For upper bound |
| $s_o$ | Flow strength of metal | 10.0 ksi | |

## B. Slip Line Method

The slip line method is a classical approach to the analysis of deforming bodies. The term *slip line* is misleading to many metallurgists because they have a specific definition for the term. In mechanics, the slip line method probably should be called "maximum shear stress plane" technique.

In slip line method, a network of maximum shear stress planes is superimposed onto the deforming body. There are a variety of restrictions on the generation of such a network. The network must adhere to specific shape requirements and boundary conditions, and provide a realistic flow field for the deforming material. The method is only valid for plane-strain conditions. Because the open die compression of a right circular

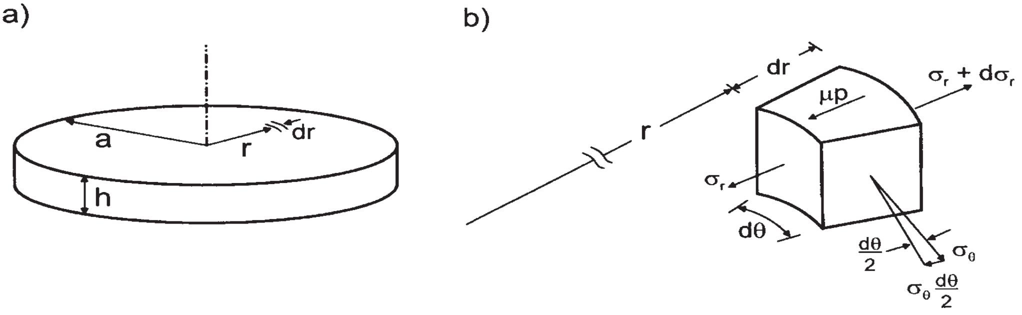

**Figure 20** Schematic of slab equilibrium analysis for disk forging: (a) general geometry; and (b) slab element used for analysis.

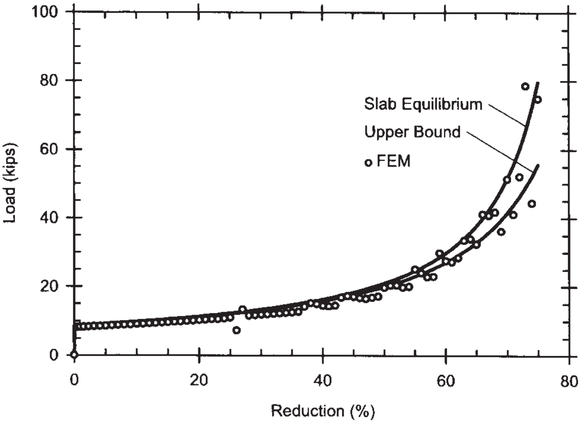

**Figure 21** Comparison of load vs. reduction curves for the modeling of disk forging via several methods.

cylinder is axisymmetrical and not plane strain, the analysis of this problem cannot be performed with the slip line technique.

Figure 23 shows a plane-strain open die forging, which has been solved by the slip line method. The figure also contains the relative averaged pressure for the deformation as predicted by the slab equilibrium technique. The plane-strain flow strength of the metal $\sigma_o'$ is $2/\sqrt{3}$ times greater than the uniaxial flow strength $\sigma_o$. The inserted diagrams show the network of maximum shear stress planes, which is used for each point in the solution. The slip line method predicts a forging load, which is lower than the load predicted by the slab equilibrium method.

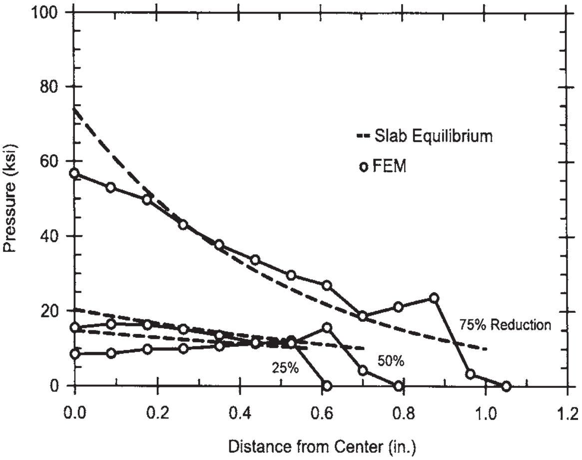

**Figure 22** Comparison of pressure distribution over the top of the disk during forging via two different modeling methods.

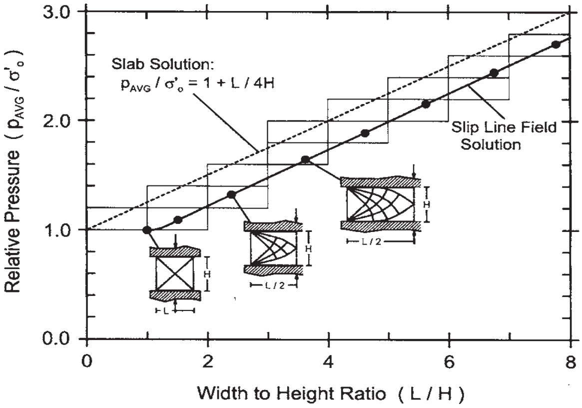

**Figure 23** Comparison of the plane-strain forging analysis by slab equilibrium method and slip line field method. (From Ref. 15.)

The slip line technique imposes a velocity field on the deforming material through the positioning and orientation of the maximum shear stress network. Hence the velocity field is an implicit assumption within the method.

## C. Upper-Bound Models

The upper-bound technique is an energy method where the energy per unit time needed by the workpiece to undergo deformation is set equal to the externally supplied energy per unit time. The primary power (energy per time) terms that must be calculated for the workpiece include: the internal power of deformation, the power to overcome friction, and the shear power. The internal power is determined from the assumed velocity field and is calculated from the strain rate field. The frictional power term is the power needed to overcome any tool-workpiece frictional interaction. The constant friction factor model is usually assumed for this type of analysis. The shear power is determined by calculating the energy per unit time associated with the internal shear that occurs over any assumed internal surfaces of velocity discontinuity.

For the open die forging of a right circular cylinder, the upper-bound solution is given as:

$$p_{\mathrm{AVG}} = \sigma_{\mathrm{o}}\left(1 + \frac{2}{3}\frac{ma}{\sqrt{3}h}\right) \tag{26}$$

where $m$ is the constant friction factor. The first term inside the parentheses in Eq. (26) is the internal power term and the second term is the frictional term. For the simple forging process being examined here, there are no shear power losses.

The upper bound, such as the slab equilibrium method, only determines a solution at a discrete instance in time. Because the velocity is assumed, the solution at other time increments is readily available as long as the flow does not change the shape of the workpiece to one for which the solution is invalid. Figure 21 shows the load-displacement curve for the forging of a right circular cylinder with the same properties assumed for the slab equilibrium solution. A constant friction factor of 0.50 was assumed, rather than the value for a coefficient of friction.

The upper-bound solution does not provide a stress field, hence a plot similar to Fig. 22 for the upper-bound approach cannot be determined.

One of the advantages of the upper-bound technique is that it determines a value for the deformation load, which is greater or equal to the actual load. Hence with the use of this method, there is a built-in safety factor for specifying the size of the equipment to be used.

A major use of the upper-bound method is to predict conditions where a process-induced defect may form within the workpiece. Because it is an energy technique, a comparison between the energy needed for sound flow can be made to the energy needed for defect flow. The flow field, which requires the least amount of energy, is the one most likely to occur. For example, this method has been successful in developing criteria for the prevention of central bursts in wire drawing and extrusions, central bursts in double hub forging, central bursts in rolling, side surface cracking in forging with double action presses, cavitation in impact extrusion, fishskin defects in impact extrusion, and the beginning of the piping defect in extrusions.

## D. Finite Element Analysis

The finite element method (FEM) is the technique that has received the most research effort during the last several decades. It is the one that produces an over-whelming amount of information about the process that is being modeled. The technique was developed in the 1960s for the analysis of elastic deformation in large complex structures (e.g., aircraft, bridges, buildings, etc.), which have a variety of constraints and loading conditions. The technique was extended in the 1970s and 1980s to the plastic deformation of metals.

In a FEM analysis, the workpiece and tools are discretized into a number of points, called nodes. The more points in the model present, the more accurate is the solution, but the more time it takes for the computer to calculate a solution. The nodes are linked to one another by elements, which obey specific deformation laws. The workpiece is given specific constraints, loads, and displacements, and an equilibrium solution is sought. If the displacements and loads are given as a function of time, the solution can be obtained as a function of time. The solution consists of the stresses and strains that exist at every node within the body and the tooling. Various interpolation methods are used to calculate values between the nodes. The solution to metal deformation problems requires the use of a computer and a skilled operator to interpret the results properly.

For the forging of a right circular cylinder with the properties given in Table 3, the load-displacement curve is shown in Fig. 21. The pressure across the top surface of the disk at reductions of 25%, 50%, and 75% is shown in Fig. 22. In both of these figures, the FEM solution is compared to other solutions. A mesh for this quarter disk was a grid of 20×20 square elements with a width of 0.025 in. The tooling was meshed with 16×7 rectangular elements 0.0714×0.0875 in. The original mesh and the deformed mesh at 75% reduction are given in Fig. 24.

In contrast to the other techniques, the velocity field is not assumed by the FEM analysis but is generated within the analysis itself. This forging of a right circular cylinder at 75% reduction exhibits both foldover and bulge (Fig. 24). Foldover is when the side surface of the disk comes in contact with the tooling surface. Bulge is when the center region of the free surface moves outward at a greater rate than the regions closer to the platens. Because the FEM is a numerical method, which produces a solution at a discrete number of points, the curves shown in Figs. 21 and 22 for the FEM analysis are not smooth.

Finite element method analysis can provide a large amount of information about the process. For example, the effective strain contours that exist within the forging at 75% reduction are shown in Fig. 25. The maximum strains occur in the center of the disk and at the original corners of the disk. The material directly beneath the platens in the center of the disk undergoes the least amount of strain. This type of information is useful for the prediction of possible shear banding. In addition, if the final properties of the product are dependent on the amount of strain, an indication of property gradients within the workpiece might be obtained from such a figure.

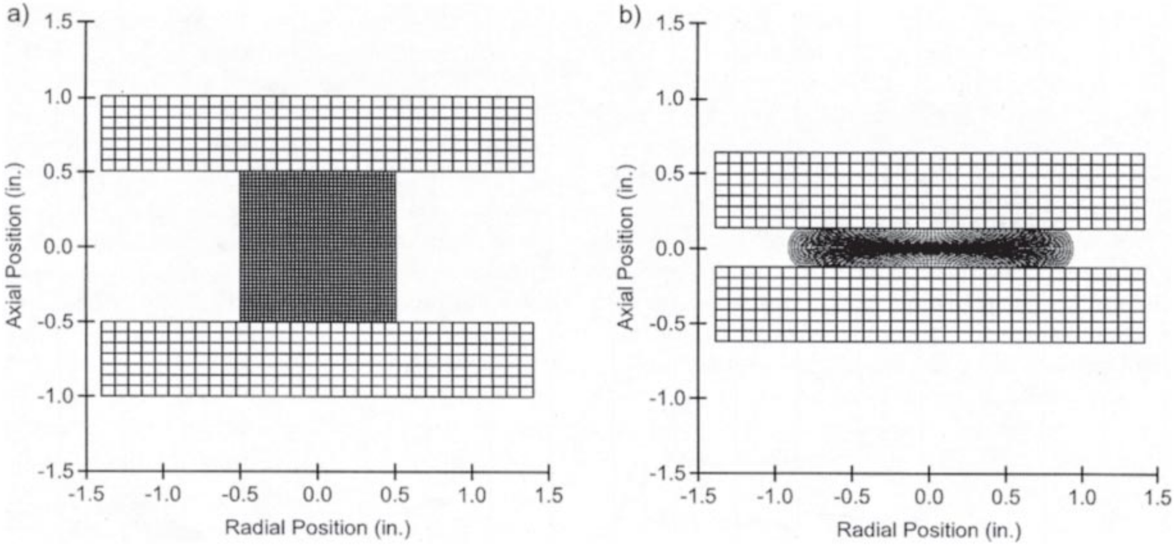

**Figure 24** Finite element mesh for open die disk forging: (a) before deformation; and (b) after 75% reduction in height. (From Ref. 16.)

One of the advantages of the FEM technique is that realistic material properties can be assumed for the deforming workpiece and the tooling. All the other analysis methods normally are performed with idealized mechanical properties for the workpiece and the tools.

## E. Modeling Limitations

Although modeling of bulk deformation processes is a very powerful and useful tool, there are several limitations that exist in all of the techniques. The first is an adequate description of the constitutive behavior of the deforming workpiece. In almost all cases, some simplification of the actual material flow behavior is assumed. To be accurate, the flow behavior should be known and mathematically characterized as a function of strain, strain rate, and temperature. If a good mathematical description for the material behavior exists, then FEM analysis could use it. Unfortunately, these descriptions, even for common metals and alloys, are not often available.

The second limitation for all of these methods is in the modeling of the frictional interfaces between the tooling and the workpiece. The two friction models, which are used in these modeling methods, are simplifications for the complex interactions that occur at the tool-workpiece interface.

A third limitation is the speciflcation of boundary conditions. The boundary conditions used for the analysis have a direct and profound effect on the results that are calculated. Poor choice of the boundary conditions, or choosing conditions that make the analysis easier rather than reflective of the real operation can result in misleading or erroneous results. The boundary conditions must be chosen with caution and care to ensure that the results validly reflect the reality of the process.

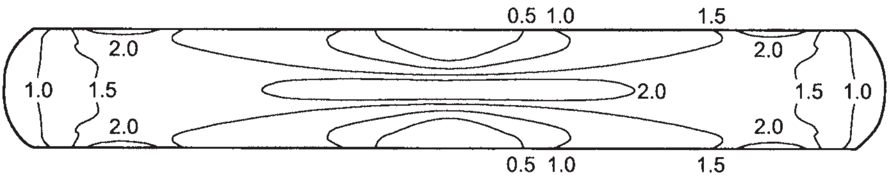

**Figure 25** True strain contours predicted by FEM for the open die disk forging after 75% reduction in height. (From Ref. 16.)

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Figure 41 Shrinkage in ductile iron plate. (A) Specimen from location A in Fig. 3.28 having an SCPAR of 78 db. (B)

Specimen from location B having an SCPAR of 62 db. (C) Specimen from location C having an SCPAR of 37 db. (D)

Specimen from location D having an SCPAR of 14 db.

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# 13 Chapter 13 Design of Carburizing and Carbonitriding Processes

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