METAL FORMING

Betzalel Avitzur *Lehigh University*

GLOSSARY

Drawing: Metal forming process whereby the workpiece is a shaped longitudinal prism that undergoes a reduction and change in its cross section area and shape while being pulled through a shaped converging die.

Extrusion: Metal forming process whereby the workpiece is placed in a chamber with an opening and is forced to escape through the opening, usually being pushed out by a mandrel.

Forging: Metal forming process whereby the workpiece is placed between an anvil and a hammer and subjected to compressive force between them.

Friction: Resistance to sliding motion along the interface between two solids.

Lubrication: Supply of substance on the interface between two sliding solids aimed at reducing the friction and/or the wear on the interface.

Metal-forming processes: Processes that cause changes in the shape of solid metal articles via plastic (permanent) deformations.

Modeling: Procedure to present a physical reality by other means.

Perfectly plastic materials: Idealization of the characteristics of metals undergoing plastic deformations.

Pressure-induced ductility: Increase in the ability of metals to undergo plastic deformations without fracturing, this ability being enhanced by high environmental pressure.

Rolling: Metal forming process whereby the workpiece is a longitudinal prism, which is placed between two opposing circular rolls that rotate in opposite directions, drag the workpiece along, and force it to reduce in cross section.

Simulation procedures: Procedures that provide representation of a physical reality through a mathematical or physical model.

Metallic components can be shaped in a manner similar to the molding of pottery. The raw material of a fundamental simpler shape is provided by a primary process like casting, powder consolidation, earlier forming processes, or even by electric deposition. Metals deform very much like soft clay or wax. Even in the solid state, permanent changes in shape can be forced upon them by displacement of relative positions between neighboring material points. To enforce these changes, external forces are applied. While soft plasticine can be molded by tiny toddler's fingers, for metal forming, specially constructed tooling, usually of hard materials, are manipulated, sometimes by colossal machinery.

A variety of processes, the equipment and tooling, and the concepts involved will be discussed in this article. This will provide an understanding of the state of the art in metal forming, typical processes (not all), and basic phenomena and concepts involved.

I. Introduction

A. PRIMARY AND SECONDARY FORMING PROCESSES

The ingots of a relatively large volume, coming as cast billets through solidification of molten metal, are usually shaped through plastic deformations into intermediate shapes. This primary shaping provides profiles that are closer to the profile of the final product and also causes a refinement of the crystal structure of the cast ingot. This refining of the structure, called recrystallization, occurs at elevated temperatures. Furthermore, metals are softer and more ductile at elevated temperatures. Thus, primary forming is done at elevated temperatures.

In the process of extrusion (Fig. 1), a billet is placed into a chamber with a shaped opening (called a die) on one end and a ram on the other. As the ram is forced into the chamber, the workpiece is forced out through the die. The extrudate, a long product (i.e., a rod), emerges through the die duplicating its cross sectional shape. The flow lines indicate that a dead metal zone forms in the corner on the exit side of the chamber where the separated ring of a triangular cross section remains stagnant.

The process of rolling, whereby the ingot is gripped by two rolls and squeezed between them is described by Fig. 2. The rolls are identical and they are rotating in opposite directions so that they grab the ingot and drag it by friction into the narrowing gap between them. The product may become thinner while passing through the rolls. Flat products are produced by cylindrical rolls, while profiles are provided by grooved rolls.

The process of forging is performed on a press or a hammer. Basically, the ingot is placed between two platens that are forced one against each other, squeezing the ingot between them (see Fig. 3). A variety of shapes can be produced between flat platens by manipulation of the ingot while the platens squeeze and release the workpiece repeatedly. Alternately, the platens may be shaped with a cavity that imparts its shape on the product.

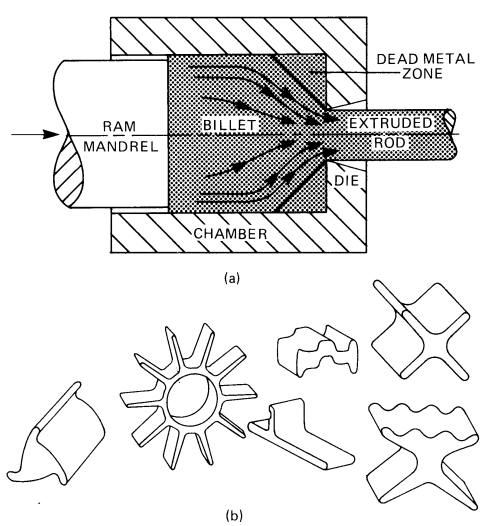


FIG. 1. Extrusion (a) and an assortment of extrudates (b).

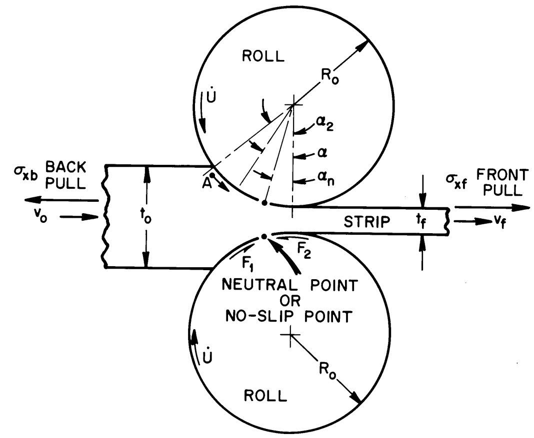


FIG. 2. Rolling. Friction forces: F_1, driving force; F_2, opposing force. Net driving force = F_1-F_2; $v_0 < \mathring{U} < v_f$ and $v_f / v_0 = t_0 / t_f$.

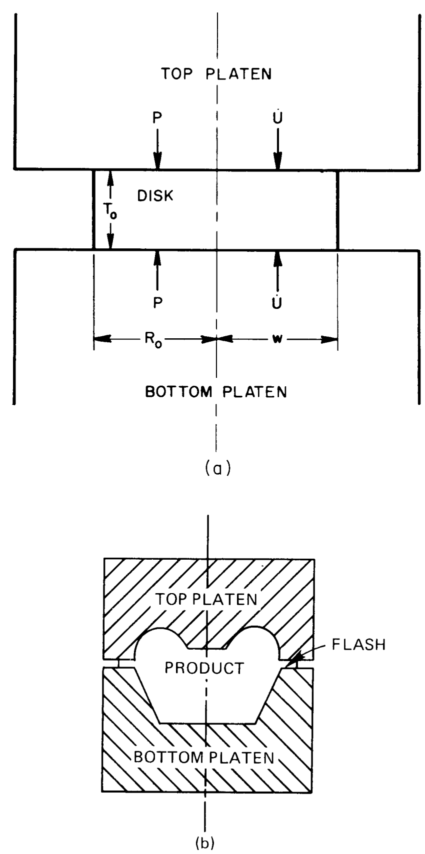


FIG. 3. Forging: open die (a) and closed die (b).

B. Interaction between the Machine, the Tool, and the Workpiece

A typical system for a metal-forming process is presented here through forging (see Fig. 4). The platens are manipulated by a hydraulic cylinder. The force applied to the workpiece through the piston and platens is contained by the frame. The resultant force on the system is zero. However, the frame must be strong enough to contain the forming forces. While the largest forging press during World War II was a 5,000 ton press available only in Germany in limited numbers, there are throughout the world today a few production presses of 50,000 to 80,000 tons. These presses are huge and expensive. The power supply needed for a press this size is an impressive system by itself. Not so long ago, the control and manipulation of the workpiece and tools were manual. Today's modern presses are automated. The following description is the state of the art in several of the most advanced designs (Lange, 1985).

The shape of the product, together with other information about the feed stock is given as the input to an online computer that activates the press and its accessories. The entire workpiece, tooling, and press manipulations schedules are calculated by the computer. Workpiece after workpiece is automatically fed to the press from its storage. An assortment of tools is stored on a rack at the press, and automatic selection of the desired tools at the proper portion of the cycle is affected. The tools and workpiece are manipulated in synchronization to shape the workpiece to the proper design by repeated forging actions. When forming of one workpiece is completed, the workpiece is removed to make room for the next one. On-the-spot automatic inspection is, on occasion, affected with possible closed loop feedback capabilities for automatic corrective measures.

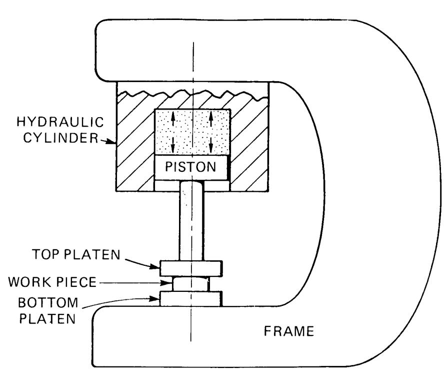


FIG. 4. Schematic of a hydraulic "C" clamp press.

Almost all of the disciplines of engineering at their most advanced stage interact in providing the present-day metal-forming system. Starting with the workpiece, knowledge of metallurgy and mechanics combine to provide an insight to its behavior. Sliding occurs on the interface between the workpiece and the tool, friction is manifested, and lubrication is exercised. Thus, tribology (i.e., the study of friction and wear) is necessary. The tools are made from hard metals and nonmetals as well, and therefore the latest advances in material science are immediately applied. Furthermore, to optimize tool wear, the latest in surface treatments, by coating, ion implantation, and laser beam surface hardening, are all practiced. In the design of the machine tool itself, all disciplines combine. To mention a few, the frame is made of any material from cast iron to plastic, which will reduce weight and noise. Hydraulics and electronics with robotics combine to provide motion inspection and vibration control. [*See* MANUFACTURING PROCESSES TECHNOLOGY; METALLURGY, MECHANICAL; PLASTICITY (ENGINEERING); TRIBOLOGY.]

C. The Status of the Metal-Forming Processes as Technology among the Industrial Processes

Metal forming is normally performed after the primary processes of extraction, casting, and powder compaction and before the finishing processes of metal cutting, grinding, polishing, painting, and assembly. With few exceptions, the bulk of the products of the metal fabrication industry are shaped by forming or a combination of forming and other processes like metal cutting or joining. Forming operations are classified as those processes where the desired shape is achieved by imparting plastic deformation to the workpiece in the solid state. Classification by (1) product, (2) material, (3) forming temperature, and (4) nature of deformation (sheet metal versus bulk deformation) can also be helpful. However, the boundaries between categories are not perfectly defined. For example, impact extrusion can be classified as a forging process or as an extrusion. It is needless to say that any specific product can be made from a number of materials, by a variety of processes, and at a range of temperatures.

II. Basic Concepts

A. Perfectly Plastic Material

Metal deformations are introduced through the application of external forces to the workpiece, these forces being in equilibrium. With the application of load to the workpiece, internal stress and displacements are generated causing shape distortions. If the loads are low, then with the release of the loads, the internal stresses will disappear and the workpiece will be restored to its original shape. It is then said that the applied loads were elastic and so were the stresses and strains. Elastic strains are recoverable on release of the loads. When the loads are high enough, the changes in shape will not disappear after the load is released. The changes in shape and the strain, those that did not disappear, namely, the permanent ones, are called plastic deformations. The loads causing plastic deformations are said to have surpassed the elastic limit. During metal forming by bulk plastic deformations (to be defined), the plastic deformations are much larger than the elastic deformations, which in general are ignored. Thus, only plastic deformations are considered. It is also recognized that plastic deformations do not involve volumetric changes. Thus, volume constancy is maintained. In metals, the load and the intensity of the internal stresses at which (plastic) flow initiates are functions of the structure, the temperature, the deformation history, and the rate of straining. It is fair to assume that at temperatures below the recrystallization temperatures at which new crystal structures emerge the material strain hardens but is not strain-rate sensitive. That is, the strength of the material increases with increased deformation levels. Above the recrystallization temperature, the material is strain-rate sensitive. That is, its strength is higher with higher rates of straining, but it does not strain harden. The point in loading where incipient plastic flow commences is called the "yield point," to be defined mathematically in Eq. (7).

A perfectly plastic material is such that it does not strain harden and is not strain-rate sensitive. The strength is not a function of strains nor of strain rates. A deformable material is said to be a perfectly plastic material (Talbert, 1984), when:

1. The material is incompressible.
2. There exists a material constant K with dimension of stress.
3. The stress deviator (s_{ij}) depends on the strain rate ($\dot{e}_{ij}$) in a quasilinear way:

$$s_{ij} = \phi \dot{e}_{ij} \tag{1}$$

where ϕ is a scalar invariant function of the principal strain rates,

$$\phi = \phi(K, \dot{e}_1, \dot{e}_2, \dot{e}_3) \tag{2}$$

These assumptions have been shown to imply that there exists a function $F, F(\dot{e}_1, \dot{e}_2, \dot{e}_3)$, homogeneous of degree –1 in the principal strain rates $\dot{e}_i$, such that

$$s_{ij} = KF(\dot{e}_1, \dot{e}_2, \dot{e}_3)\dot{e}_{ij} \tag{3}$$

Moreover, the ideal materials defined above have a yield criteria of the general form

$$F(s_1, s_2, s_3) = 1/K \tag{4}$$

where s_1, s_2 and s_3 denote the principal stress deviators. The same constitutive function F thus enters in the definition of the constitutive relations and of the yield criterion.

Dr. Talbert (1984) specifies the function F for four popular and different perfectly plastic materials named after Tresca, Mises, and others. For the Mises perfectly plastic material

$$F(\dot{e}_1, \dot{e}_2, \dot{e}_3) = [2/(\dot{e}_1^2 + \dot{e}_2^2 + \dot{e}_3^2)]^{1/2} \tag{5}$$

which in an arbitrary Cartesian coordinate system reads

$$F = 1/\sqrt{\tfrac{1}{2}\dot{e}_{ij}\dot{e}_{ij}} \tag{6}$$

so that the yield criteria becomes

$$\tfrac{1}{2} s_{ij} s_{ij} \le K^2$$

or

$$\tfrac{1}{2}(s_{11}^2 + s_{22}^2 + s_{33}^2) + (s_{12}^2 + s_{23}^2 + s_{31}^2) \le K^2 \tag{7}$$

where s_{ij} are the components of the stress deviator and K is a constant property of the material to be determined experimentally. As long as the scalar quantity on the left of Eq. (7) does not reach the value of K, the material does not deform. On reaching the value of K, plastic flow commences, The tensile test is a most common test to evaluate K. Thus, if the load stress in tension at the yield point is σ_0, then $K = \pm\sigma_0/\sqrt{3}$.

B. Flow

A pattern of deformations is known when specified by a velocity field. A velocity field is defined through the vector $\mathring{U}_i$ in space, confined to the workpiece. In a Cartesian coordinate system of X_1, X_2, and X_3, at any instant of time, the velocity vector is $\mathring{U}_i(X_1, X_2, X_3)$ (where i =1,2,3). The strain–rates components can be derived from the velocity vector as follows:

$$\dot{e}_{ij} = 1/2[(\partial \dot{U}_i / \partial X_j) + (\partial \dot{U}_j / \partial X_i)] \qquad (8)$$

and by Eqs. (3) and (8), the components of the stress deviator can be determined from the velocity field and the strength constant K.

$$s_{ij} = K\dot{e}_{ij} / \sqrt{\frac{1}{2}\dot{e}_{kl}\dot{e}_{kl}} \qquad (9)$$

C. Work and Power of Deformations

When the stress deviator components and the strain rates components are known, the internal power of deformations per unit volume can be derived as follows:

$$\dot{\omega}_i = \sigma_{ij}\dot{e}_{ij} \qquad (10)$$

and since $s_{ij} = \sigma_{ij} - s\delta_{ij}$ where $s = (\sigma_{11}+\sigma_{22}+\sigma_{33})/3$ and $\delta_{ij}=1$ if $i=j$ and $\delta_{ij}=0$ if $i \neq j$, by Eq. (10)

$$\dot{\omega}_i = 2K\sqrt{\frac{1}{2}\dot{e}_{ij}\dot{e}_{ij}} \qquad (11)$$

Thus, the internal power of deformations is determined from the strain rates components as derived by Eq. (8) from the velocity field vector and from the material constant K.

Although the characteristics of metals are more complex than those described here by a perfectly plastic metal, we will not expand further. The treatment becomes too complex, and the bulk of the study of metal forming is served well with the simpler model.

D. Friction, Lubrication, and Wear

In all of the processes described in Figs. 1-3, there exits a sliding motion along the interfaces between the workpiece and the tools. Whenever sliding occurs between solids, a resistance to the sliding motion is observed. This resistance is called friction. Friction resistance is accompanied by damage to the surfaces, which is mostly manifested by the wearing of the surfaces. The resistance to sliding, measured as a shear stress per unit surface area of contact (τ), is a complex function of many parameters, including workpiece and tool materials, surface smoothness of the tool, and speed of sliding. Friction and wear are also controlled by the introduction of lubricants between the interfacing surfaces. The lubricant serves not only to minimize friction and wear but also to cool the surfaces by removing the heat generated through sliding. Most effective lubrication methods may provide a thin film of lubricant separating the two surfaces completely. When full liquid film separation is created, a condition of hydrostatic or hydrodynamic lubrication prevails, minimizing the friction and wear. The energy generated through sliding can be calculated by

$$\dot{\omega}_f = \tau\Delta v \qquad (12)$$

where τ is the friction resistance to sliding, and Δv is the relative sliding speed.

III. Typical Processes

Several processes representing a diverse spectrum of secondary and primary metal forming operations are covered in this section. Only forging and wire drawing are dealt with in some depth, covering also the press system. The other processes are covered only briefly.

A. Forging

Forging is a most popular production process because it lends itself to mass production as well as to the production of individual sample parts. The origins of forging may be traced to the ancient process of hammering of gold foil, between a rock, the anvil, and a stone, the hammer. In hammering, the inertia of the fast moving hammer provides the required deformation energy and force, while in pressing the force is static. Usually the final shape is imparted on the workpiece by manipulating the workpiece between the flat anvil and the flat hammer as the hammer hits the workpiece repeatedly. Complex shapes can be hammered by skilled blacksmiths. A conical protrusion from the anvil, holes in the anvil, a variety of pegs with different cross sections, and auxiliary tools, including a large selection of shaped hand hammers, may assist the blacksmiths and their helpers (see Fig. 5).

Today, hand-held hammers are replaced by mechanical and hydraulic presses. When a large number of identical components are manufactured, the open dies are replaced by closed dies (Fig. 3), each with a shaped cavity to impart its shape to the product. The workpiece does not have to be manipulated, and the operator therefore does not have to be skilled; completion of the product can be achieved in one stroke and processing efficiency is high. Feeding the blank and ejection of the product are automated. Mass production of a technological age emerges out of the ancient art for ornament and artistic values.

Generally speaking, hydraulic presses (see

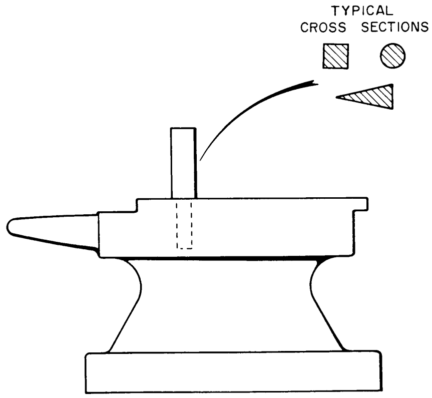


FIG. 5. The tools of the blacksmith.

Fig. 4) are slower than mechanical presses or hammers (see Fig. 6). Furthermore, the larger presses, carrying higher loads or longer strokes are hydraulic. Thus, the mechanical press is more suitable for mass production. Contact time between the tool and the workpiece is shorter on a mechanical press, protecting the dies better against heating during hot forging. Mechanical presses are recommended for open-die forging, and when used for closed-die forging, a flash is usually incorporated. The role of the flash and when it can be eliminated are to be discussed soon. For closed-die forging without a flash, a hydraulic press is recommended. Mechanical presses for closed-die, precision flashless forging as economic alternatives have recently been introduced in the market and proved successful. The largest forgings, for example, airplane wing frames, are forged on the largest presses (with up to and over 50,000 tons forging force), which are hydraulic presses.

The schematic of the forging of a flat component with flash with closed dies is presented in Fig. 7. The cavity between the top and bottom dies dictates the shape of the component. The original shape of the blank may be a predetermined length of a rod with a square or round cross section. It is also quite common to design dies with several cavities for the production of several components in each stroke of the press. The blank passes, in several steps, through a succession of pairs of dies in which it gradually approaches the final nominal desired shape of the product. The cavity between the pair of final dies is designed to be as close as possible to the nominal size of the product, but not precisely to the product's dimensions. The cavityis oversized for a number of reasons; the most important ones are the following.

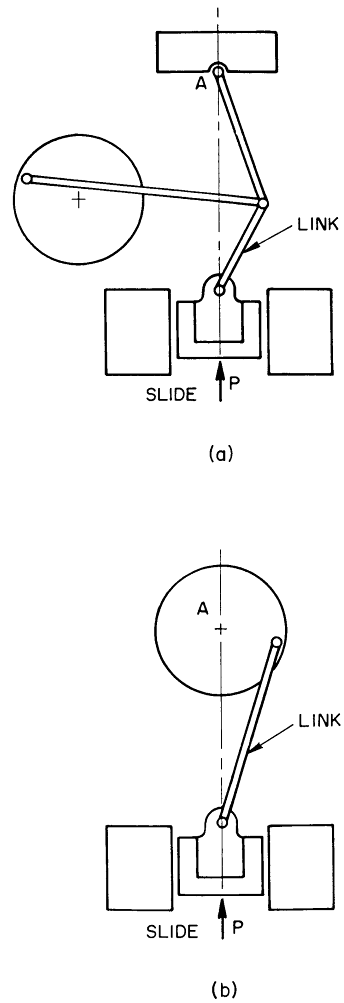


FIG. 6. Schematic of mechanical presses: knuckle joint press (a) and crank press (b).

1. Sharp corners require very high forging pressures to be fully filled. Since such pressures cannot be well tolerated by a die, the cavity is made slightly oversized, and the "degree of fill" of the corners becomes controlled by the flash. The forging force and pressure start to climb from the moment that first contact and compression are established between the workpiece and dies. In the beginning of the stroke, the blank does not match the shape of the cavity. The area of contact and the pressure increase as the dies approach each other. At the end of the stroke, the shape of the workpiece conforms to the shape of the cavity and pressure is at its peak. Shape corners can never be completely filled, and they are usually roundedor underfilled. Furthermore, rounded corners

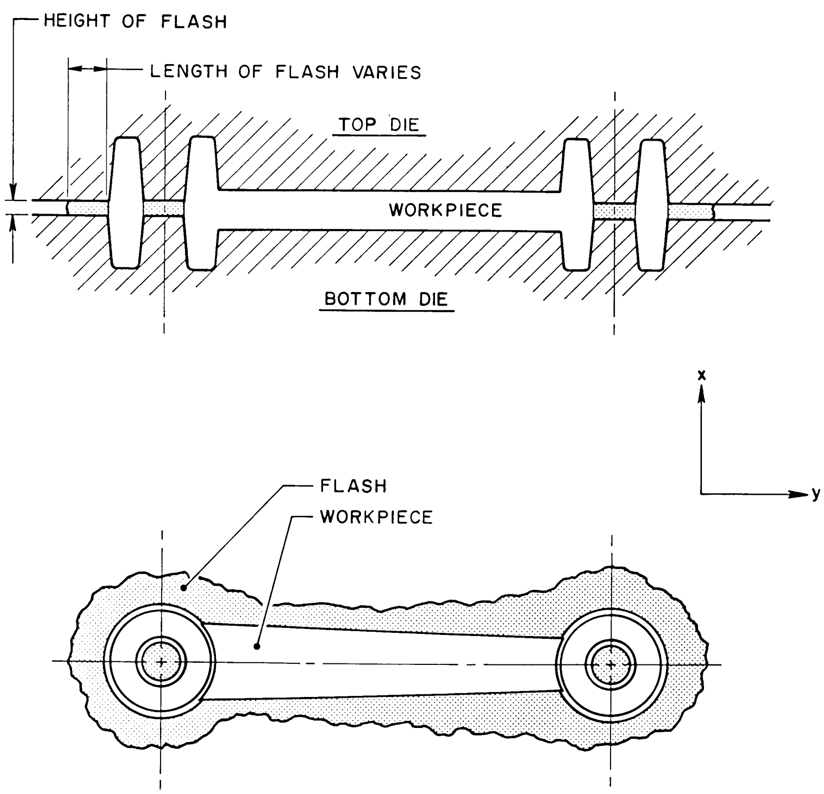


FIG. 7. Schematic of forging of a flat component with flash.

prolong tool life when compared to sharp corners that crack easily. The peak forging pressure is achieved when the top die reaches its lowest position; this position can be adjusted and thus the thickness or height of the flash can be controlled. The thinner the flash, is, the higher the forging force is. With the need or desire to fill sharper and sharper corners, a need arises for higher forging pressures, which are obtainable through thinner and longer flashes.

2. Variations in the volume of the incoming blank have to be tolerated and compensated by the fill of the flash.

3. Variations from one product to another are inevitable because of size changes of the blank, temperature and strength changes, etc., and because of the elastic flexing of the press.

4. Some surfaces should be machined after forging for improved surface finish, removal of scale caused by hot forging, etc.

So far, it has been established that the fill of the cavity by the workpiece is promoted through the flow of excess material into the flash, since the blank is cut to a size larger than that of the final product. Variations in the volume of the blank are minimized to a practical tolerance. The smallest permissible volume of the blank is larger than the product size to assure a minimum flash and thus a minimum value of the peak forging pressure, which is dictated by the required corner radii.

Note that excess volume of the blank does not by itself assure a fill of the cavity. If the spacing between the dies at the bottom of the stroke leaves a flash height that is too large (and thus a forging pressure too low), the cavity may not fill, in spite of the fact that a flash has been created. In this case, the flash will flow outward too easily, leaving empty spaces in the corners of the cavity.

Other means to assure filling of the thin webs and sharp corners with moderate loads call for isothermal forging of super plastic materials (Section IV, D) and forging in the mashy state (Section IV, D). Recently, forming to “near net Shape” was introduced by flashless forging. The matching of the top and bottom dies to the form of a cavity may be designed without provision for a flash. Such design changes require that, rather than facing each other at contact, one die enters the other.

By eliminating the flash, the following advantages are gained.

1. The volume of the blank is reduced to the nominal volume of the finished product. This precipitates savings in material.
2. The dimensions of the forging may conform closely to the final dimensions of the product, eliminating subsequent machining. Better corner filling can be accomplished due to the higher pressures associated with flashless forging.
3. The strength of a product after flashless forging is superior to that forged with a flash, since fibering flow lines in a flashless forging conform to the shape of the product, whereas in a forging with a flash they do not.
4. Usually flashless forging is performed in one forging step, from a blank of uniform cross section to a final shape through a single pair of dies, eliminating intermediate forging and (sometimes) annealing steps.

On the other hand, by eliminating the flash, much stricter tolerances are imposed on the blank. Too small a blank and the cavity will not be filled. Too large a blank and the press load will be excessive to the point of causing die breakage. Better choices of tool material and a higher degree of expertise in die design are required. Flashless forging is gaining popularity and every day new components not produced hitherto by the process are being added.

B. Flow through Conical Converging Dies

Figure 8 represents a billet and die. A variety of cross-sectional profiles can be produced; however, in the following simplification, the billet is a cylindrical rod of radius R_0; the rod is

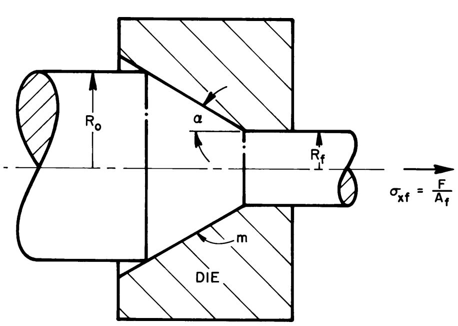


FIG. 8. Flow through conical converging dies; $\sigma_{xf} = f(R_0/R_f,\ \alpha,$ and $m)$.

reduced to radius R_f by forcing it to pass through the conical converging die. Reduction is measured from the cross sectional area of the billet at the entrance to the die (A_0) to that at the exit (A_f).

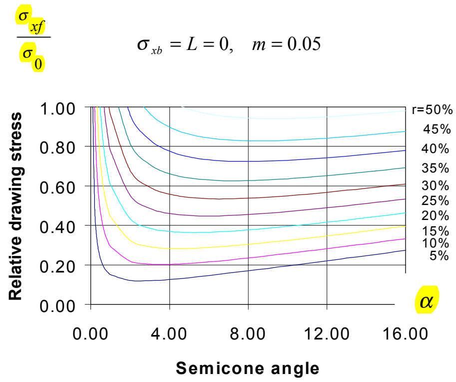
Besides the choice of the material itself, three variables (the independent process parameters) involved in the reduction process are noted at once. They are, the reduction, the semicone angle (α) of the die, and the severity of the friction between the workpiece and the die.

These three process variables-reduction, cone angle, and friction-are independent in that the process planner may exercise a degree of freedom in choosing their values. The severity of friction, for instance, is controlled, within limits, by choices of lubricant, die material and finish, speed, etc.

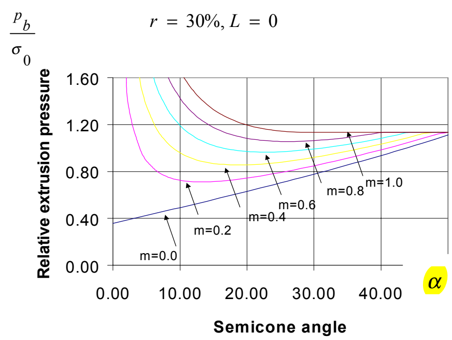
The above three parameters are the primary factors affecting the process and their effect on the first dependent parameter the drawing or extrusion force will be analyzed first. Other independent parameters play a role during processing. For example, we will find that the drawing or extrusion force is linearly proportional to the flow strength of the material, but when inertia forces are neglected, it is independent of the speed (when a Mises' material is considered). The power, on the other hand, is linearly proportional to speed. Furthermore, one may consider isothermal processing, where temperature is not a factor, and then extend the treatment to handle adiabatic processing and temperature effects. Thus, at first, only the effect of the three independent parameters ($r\%$, α, and friction) is considered.

The force required for drawing or extrusion can now be characterized. In Fig. 8 the drawing force F (or drawing stress, $\sigma_{xf} = F/A_f$) is obviously a function of reduction (larger reduction required higher force), cone angle, and friction, and similarly for extrusion force F (or extrusion stress, $\sigma_{xb} = F/A_0$). In short, the motivation force or stress causing the drawing or extrusion is a dependent variable, which is a function of reduction, cone angle, and friction. Description of the drawing force, for example, as a function of these three independent variables, may be undertaken by either an experimental approach or an analytical approach.

Figure. 9 illustrates the characteristics of the relative drawing stress (or extrusion pressure or force) as a function of the semicone angle of the die (abscissa) and of reduction (parameter). The relative drawing (or extrusion) stress is the motivation force divided by the cross-sectional



(a)



(b)

FIG. 9. (a) The effect of α and reduction on the relative drawing stress. (b) Relative extrusion pressure versus semicone angle and constant shear factor.

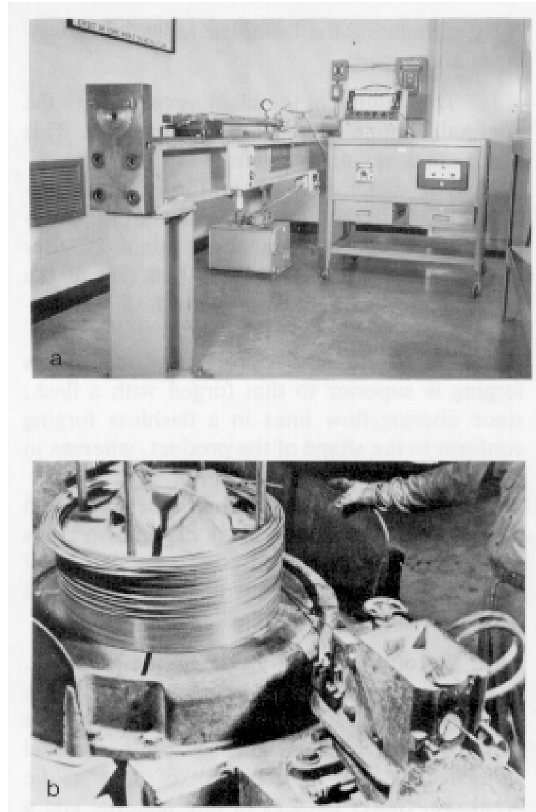


FIG. 10. A drawbench (a) and a bull block (b) for wire drawing.

area on which it acts and by the flow strength σ_0 of the workpiece. With too small a cone angle, the length of contact between the die and the workpiece is excessive and thus friction is predominant and makes the force excessive. As the cone angle increases, friction drops very drastically and so does the drawing force. An optimal angle is reached for the power. A further increase in the cone angle causes large distortions and excessive resistance to this distortion to offset what has been gained on friction, and thereafter redundant work (caused by distortion) is a predominant factor, not friction, A further increase in the die angle produces a further increase in the total power. For larger reductions, as well as for higher friction values (τ), the drawing force and the optimal angle that minimize it are increased. For the definition of the friction factor (m) see IV, C.

Flow through conical converging dies can be imposed by drawing on the emerging product (in a process called wire drawing), by pushing-in processes called extrusion, or by a combination of the two. Only limited reduction is achieved in drawing in a single pass because the tension permitted on the emerging wire should not exceed the strength of the product or the wire will tear. Wire drawing can be achieved in straight, short products or by pulling while coiling over a drum of very long wire (see Fig. 10). Occasionally a long, straight product can be produced by the equivalent of two, hand-over-hand pulls. A tandem arrangement of many blocks, one after each other, may be used to affect large total reductions.

When a billet is pushed through the die in the process of open-die extrusion (Fig. 11), the reduction is limited, just as in wire drawing, because here the allowable driving force is limited or the feedstock will be upset between the die and the driving force. For larger reductions, the process of extrusion through a closed chamber as described by Fig. 1 is used. In the process of hydrostatic extrusion (Fig. 12), the billet is pushed through the die by a pressurized

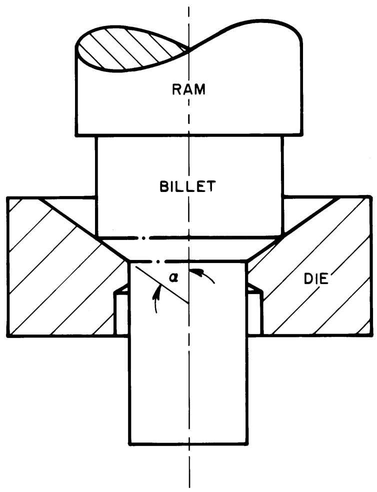


FIG. 11. Open die extrusion.

liquid. Occasionally liquid under pressure may be introduced at the exit to affect a process of pressure-to-pressure extrusion.

C. Rolling

In the process of rolling, long products of a variety of cross-sectional shapes can be produced

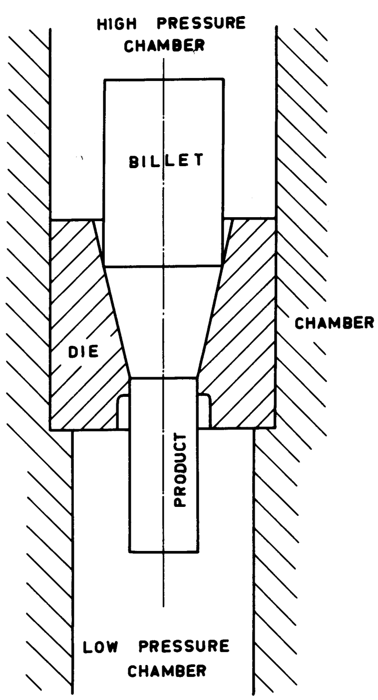


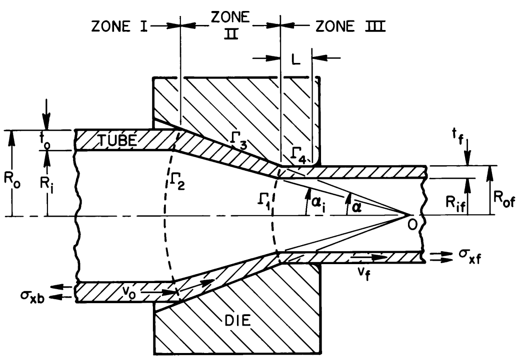
FIG. 12. Hydrostatic extrusion.

by forcing the feedstock to pass through the gap between rotating rolls. The rolls transfer energy to the workpiece through friction (Fig. 2). In flat products (strip), the strip is dragged by the rolls into the gap between them. It decreases in thickness while passing from the entrance to the exit. Meanwhile its speed gradually increases from v_0 at the entrance to v_f at the exit. Under regular rolling conditions, the strip moves slower than the rolls at the entrance to the gap between the rolls ($v_0 <$ Ů$_i$) and faster than the rolls ($v_f >$ Ů$_i$) at the exit, with a neutral point in between at which the speeds of strip and the rolls (Ů$_i$) are equal ($v_n =$ Ů$_i$). This neutral point is also called the no-slip point. It can be successfully argued that a *no-slip region* exists about the neutral point. The friction force acting along the surfaces of the rolls between the entrance and the neutral point (F_1) advances the strip between the rolls, while the friction force acting between the neutral point and the exits (F_2) opposes the rolling action. The difference between the friction on the entrance side and the friction on the exit ($F_1 - F_2$ in Fig. 2) provides the necessary power for rolling. The position of the neutral point is automatically determined by the power required to deform the strip and to overcome friction losses. In the conventional range of reductions practiced, the larger the reduction attempted, the farther the neutral point moves toward the exit, so that F_1 increases, F_2 decreases, and the net friction drag force increases to supply the higher power demand. Larger reductions can be achieved until the neutral point reaches the exit ($v_f =$ Ů$_i$). Then the maximum reduction possible is achieved and the process becomes unstable. If larger reductions are attempted, the rolls will skid over the strip and the strip will stop altogether.

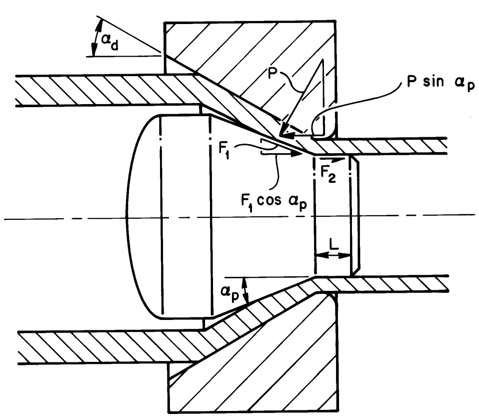
Larger reductions also require higher pressures on the rolls. Large pressures on the rolls cause more and more flattening and bending of the rolls. A limit on the amount of reduction that can be taken is set by one of two causes. When excessive pressure is limiting the maximum reduction, it is said that limiting reduction or limiting thickness is reached. If the neutral point reaches the exit and the rolls start to skid over the strip, it is said that maximum reduction is reached. The process of rolling is effectively controlled by the application of front (σ_{xf}) and back (σ_{xb}) tension to the strip on both ends of the rolls. However, the process of rolling is affected by the friction drag. An increasing number of metal forming processes were introduced recently, whereby friction provided the motivation force. These processes are classified as friction aided processes (Avitzur, 1982, 1983), and because the motivation source is applied directly to the deformation region, these processes are typified by their ability to impose excessive or unlimited reductions in a single pass.

D. TUBE MAKING

Tubes and tubular products are made essentially from all metal and by all metal-forming processes available. In Fig. 13 a tube of larger diameter is reduced to a smaller one by the process of tube drawing, similar to wire drawing, which is called (free) tube sinking, without specific control of the inner diameter of the product and by the processes of tube drawing with a floating plug, whereby the inner diameter is controlled by a plug, In tube drawing with a floating plug, the plug is free to move axially, and its position at the throat of the die is maintained automatically by the balance of the friction force and interface pressure with the tube. Special care in the design of the plug and die geometry must be taken so that the plug will stay in position, effectively control the inside diameter of the tube, and prevent tube tearing.



(a)



(b)

FIG. 13. Tube sinking (a) and tube drawing with a floating plug (b).

E. CAN MAKING

Cans can be made by deep drawing or impact extrusion and then wall thinning can be affected by the process of ironing. The process of deep drawing uses a rolled sheet, from which a properly contoured blank is stamped for the production of cans and other products. Bathtubs, kitchen sinks, and autobody components are typical deep-drawn articles. However, only cylindrical cans (also called "cups"), such as cartridges, aerosol cans, and beverage cans, will be discussed here. Blanks for cylindrical cups are circular disks.

Here, the process of deep drawing is covered and compared with impact extrusion and ironing. In the deep drawing of a cylindrical cup, a planar disk is transformed into a cup with a flat bottom, cylindrical walls, and an open top. As shown in Fig. 14, the disk is placed over the opening in the die and forced to deform by a moving ram (also called the punch). As the ram moves downward, it pulls the flange toward the center. The flange is held between the die and the blank holder, with the purpose of preventing the flange from folding upward. The blank holder is also called the "blankholder," "pressure pad" or "hold-down ring." The flange moves inward radially while its inner side bends over the rounded corner of the die and transforms from a flat disk to a circular tube. The bottom is not deformed, while the cylinder is already deformed but is not undergoing further deformation also, the toroidal

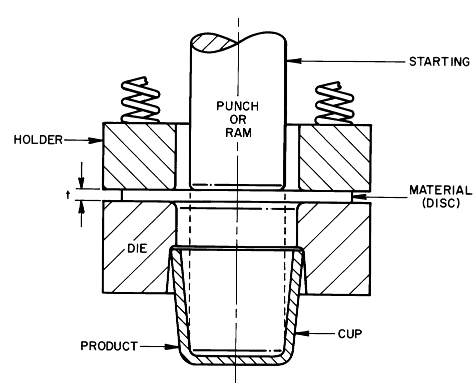


FIG. 14. Deep drawing.

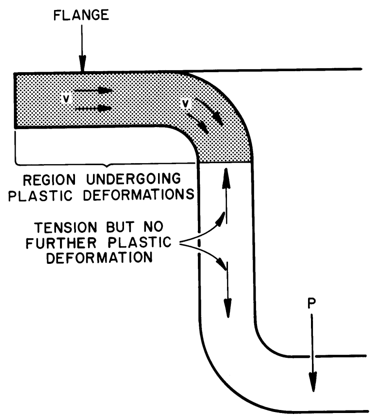


FIG. 15. The pattern of deformations in deep drawing.

section between the cylinder and the flange is bending, and the flange is undergoing plastic deformation (see Fig. 15).

The process of impact extrusion (also called inverse extrusion, backward extrusion, or piercing) is utilized to produce hollow shells from solid rods or disks. Schematically (Fig. 16), a disk (slug) is placed in the cavity of a female die and then the ram (mandrel, punch, or tool) is pushed into the raw material. While the ram moves downward, the wall of the produced can moves upward, escaping through the annular gap between the ram and the die. Because the wall of the product moves upward in the direction opposite to that of the downward motion of the tool, the process is sometimes called inverse or backward extrusion. In most of the manufacturing practices involved, the product is made on a fast mechanical press; and the name "impact extrusion" has resulted. A hexagonal

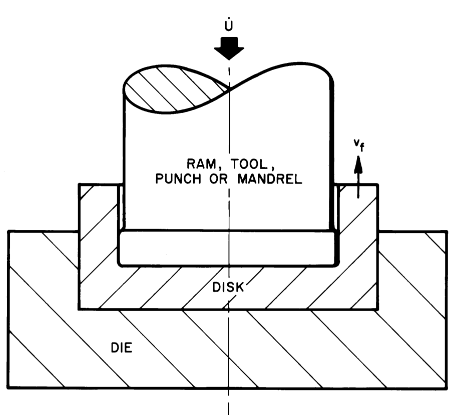


FIG. 16. Schematic of impact extrusion.

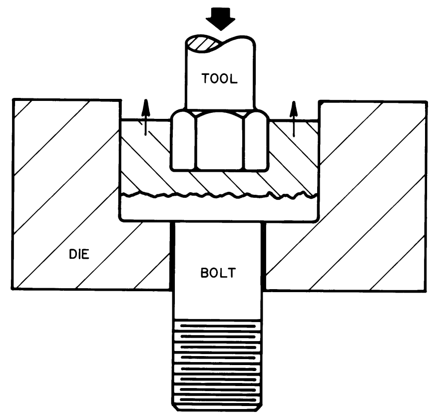


FIG. 17. Hexagonal cavity produced in bolt making.

cavity produced in the head of a steel bolt is shown in Fig. 17 and an assortment of aluminum containers is shown in Fig. 18. The well-known white metal toothpaste tube needs no illustration.

Ironing is usually performed after either deep drawing or impact extrusion when a thin-wall cup is required. This same process is often applied in the thinning of tubes. This presentation is concerned with the ironing of thin-wall cups, of which the beer can is a classic example. The deep-drawing operation is more suited for heavy or medium gauge cups of relatively restricted depths. For the production of longer cups of thinner walls, ironing can be used.

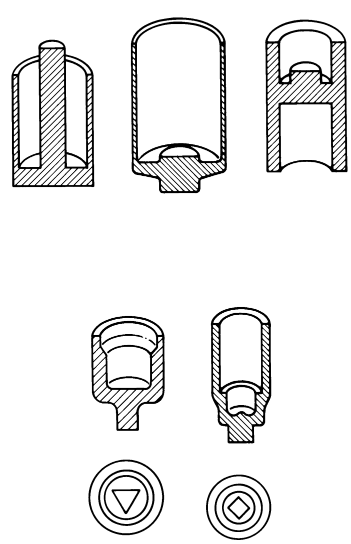


FIG. 18. Variety of shapes possible by impact extrusion.

A cup (Fig. 19) of inner radius R_i, wall thickness t_0, and fairly small height H, is first produced by deep drawing. The thickness t_0 is usually much less than the radius R_i. Then, during ironing the cup is forced to flow into a conical die of semicone angle α and inner radius R_f and is pushed downward at a velocity v_f by a punch of radius R_i over which the cup is mounted. The gap between the die and the punch (R_f -R_i) is the thickness t_f: this is the final thickness of the cup, and $t_f < t_0$. As the punch advances, the wall of the cup extrudes through the gap and its thickness decreases from t_0 to t_f while the length H increases. The outer radius of the cup decreases from R_0 to R_f while the inner radius remains constant at R_i.

The punch force P is transmitted to the deformation zone (Fig. 20) partly through the pressure on the bottom of the cup, further by tension on the wall, and partly through friction. As the friction between the punch and the inner surface of the cup increases, less tension is exerted on the wall, thus enabling ironing with larger reduction. By differential friction (i.e., by having the ram friction higher than the die friction) and proper choice of die angle, unlimited amounts of reduction can in principle be achieved through a single die (Avitzur, 1983).

As of recently, processing of polymers in the solid state is performed by the same metal-forming process described in the preceding paragraphs. The molecular orientations imposed by this process enhance the strength properties of the product. The product is made into its final shape with no machining (Austen *et al.*, 1982).

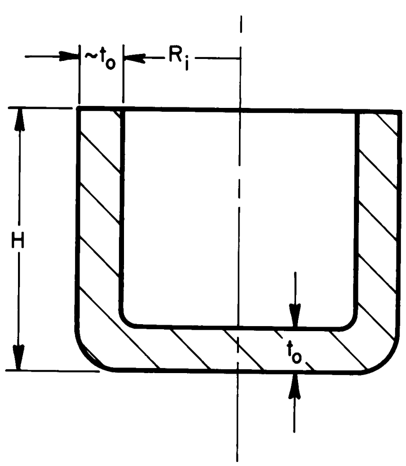


FIG. 19. Deep drawn cup; $t_0 << R_i$.

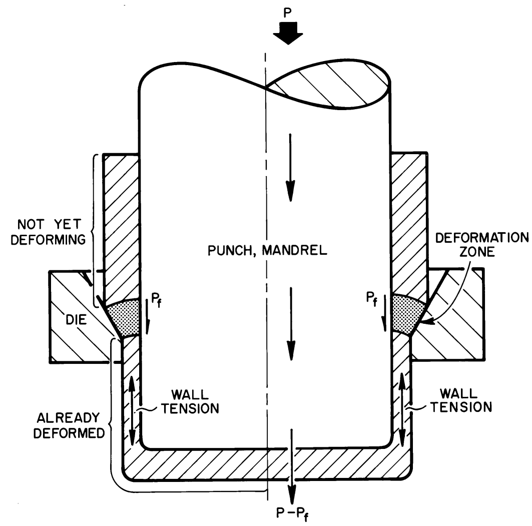


FIG. 20. Transmitting the punch force to the deformation region.

IV. Phenomena

A. Pressure-Induced Ductility Reversible Flow, and Metalworking under Pressure

The most significant factor controlling the application of metal forming as a manufacturing process is the ductility of the workpiece. Metallurgical aspects determine the ductility of the workpiece at standard room temperature conditions. The most popular experimental procedure to determine ductility is the tensile test. One traditional method to improve the ductility of metals is heating, which causes most metals to soften and become more ductile. Thus, traditionally, heating was employed both to reduce the required forming forces and to increase the amount of deformation possible.

The indication that ductility, or the lack of it, is not an inherent and solely metallurgical property, but a property that can be controlled by mechanical means (namely, environmental pressure), was suggested by Bridgman (1949). He showed that the ductility of metals as manifested by the stress-strain curve increases with the mean superimposed hydrostatic pressure. The terms mean stress, average stress, hydrostatic stress or pressure, and environmental pressure are used interchangeably. Not only the metallurgical parameters of the workpiece but also the processing parameter pressure dictate the formability. This phenomenon, the increase in ductility with the environmental pressure, is called *pressure-induced ductility* (PID). As suggested by Bridgman, the mechanism of PID is the restraining effect of environmental pressure in inhibiting void initiation and growth. Since the growth and coalescence of voids are prerequisites to ductile failure, their arrest extends formability, thus increasing ductility. For the mathematical treatment of the effect of pressure on the deformation and strength of a tensile bar and on void formation and prevention (Talbert and Avitzur, 1977). This increase in ductility by superimposed hydrostatic environmental pressure was confirmed by Bobrowsky *et al*., (1964), Pugh and Green (1956), Alexander (1964-1965), and many others.

With the renewed research into hydrostatic extrusion, a convenient tool was developed for the investigation of PID and its implementation in metal forming, namely, metalworking under pressure (MUP). For example, by pressure-to-pressure hydrostatic extrusion, the environmental pressure can be controlled as an independent process parameter, through the control of the receiver pressure, separately from the reduction, die angle, friction, or temperature. Bridgman was able to demonstrate the PID phenomenon by extruding marble, a brittle material by all counts, into a high-receiver pressure. The extrudate came out as a sound product. A prevailing theory today in geology is that rocks deep underground are capable of undergoing plastic deformations in a ductile manner because they are constrained by high environmental hydrostatic pressure. MUP for many hard to deform metals or shapes is demonstrated through pressure-to-pressure extrusion and implemented in industry. While MUP had been sporadically employed earlier, Bridgman's pioneering work gave the phenomenon an identity, and since then it has been applied deliberately in many processes. A wide range of processes to which PID can be utilized in MUP are included in these five categories: (1) forming, (2) cropping and shearing, (3) bonding, (4) powder compaction, and (5) reversible flow from smaller to larger cross sections (Avitzur, 1983).

B. High Energy Rate Forming

Up to this point, the processes described were achieved through static loading, as in the forging of a disk between two platens of a press (Fig. 1). We now examine how the same result (upsetting) can be achieved by a high-energy rate-forming (HERF) process. (The process is also called high-velocity or HVF).

If, hypothetically, the disk is thrown with a high speed at the bottom platen, the entire kinetic energy of the rushing disk will be absorbed at the moment of impact with the platen. If the projectile achieves bullet speeds, it may, on impact, either penetrate the platen, like an armor-piercing bullet, weld to the platen, deform, or undergo two of the above simultaneously.

Figure 21 represents the most common design for the use of explosives in a HERF process. A blank made of a plate or sheet metal is placed over a die cavity of the desired shape. A vacuum must be formed in the cavity below the blank by evacuating the air. The tank above the bank is filled with water. An explosive charge is placed just below the surface of the water, directly above the center of the blank.

When the explosive charge is detonated, a shock wave moves through the water. Water is a very effective shock-wave-transmitting medium through which the impact of the explosion is transmitted from the source to the workpiece target.

The effectiveness of the energy transfer is demonstrated by observing uses in other fields. For example, sonar under water is most efficient and sensitive. The destructive force of the shock wave has been used for centuries (now illegally) by fishermen to destroy (or to stun) all life in a vast sea or pond space. Submarine warfare demonstrates the sharpness by which the shock wave from a bomb hits the submarine, as if it had been hit directly by a hammer.

On reaching the blank, the shock wave hits it so hard that the blank rushes downward and conforms to the cavity. Once the shock wave has hit the blank and set it in motion, the rest of the operation is performed by the inertia of the

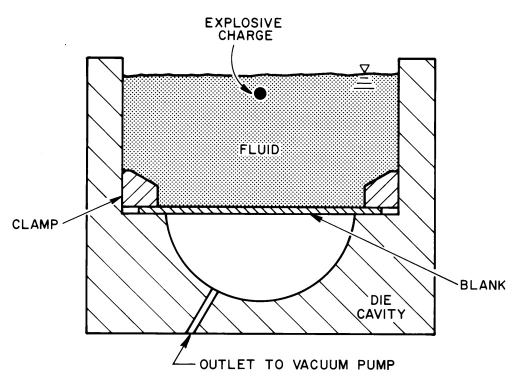


FIG. 21. Schematic of explosive forming.

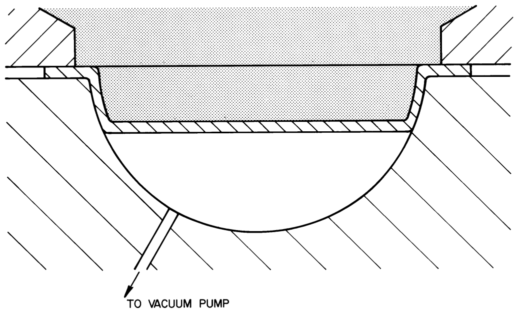


FIG. 22. Intermediate shape.

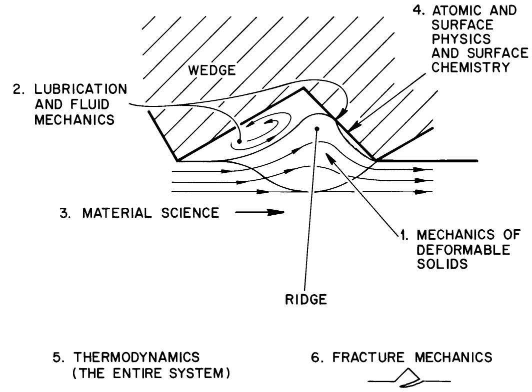


FIG. 24. Disciplines affecting friction and wear.

moving blank. The blank moves downward as a plane during forming. Halfway through the operation the part would look like a flat-bottomed bowl with sides conforming to the cavity. This intermediate shape is shown in Fig. 22. This shape would also result if the explosive charge were insufficient to complete the operation. For smaller parts the surge of energy can be provided through other chemicals or by an abrupt electrical discharge of energy from a battery of capacitors.

C. FRICTION AND LUBRICATION

One of the last frontiers in the understanding of metal forming is the friction phenomena between the tool and the workpiece. No matter how much care is taken to form a smooth tool surface, the surfaces of both tool and workpiece are irregular surfaces with peaks and valleys. Opposite peaks clash with each other, resulting in damage to both surfaces. Temperature rises due to the rubbing action. A thin layer under both surfaces undergoes severe plastic deformation.

Models of the typical behavior of the asperities of the surfaces of two solids interfacing one another under pressure, and sliding with respect to each other, are described in Fig. 23. Many more possible outcomes of the clashing of the asperities may occur. One specific behavior, described in part (b) of Fig. 23, is the steady state flow of the asperity, identified as the wave motion. In the model of this motion, the "wave model" (Fig. 24), wedges of the harder surface indent into the softer surface because of the applied pressure, thus producing opposing ridges on the surface of the softer component (Leslie, 1804). According to Leslie, the ridges are supressed down under the sliding wedges, only to rise again in front of the moving wedges. This perpetual supression and uprising of the ridges are motions similar to the motion of ocean waves.

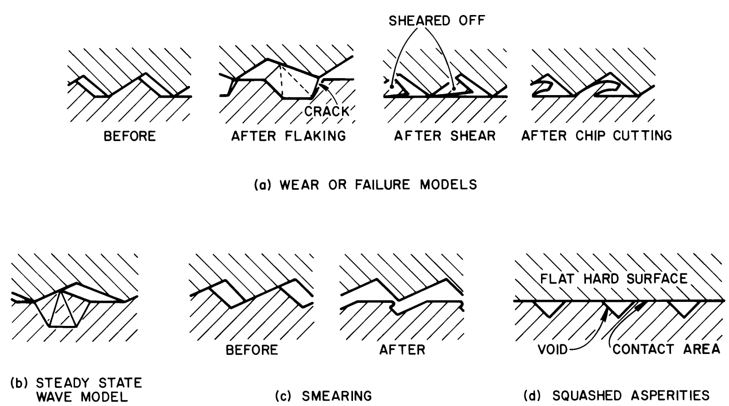


FIG. 23. Several patterns of distortion of asperities.

The wedges and the ridges are the asperities. The gap between the opposing asperities is filled with lubricating liquid, establishing boundary lubrication. As sliding is maintained, the ridges are mobilized and an eddy flow is established in the trapped lubricant (Avitzur, 1990). The eddy flow creates high shear within the lubricant. This shear generates power losses, heating, and liquid pressure. The shear, the power losses, and the pressure, all increase with increasing speed and viscosity of the liquid. The power required to mobilize the ridges and to establish eddy flow in the lubricant is calculated, and thus the friction resistance to sliding is determined. Simultaneously, the pressure generated in the liquid as a result of shear is also evaluated. It becomes clear that the height of the ridge, due to indentation, is inversely proportional to the speed of sliding. The higher the sliding speed, the higher the liquid pressure that is countering the loading pressure and the smaller the indentation. At high enough speeds the entire load is supported by the pressure generated in the liquid, indentation is eliminated. And hydrodynamic lubrication commences.

A classic presentation of the resistance to sliding as a function of interface load is shown in Fig. 25. When the load (p) is low or intermediate, the resistance to sliding is proportional to the load and, as suggested by Coulomb (1785) and Amonton (1699), $\tau = \mu p$ where μ is the coefficient of friction (Bowden and Tabor, 1954, 1964). With increasing load the resistance levels to reach a plateau, $\tau = m\sigma_0/\sqrt{3}$, where m is a constant friction factor. Both the proportionality factor and the plateau are functions of the irregularities of the surface and of the effectiveness of the lubrication (Wanheim, 1973; Avitzur, 1984). In Fig. 25 m_0 represents the inverse effectiveness of the lubrication and α represents the steepness of the irregularities on the surface of the die. During the metal forming the interface pressures required to impose plastic deformations on the workpiece are high, and the constant friction resistance indicated by the flat portion of Fig. 25 is realized, unless film lubrication comes into effect as described next.

In processes like wire drawing or rolling, the deforming workpiece continually passes through the tools. These processes (unlike other bulk processing, i.e., forging), classified as "flow through" processes, are executed at high speeds and thus are most efficient. Being continuous, they minimize manual handling and lend themselves easily to mechanization and automation. Rolling on a finishing mill may be

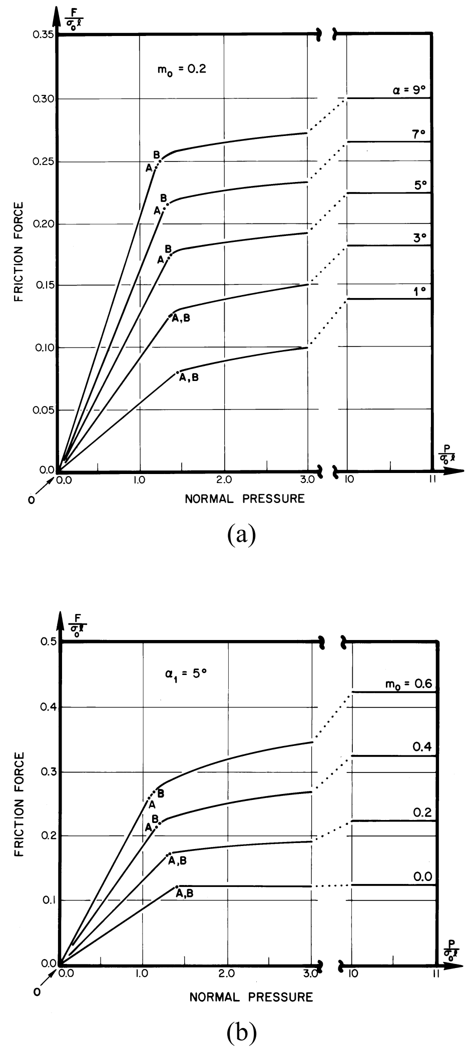


FIG. 25. Friction versus load; (a) with wedge angle (α_1) as a parameter, and (b) with the friction factor (m_0) as a parameter.

performed at 10,000 ft/min, and even higher speeds are reached in wire drawing. At high speeds, an entry (or inlet) zone develops whereby fluid from the entrance squeezes as a wedge between the workpiece and the die. In Fig. 26a for wire drawing, this wedge extends partway through to the point defined by R_i, where $R_0 > R_i > R_f$. The faster the drawing is, the smaller are R_i and the contact zone between the workpiece and the die. As long as $R_i > R_f$, the liquid dragged by the workpiece (and the rolls, in the case of rolling) into the wedge cannot escape through the exit and must return to the entrance. The profile of the lubricant flow through any cross section is described in Fig. 26b, showing that at the surface of the workpiece flow, speed

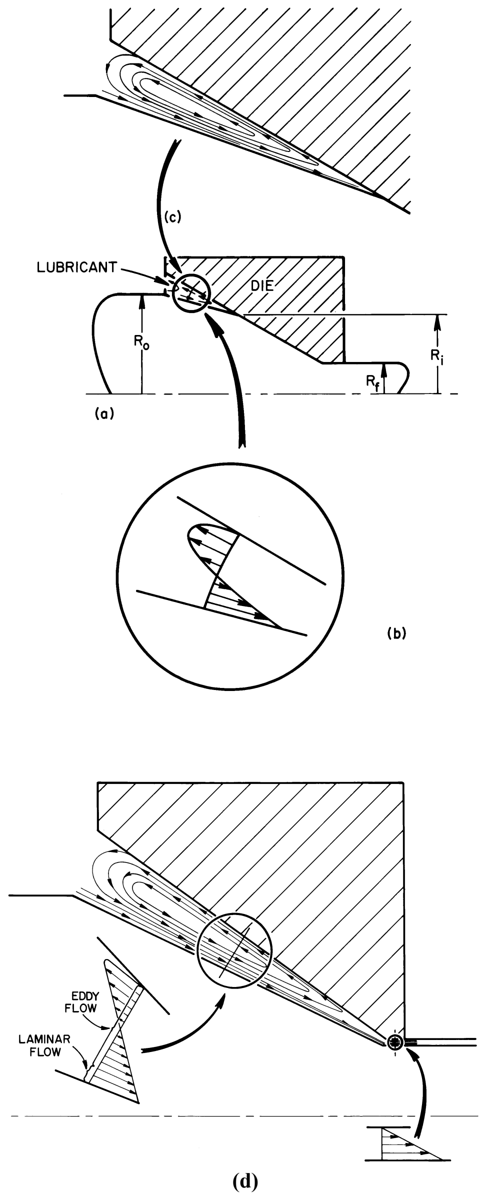


FIG. 26. Lubricant film: (a) entry zone, (b) velocity profile of lubricant, (c) eddy flow in entry zone, and (d) hydrodynamic lubrication.

is equal to the speed of the workpiece, and at the surface of the tool, speed is equal to the speed of tool. The total volume rate of the liquid passing through any section is zero. Thus, in the outer annulus, closer to the surface of the die, liquid flows in the general backward direction. At some intermediate point, where a reversal of the direction of flow occurs, the velocity component is zero (Fig. 26b). Liquid at that point does not flow in or out. It does however flow into the wire or into the die as shown in Fig. 26c.

The loops in Fig. 26c show flow lines in the inlet zone. The eddy current flowing in a closed loop retains practically the same particles of liquid and its contaminants. This circular motion is associated with high-speed gradients and shear strain rates within the liquid. The temperature of this trapped liquid in motion may rise appreciably. A very thin layer of lubricant at the surface of the wire maintains a sort of laminar flow with the wire. This layer, through the labyrinth of voids between the workpiece and the die escapes with the wire through the die exit. Being extremely fine, this layer does not constitute hydrodynamic film separation. Since metal to metal contact decreases due to an increasing liquid wedge as a result of increasing workpiece speed, it follows that friction drops too with increasing speeds, as shown in Fig. 27.

The range of the resulting changes in the power consumed through the mobility of the ridge, and through shear losses in the trapped lubricant due to the eddy flow, is wide, as demonstrated by Avitzur (1990). The complexity of the characteristics of friction is evident from the calculated value of the global friction factor *m*, as presented in Fig. 27. The abscissa is the Sommerfeld number (*S*), the ordinate is the global friction factor (*m*), and the parameter is the normal load (*p*) on the interface between the two sliding bodies. The local friction factor is m_0 = 0.6 while the asperity's angle is $\alpha = 1^\circ$. For the lower load values ($p = 2$) the characteristic behavior of the Stribeck curve (1902) is observed. The static friction factor value of *m* is highest when no sliding occurs. With increasing speed or Sommerfeld number values, resistance to sliding drops because the ridge size reduces sharply. Higher-pressure values produce higher resistance to sliding. Note also that for higher pressures the height of the ridge is higher, and therefore the thickness of the film of the trapped lubricant is thinner. Furthermore, increases in Sommerfeld number values are not as effective in reducing the height of the ridge, and thus for high pressures, the lubricant film remains thin even with increasing values of Sommerfeld number.

An interesting point can be observed here regarding the die wear, called the "ring" at the entrance. The eddy current of the trapped liquid in the wedge causes an excessive liquid temperature rise and liquid contamination; together with the pressure rise due to the reversal of flow, it may erode the die in the same manner as the water flow in the river bend erodes its bank.

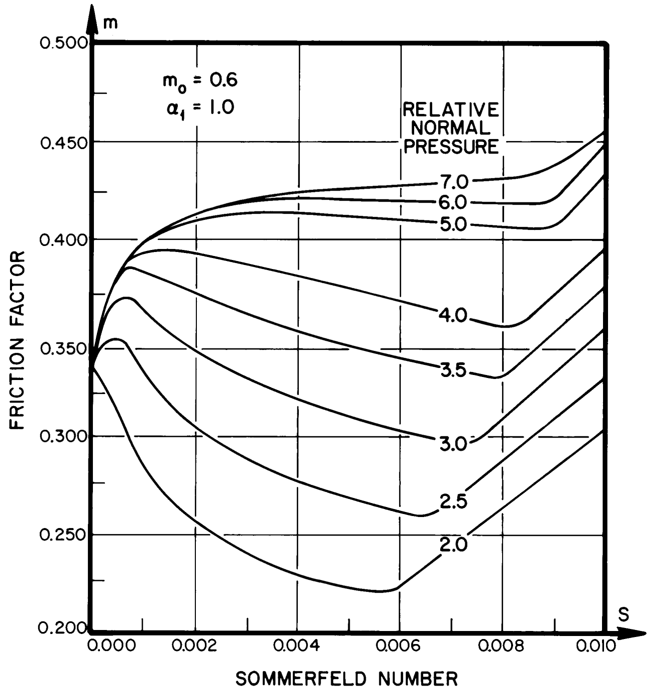


FIG. 27. Global friction vs. Sommerfeld number, at high pressures.

With increasing speed, a critical value is reached at which $R_i = R_f$ and the wedge extends to the entire conical surface of the die. At that point and beyond, a thin film of laminar flow commences at the surface of the wire, This flow will proceed through, from the entrance to the exit of the die. The film will separate the wire entirely from the die. This separation will exist along the bearing (land) of the die (Fig. 26d). The wedge of eddy flow may or may not disappear while the liquid escapes from the entrance side of the die to the exit of the laminar flow. Full separation between the workpiece and the die and hydrodynamic lubrication commence. When hydrodynamic lubrication prevails, the friction is represented by the shear within the liquid in the following form:

$$\tau = \eta(\Delta v/\varepsilon) \qquad (13)$$

Where η is the viscosity of the lubricant, Δv is the sliding velocity between the workpiece and the tool, and ε is the thickness of the lubricant's film.

The Sommerfeld (1904) number can be defined as a function of viscosity, velocity, wire size, and strength in the following manner: $S = \eta v_f/(R_f\sigma_0)$. When the Sommerfeld number reaches a critical value (S_{cr}) and above, hydrodynamic lubrication prevails. The higher the Sommerfeld number, above the critical value, the thicker the film becomes, separating the workpiece from the tools.

For processes where high speeds cannot be attained (forging, deep drawing, etc.), a film of lubricant can be introduced between the tool and the workpiece by externally pressurized liquid. Hydrostatic lubrication then prevails.

D. Hot versus Cold and Warm Forming and in Between

Up to World War II, only soft metals had been extruded on a large scale. In normal operations, lead was extruded at room temperature, aluminum either cold or hot, and copper hot. The extrusion of steel was severely limited by lubrication problems. Excessive friction along the die wore it out so quickly that a satisfactory extrusion was impossible. On the other hand, even moderate friction along the chamber wall entailed a considerable increase in the required force so that direct extrusion had to be limited to very short billets. Of course, indirect extrusion, where the die is inserted in the movable ram and not in the opposite end of the chamber, could have been quite beneficial by offsetting this increase, but in production it was limited to special cases due to design difficulties. Its main use was in laboratory studies, where it is desirable to eliminate varying friction, the better to observe the process variables.

The Ugine-Sejournet process (Sejournet, 1955; 1966) is based both on the use of a lubricant in a viscous condition at extrusion temperature and on a separation between the lubrication of the chamber wall and that of the die. A steel billet is heated to the extrusion temperature and then rolled in a powder of glass. The glass melts and forms a thin film, 0.5 to 0.75 mm (20 to 30 mil) thick, of viscous material coating the lateral surface of the billet and separating it from the chamber wall. The relevant coefficient of friction is thus so reduced that the force required for the extrusion is practically constant throughout the extrusion, whatever the length of the billet and with the exception of a starting point.

On the other hand, a thick solid glass pad, 6 to 18 mm (0.25 to 0.75 in) thick, rests on the entry face of the die, which, for this purpose, is at least partly flat. The front face of the billet (Fig. 28) shapes this glass pad into a longitudinal contour corresponding to the metal flow and, at the same time, melts a thin layer of glass, which will drift along with the outflowing metal and will lubricate its contact with the die. This melting will continue during the whole extrusion and ensure a continuous supply of viscous lubricant between die and extruded product. There is no metal dead zone, and a shear effect occurs in the viscous lubricant. Note that the actual film thickness of the lubricant is exaggerated in Fig. 28.

This process has been developed to such an extent that appropriate powdered glass can be

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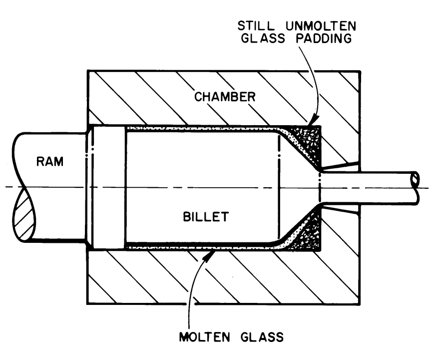

FIG. 28. Steel extrusion by Ugine-Sejournet process.

found for any specific temperature range. The thickness of the glass layer on the finished product is of the order of 1 mil, and after cooling it is easily removed. Initially devised for steel, the Ugine-Sejournet process has been extended to practically all metals and alloys that have a deformation temperature either above that of steel or limited to a narrow range.

Present-day trends in metal forming tend toward the replacement of hot forming and other manufacturing processes by cold forming. Some of the advantages are stronger products, better dimensional precision, surface finish, and savings in material waste. In the extrusion (and other forming operations) of steel, cold forming became feasible with the introduction of phosphate coating, a development that complements (and competes with) the Ugine-Sejournet process, When the steel surface is coated, the spongy phosphate coat absorbs the lubricating liquid, which thus becomes highly effective in reducing friction and wear.

One may say that both developments, the Ugine-Sejournet process and phosphate lubrication, are breakthroughs that solved friction and wear problems. Without these solutions, the metal forming of steel would not be where it is today.

When forming is conducted at temperatures above room temperature but below the recrystallization temperature, it is called warm forming. Today, many forming processes are performed warm to achieve a proper balance between required forces, ductility during processing, and final product properties. During warm forming of most steels, a specific range of temperatures (where the steel hardens by precipitation hardening) should be avoided. With today's sophisticated equipment for the control of temperature and its distribution, the choice of the working temperature may be more precisely followed to ensure optimal production, as typically demonstrated by precision closed-die flashless forming.

Hot forging is usually done with high-alloy tools that can withstand elevated temperature. Tool-life considerations require as short a time of contact as possible between the tool and the workpiece; thus mechanical presses that do not dwell at the bottom of the stroke are recommended for hot forging. Hydraulic presses are commonly used for cold forging, especially of large components; recently they have been replaced for smaller parts by the faster mechanical presses. So today, the choice of mechanical versus hydraulic press may be

Table I. Process Comparisons

Criteria	Mode			
	Hot	Cold	Warm	Isothermal
Ductility	Good	Poor to Good	Moderate	Ideal
Forming Loads	Moderate	High	Moderate	Low
Forming Rate	Fast	Fast	Fast	Low
Dimensional Precision	Poor	Good	Moderate to Good	Good
Surface Finish	Poor	Good	Moderate	Good
Material Conservation	Poor	Moderate	Good	Good
Die Cost	Moderate	Moderate	High	High
Die Life	Poor	Good	Moderate	Poor

decided, not only by the temperature of forging, but also by part size and production volume.

The choice of one process over another, for any product, depends on many factors, including the material of the workpiece, the size, quality, and quantity required, and the producers' likes and dislikes. Some of the criteria for this choice are covered briefly by Avitzur (1983), and a condensed summary is given in Table I.

Forming in the mashy state is an emerging technology. Observing the tensile properties of metals, especially those of metal alloys, it is noted that the gradual drop in strength with increase in temperature undergoes a discontinuity in slope at the solidus line (see Fig. 29). The solidus line represents the temperature at which a solid metal alloy starts the transformation into the liquid state. This transformation proceeds gradually on heating, so that larger and larger portions of the specimen become liquid with increasing temperature until the liquidus temperature is reached, at which point the entire specimen melts. The way alloys liquefy is unique. First, drops of liquid nucleate at the grain boundaries. When the temperature rises only slightly above the solidus temperature and only a small percentage of the workpiece is liquid, the entire network of grain boundaries is already liquid and each individual grain floats in liquid. This condition accounts for the drastic change in strength at this temperature and explains the different behaviors of metals during forming in the mashy state (Kiuchi *et al*., 1979a; 1979b). [*See* PHASE TRANSFORMATIONS, CRYSTALLOGRAPHIC ASPECTS.]

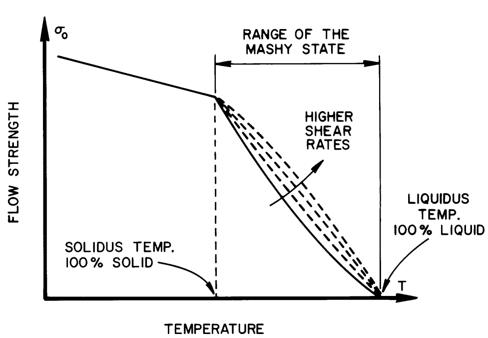

FIG. 29. Strength characteristics in the mashy state.

Plastic deformations in the mashy state occur mainly through solid grains sliding along the liquid grain boundaries. During compacting, the grains themselves may simply be rearranged relative to one another like sand or powder. The viscosity of the liquid metal and the thickness of the liquid layer determine the strength of the workpiece. Furthermore, the rate of shear within the liquid layer [see Eq. (13) and also Avitzur, 1979] determines the resistance to flow; the higher the rate, the higher is the resistance. The dashed lines in Fig. 29 indicate higher strengths for higher shear rates. In actual forming, these higher shear rates are caused by several factors. For example, they can be brought about by higher forming speeds, as with higher ram speeds in extrusion and forging. In the forging of disks, for a constant ram speed, the thinner the disk, the higher are the shear rate in the liquid and the resistance to flow.

In the application of forming in the mashy state, precautions must be taken to prevent squeezing of the liquid outward through the surface. For example, in extrusion, the billet is usually heated to the mashy state and placed in a preheated chamber. When the extrusion takes place, the extrudate may heat up due to deformation and friction, and thicker layers of the grain boundaries may then melt. Preventing the liquid grain boundaries from squeezing out is of utmost importance and can be achieved by cooling the product at the exit. Closed-die forging is advantageous for forming in the mashy state because the confinement of the workpiece in the die automatically safeguards against liquid escape.

In general it is observed that forming in the mashy state at a higher temperature and liquid phase results in lower required pressures but with products of inferior properties (i.e., lower tensile strength combined with cast dendritic structure of lower ductility). Comparisons between forging from the melt and forging in the mashy state are made in Table II.

Forging from the melt is a process that competes with forming in the mashy state. Forging from the melt is accomplished by pouring molten metal into a mold, which serves as a die, and applying ram pressure while freezing progresses, (Ramati *et al*. 1978). As the molten metal gradually solidifies, its volume decreases and the ram force must be applied continuously. The surface of the workpiece freezes first. A drastic volume drop is associated with the phase transformation on freezing from the liquid to solid phase. This volume change due to phase transformation is vastly greater than the shrinking that occurs with the temperature drop in the solid state. Thus, as the interior freezes and shrinks, the ram advances into the workpiece and (depending on the skin temperature) causes the skin, which is already solidified, to fold over, wrinkle, and even crack. Skin defects are a major obstacle in the application of forging from the melt. Nevertheless, aluminum automobile wheels are mass produced by this process, as well as by forging in the mashy state. The two processes are competing for the same products.

TABLE II. Comparison between Forging from the Melt and Forging in the Mashy State

Forging from the melt	Forging in the Mashy state
On solidification, the workpiece conforms to the die cavity	Upsetting to any degree can be incorporated. The billet's shape differs from the cavity's
Solidification starts at the interface with the die, while the interior is still liquid. When the interior freezes, the volume is reduced, the punch (or top die) goes deeper, and the previously frozen skin wrinkles.	The liquid phase is uniformly spread through the workpiece on the grain boundaries, permitting easy shifts of grains throughout the workpiece.

Presently, workers in the field on production problems prefer the process of forging from the melt, also called "forge squeeze," "molten squeeze," or other similar terms, over forging in the mashy state. However, progress in the work on forging in the mashy state suggests some potential advantages, especially in extrusion of composites containing filamentary hard whiskers. A solution is still being sought for the best mode of mixing the matrix alloy with the whiskers.

E. Soft Tooling

In a typical metal-forming operation, the shape of the product is imposed by the tools. Thus, the tool is required to have a higher strength than that of the workpiece. For our purposes, tools include dies or rolls in drawing, extrusion, forging, and rolling; they also include the chamber and ram or punch in extrusion or deep drawing. However, there are techniques where the tool is softer than the workpiece.

For example, during the process of conventional ram extrusion, the ram or punch that pushes the billet through the die does not control the shape of the extrudate (product). The shape of the product is controlled solely by the shape of the opening in the die. The hard ram of conventional ram extrusion is replaced by a soft tool, the liquid, in the process of hydrostatic extrusion.

Components, mainly those produced from sheet metal or from tubing, can be shaped by a hard tool on one surface only. The contour of that surface will control the contour on the opposite side without the use of a hard, shaped tool on that side. Such components may be candidates for soft tooling.

Brake-press bending of a strip into an angle forming a channel is shown in Fig. 30. In the top picture rigid tooling is shown, while in the bottom picture, the female die is replaced by an elastomer. During rigid tool forming, the region of deformation in the vicinity of the bent corner is in contact with the ram only and is free on the other side. When bent with a female die of a soft yielding material, the bending corner is confined by the hydrostatic pressure imposed by the soft

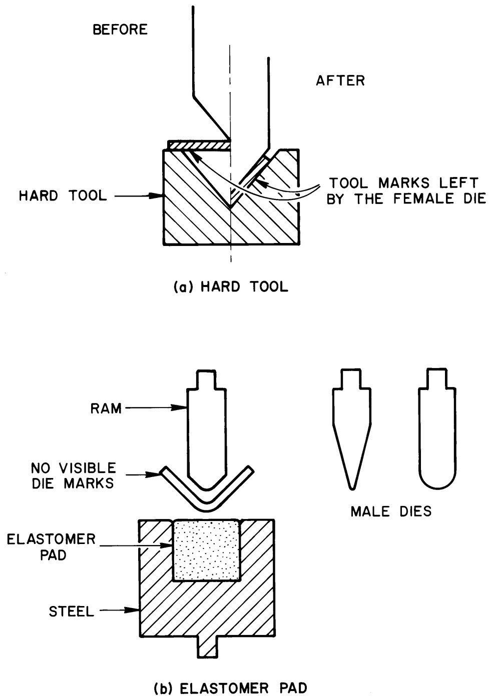

FIG. 30. Brake press: (a) hard tool and (b) elastomer pad.

tool, with beneficial effects on ductility in the deformation region. The hydrostatic pressure can easily be controlled through the strength of the elastomer material, the geometry of the elastomer, and its support.

The examples shown in Fig. 30 pertain basically to sheet-metal bending processes and to thin-wall tube forming. Even in this restricted area, only a small selection of shapes has a potential for soft tooling.

The main incentives for the use of soft tooling are the low cost of tooling and the ductility of the workpiece affected by the hydrostatic component of pressure that the soft tool exerts.

Usually the male component of the die is the hard tool, and the female component is the soft tool. There is no shaping of the soft tool, and the die cost is less than half the cost of hard male-female die set.

The soft tool may have to be replaced more often than the hard tool, but the elastomer pad is easier and cheaper to replace than a machined, heat-treated, and polished tool-steel die. The elastomer pad of Fig. 30b can be placed in four alternative positions before it is replaced. The most usual elastomer material is rubber or urethane of controlled hardness. Avitzur (1983) presents alternative designs in which liquid under pressure replaces the elastomer. Thus reasonable and sometimes unlimited lifetimes can be expected of the soft tool.

A major problem in sheet-metal forming, especially in a brake press, is springback caused by the residual (elastic) stresses. For example, if a bend with an included angle of 90° is desired for the channel, the ram might have to be designed with an 85° included angle. Any reasonable change in the design of the ram is compatible with the basic design of the soft counterpart.

Brake-press bending with the hard tools may leave tool marks, which are eliminated when soft tools are employed. On the other hand, when hard tools are used, a smooth product surface with duplication of intricate designs can be achieved, while the surface finish achieved by soft tooling is rough and intricate designs can be duplicated only on the side facing the hard tool.

Earlier in this section, the beneficial effect of the environmental hydrostatic pressure of soft tooling on the ductile behavior of the workpiece was mentioned. For example, in Fig. 31a, the deep drawing of a cup with soft tooling is described. When a cup is drawn with a spherical-nosed mandrel without the soft tool opposite to the mandrel, the depth of draw is limited by stretching, thinning, and consequent tearing of the workpiece over the mandrel. When a soft tool presses the workpiece against the mandrel, sliding between the workpiece and the tool is arrested and stretching and thinning are minimized, deterring cup tearing and extending the possible depth of draw. Furthermore, soft tooling can be adapted to a standard press.

Replacement of the elastomer in Fig. 31a with a pressurized fluid is described in Figs. 31b and c. While the design of the liquid pressure chamber can be adapted for a standard press design, hydroforming and hydromechanical forming are performed on specially designed presses with the pressure chamber and pressure supply mechanisms as integral parts of the press. The processes of hydroforming are also called “rubber-diaphragm-forming.”

In Figs. 31b and c (hydroforming), the pressure chamber is sealed by a diaphragm, separating the workpiece from the fluid. During hydromechanical forming the workpiece is in direct contact with the liquid, with the seal at the blank holder to prevent liquid leakage. As the punch advances, the pressure in the chamber rises, causing the workpiece to wrap around the punch. Raising the pressure too early may lead

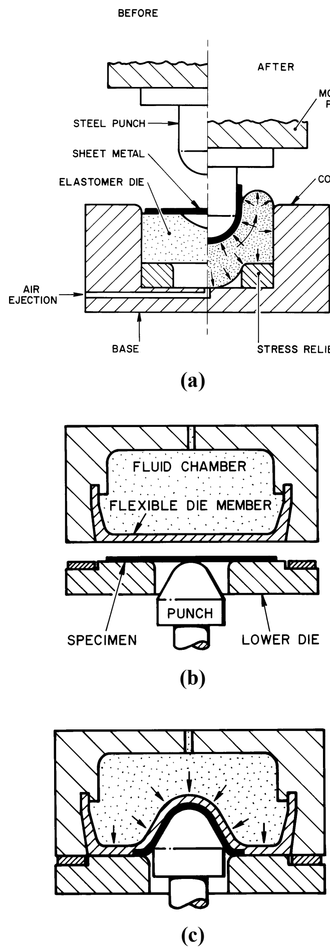

FIG. 31. Deep drawing with an elastomer die. (a) Deep drawing with an elastomer pad; (b) & (c) deep drawing with pressurized fluid; (b) before, (c) after.

to tearing, while too little pressure at the early stages leads to wrinkling. When a very thin blank is to be hydroformed, it is customary to back the blank with a dummy blank of iron or copper. The sandwich material is formed in unison, so that wrinkling is avoided. The dummy blank is called a "water sheet."

One fluid pressure chamber may serve for the production of a variety of components in a range of sizes. When a changeover to another product takes place, only the punch need be changed. The liquid pressure can be programmed independently of the position of the punch. Thus, changes in the pressure versus time can be effected to maximize the drawability of the component. In contrast with the use of elastomers, these pressure changes can be effected without tool modification. The advantage of controlling the pressure sequence independently is in higher drawability.

The use of soft tooling and high temperature combine together in the implementation of metal forming with super plastic flow. The phenomena of superplasticity have been observed in the characteristics of many metal alloys. With certain small-grain structures and in certain ranges of elevated temperature, these alloys may flow practically without limit under very small loads but at very low rates of straining. A tensile specimen made of a superplastic metal when tested at the proper temperature at a low enough rate will undergo over 1000% elongation and will stretch like viscous glass into a fiber before separation. The superplastic material in the state of superplasticity is highly sensitive to the rate of straining. Any section that temporarily remains slightly larger in cross section will instantly proceed to stretch at higher rates than the smaller sections because the strain rate is inversely proportional to the area. Thus, the stretched portion of the specimen is automatically maintained at a uniform diameter. When the same tensile rod made of superplastic alloy is tested at room temperature. The superplastic behavior vanishes. Such a test will exhibit higher strength and a stress-strain curve (Avitzur, 1983).

Thus, a superplastic alloy may be formed with simple tooling and very low loads when it is brought up to its superplastic temperature. When the desired shape is obtained and the temperature is lowered to room temperature, the part possesses high strength and can serve as a load-carrying structural component. However, some superplastic materials will creep slowly and get out of shape if loaded for a long time.

Titanium alloys can be forged in the superplastic range into a rotor of a turbine engine with the blades intact. Another typical superplastic material is the alloy of zinc with aluminum and minute additions of copper, magnesium, and other elements. A popular superplastic zinc alloy is 78% zinc by weight with 22% aluminum and is called 78-22 alloy. At room temperature, the strongest zinc alloys exhibit ultimate strength of about 4000 kg/cm^2 (60,000 psi) and a reasonable ductility. At 260°C this material is in its best superplastic state. The range over which this material exhibits its high formability is between 250°C (480°F) and 275°C (527°F), which is a narrow range. Objects such as the carrying case of a typewriter are made of this alloy or from a polymer.

In Fig. 32 a mold made of two halves split

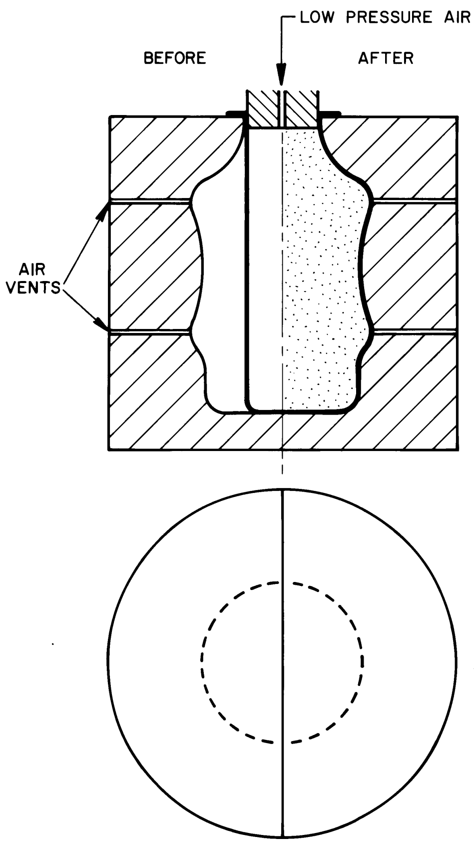

FIG. 32. Pressure-aided deep drawing.

parallel to the axis of symmetry is delicately decorated on its interior. A thin-wall, deep-drawn cup is heated and placed in the die assembly. The opening is sealed and air or argon gas at low pressure (above atmospheric) is pumped into the cup. Very slowly the cup expands and fills the mold perfectly to reproduce every detail of curved design.

Alternately, a flat sheet may be placed over the cavity of the mold. Vacuum may be introduced in the interior, sucking the sheet into the cavity. If desired, the operation may be initiated by vacuum and completed by pressure.

While the above process is slow, the equipment is simple and inexpensive and so are the dies. Very low loads are exerted, and the die life is unlimited. Even when a battery of dies is engaged to increase production rates, the overall economy of the process is retained because of the low cost of tooling and equipment. Because the processing is conducted at a constant temperature, it is also termed isothermal processing.

V. Replacing Brute Force

As larger and larger components of stronger and stronger metals are in growing demand for forming processes at room temperature, even the largest available equipment of conventional design, for bulk deformation by static loading, is no match for the job. Finesse must replace brute force. Some of the measures are old and still usable today. Inertia forces may replace static loading as in hammering. Today the repeated beatings may be applied through ultrasonic exitations of the tooling. Another concept calls for the application of the load locally, to affect minute changes at a spot, and transversing the spot throughout the entire workpiece, several times over, if needed. One class of processes is called rotary forming, and spinning is the example presented here. The local load is much smaller and therefore so is the equipment. Usually the processing time per part is higher, but large components are not produced in as many numbers as smaller ones. The mechanics of the process of spinning are similar to those of pottery-making a clay vase. Only the materials of both workpieces and tools are different.

A mandrel shaped to conform to the interior of the product is clamped to the rotating head of a spinning machine (See Fig. 33). For ages a stick of hard wood, with or without a copper tip, has been manipulated against the blank, back and forth, progressively laying the thin gauge blank against the mandrel. Holes, at intervals on the bed of the machine, are pegged to provide

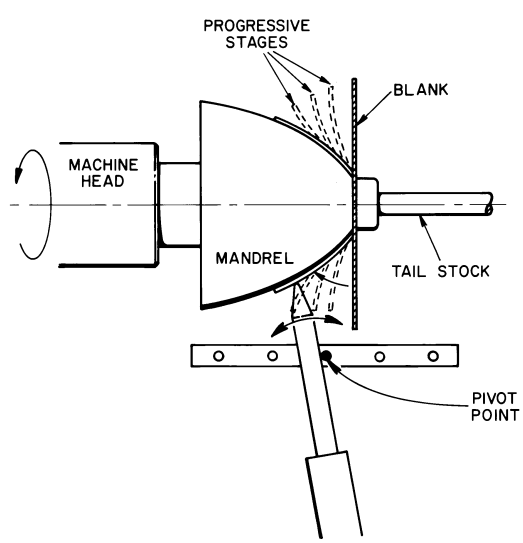

FIG. 33. Conventional manual spinning.

support and leverage for the operator. When necessary the leverage mechanism is made more complex. The operator may strap himself to the frame of the machine, like a window washer on a tall building. Two operators may assist one another, and heavier gauges of harder material can be worked by heating the workpiece. The friction between the tip of the stick and the workpiece is large. In later models, especially in power-mechanized spinning, the solid tip of the stick is replaced by a roller to minimize friction losses, replacing sliding by rolling friction.

The proper manipulation to achieve good results was an art gained by experience. Because of springback (which is a major factor in spinning with manual tool manipulations) and the closeness of the operator to the operation with no safeguards, all "old-timers" in spinning carry scars caused by close encounters with the edge of the rotating blank.

Cooling pots and frying pans of aluminum and copper and like products were made by conventional manual spinning. They still are in some developing and under developed regions of the world. Precision of size and wall thickness and repeatability are not critical for such products and cannot be achieved by hand spinning. The process is slow, labor-intensive, and unsuitable for mass production. But the tooling can be made simple and inexpensive.

Occasionally prototype development on a limited production basis is produced by hand spinning, even today, and even in advanced technological societies. Changes are easy and inexpensive to introduce. Some experienced spinning machine operators can produce vessels of complex shapes without the support or backing of the mandrel to define the desired shape. Changes in shape and narrower sections can be improvised on the spot.

Next, spinning of cones and vessels will be presented, and then tube spinning. When mechanized, spinning is more economical for the production of small numbers of pieces than deep drawing because of the low setup time and costs of spinning. The pattern, for example, can often be made of wood or aluminum, thus saving tooling expense.

For the last thirty years the trend has been toward mass production with power spinning. The advantages of replacing manpower by mechanical power are the same for spinning as for any other industrial process. However, mechanical power requires a control system, and controls require prediction of the forces and motions to which the machine has to be set. In spinning operations, as they are performed today, this means the following things: (1) the tool is usually no longer manipulated back and forth, but performs the deformation in one pass; (2) the rotational speed, the feed, and the head-in pressure have to be fixed and preset before spinning is started.

Most recently, numerically controlled (NC) machines have been offered. The following advantages are claimed:

1. They have the ability to produce and execute extremely complex programs to make extremely complex parts, impossible hitherto.
2. They have the ability to make minor program adjustments during initial runs for optimization of machine and material utilization.
3. They have the ability to make short runs and store programs for reuse.
4. There is a high degree of repeatability.

In the early days of mechanized spinning, the manual application of the tool to the workpiece was replaced by two hydraulic piston and cylinder assemblies pushing the tool carriage against the workpiece and in the feed direction. The path of the tool was dictated directly by a template. With the further advance of hydraulic control systems, the guidance of the tools was delegated to a closed-loop feedback system whereby a stylus that followed the template activated, through valves, the pistons that controlled the motion of the tools. The template could be scaled up or down, and in more sophisticated methods a drawing could replace the template. The spinning could be performed by several passes of the tool, changing the position of the template, or the drawing, for each pass.

With the introduction of the stylus control, manual manipulation of the tool could be reintroduced. While the power is supplied through the hydraulic pistons, the positioning of the tool can be delegated back to manual manipulation and the tool can be applied repeatedly as shown in Fig. 33. Brute force, applied by the machine, is delicately controlled manually. While this option is feasible, it is infrequently applied, because the last generation of skilled manual operators is fast disappearing. In Fig. 34b, for power spinning of a cone, the tool(s) advance only once, in a motion parallel to the surface of the mandrel from top to bottom, pushing the flange ahead downwards while laying the workpiece under the roller flat onto the mandrel.

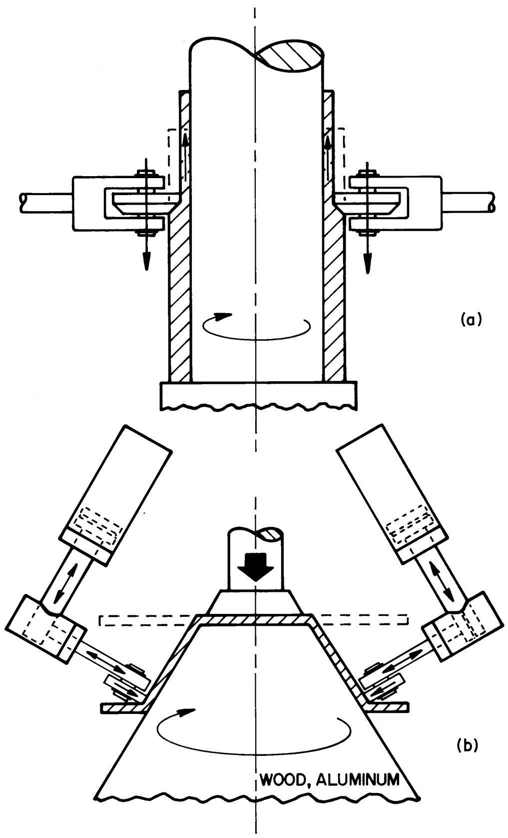

FIG. 34. Multiple spinning heads.

The strong head-on pressure applied during power spinning with a single tool causes high bending moments on the mandrel and asymmetric loads on the machine. Mechanized spinning machines are designed with two symmetric tool heads (see Fig. 34) and sometimes, in vertical tube-spinning machines, with three heads. The individual heads are usually arranged in tandem. For example, in tube spinning (Avitzur, 1983) one head may take half of the reduction in thickness while the second head follows by several revolutions and takes the second half of the reduction.

In tube spinning (also called "cylindrical flow forming"), a heavy-gauge tube is mounted over a rotating mandrel. The tool holder, with the roller pressing against the tube, advances slowly in the axial direction as the workpiece rotates under the tool. The wall thickness decreases locally under the pressure of the tool while the tool gradually advances through the entire tube surface. During tube spinning the thinning of the wall results in elongation of the tube in the axial direction with no change in the nominal diameter.

VI. Approaches to Understanding Metal Forming

A. Analytical versus Experimental Approach

When developmental work is conducted with production equipment in the plant, it disrupts operation of the plant and causes intolerable expenses. It is common practice to establish separate research and development activities. The full spectrum of such an activity and the alternative approaches, complementing one another, are presented in Fig. 35.

Short of doing developmental work on a production scale, all other methods can be classified as modeling or simulation. In Fig. 35, the pie is divided into formulation and a physical lab of simulation methods or into mathematical and physical modeling sections. Mathematical modeling is further divided into analytical and numerical modeling. The old, but still in existence, method of developing and using empirical expressions is overlooked here.

B. Physical Modeling; Scaled-Down Models and Visioplasticity

The most common physical modeling procedures are modeled by scaling down of size or by experimenting with modeling materials. In either case the equipment may be highly instrumented with sensors and recording and control capabilities that are not used on production equipment. When the proper tooling

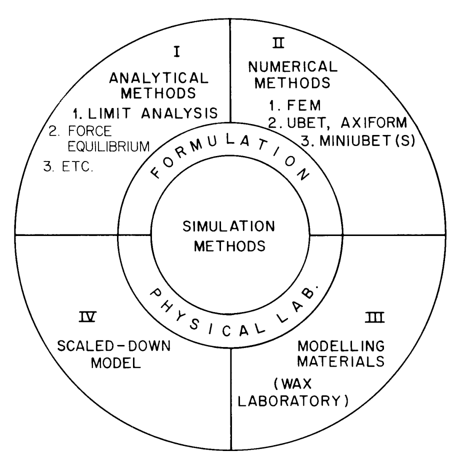

FIG. 35. Classification for planned activities in metal forming.

and procedures to produce the desired product have been identified by physical modeling, the transition to the production mode is usually smooth with no surprises.

Scaling down of the size of a component with which the experimental work proceeds brings savings in materials, tooling, equipment size, space requirements, and operating costs as well as expediting the development stage. The discussion of mathematical modeling will show that for metal forming at room temperature the scaling up is automatic, and conditions, for example, that prevent failure on small-scale models are identical to those required for the production size.

The loads employed to impose plastic flow in the scaled-down model are proportionally lower than those required for the production size. Thus, the measured loads from the experiment provide the information regarding loads to be needed for production runs.

Production equipment can be replaced in the laboratory by less expensive means when the actual workpiece is modeled by a softer material. Lead was used to study flow patterns for many years. Plasticine and wax are very popular today. Since the loads are smaller, expensive die materials can be replaced by aluminum, wood, or Plexiglas. The equipment itself need not have a strong frame or a large power supply. It can be built at a fraction of the cost of production equipment and is inexpensive to operate. Several laboratories have been built for modeling material simulation by wax.

To make the model realistic, waxes can be mixed with additives so that their properties may resemble those of the workpiece material. Strain-hardening properties and strain-rate behavior can be controlled by those additives. Even tool materials can be chosen so that tool rigidity can be made to match the strength of the wax in the same manner that the real tool will relate to the workpiece. Friction conditions can be controlled by means of lubrication to best simulate the friction conditions during actual production (Wanheim, 1978-1979). The main purpose of studying through modeling materials is to observe the flow patterns and thus to develop dies that produce a sound product.

A picture of a cross section along the axis of symmetry of a multilayer wax forging is reproduced here as Fig. 36. The original cylindrical workpiece was constructed from two colors of wax, checkered in coaxial cylinders and flat planes normal to the axis of symmetry. Each rectangle represents a ring of rectangular cross

FIG. 36. Wax models. (From Wanheim, 1978-1979).

section. The boundaries of the rectangles form a rectangular network of grid lines. These billets can be forged, extruded, rolled, or formed by any other conceivable metal-forming process. A full billet can be formed by using a complete set of dies. On completion of the forming process, the billet can be sliced and the deformation pattern studied. On the other hand, half billets can be formed and the flat surface may be exposed to view through a Plexiglas window. Pictures of the deforming specimen can then be taken at predetermined intervals. The position coordinates of each corner of the checkered grid can be determined at each interval. This procedure is defined as "visioplasticity." The data is then fed into a computer with a program that will determine the following: (1) a displacement field, (2) a velocity vector for each point at each moment. Thus, when the velocity field is fully determined, (3) a strain-rate field is calculated from the velocity field; (4) a stress field is calculated from the strain-rate field, the history of deformation, and the characteristic stress-strain relationship for the workpiece; (5) the stress load on the surfaces of the die is calculated from the stress field, and (6) the measurement of the total load during forming is determined. By integration of surface stresses on the die over its entire surface, the load is calculated and compared with the measured total force.

In parallel with the study of the distorted grid in the workpiece, the deformations of the die itself are occasionally measured by the light photoelastic method. In those cases, it is possible to compare the stresses in the die, including sites of stress concentration and their levels, with those derived from the workpiece.

The far-reaching program described here is still in its developmental stages. Nevertheless, the results achieved so far leave no doubt about the contributions already made and the potential value of this approach. Preliminary tooling for new products and even for new processes can be designed reliably by using a modeling materials laboratory at a fraction of the cost of running developmental work on production equipment.

C. Analytical and Numerical Methods of Modeling

Exact solutions are not available for problems in metal forming. Approximations and simplifying assumptions are inevitable, and many approaches-slug equilibrium, slip-line techniques, and others-have been partially successful.

Limit analysis (Avitzur, 1980) is a promising approach and is being used with increasing frequency. In this approach, as applied to the study of drawing or extrusion force, two approximate solutions are developed. One, the upper-bound solution (Kudo, 1960, 1961) provides a value that is known to be higher than or equal to the actual force; the other, the lower-bound solution, provides a value that is known to be equal to or lower than the actual force; the actual force thus lies between the two solutions. For example, in Fig. 37 with the drawing stress as ordinate and the semicone angle of the die as abscissa, upper- and lower-bound solutions are plotted for several reductions together with corresponding measured values of the actual stress. Even when experimental results are not available, it is expected that the actual stress and the exact solution, if these were available, would lie between the upper and lower bounds as obtained analytically. Thus, by limit analysis, an approximate solution is given with an estimate of the maximum possible error. The gap between upper- and lower-bound solutions may be narrowed by providing several upper bounds, choosing the lowest, and by providing several lower bounds, choosing the highest. Upper- and Lower-bound solutions are obtained only by following strict rules (including the requirement of the proper description of friction behavior and material characteristics). A full illustration of limit analysis is given by Avitzur (1983).

A large number of analytical approaches complement the still existing empirical expressions. Each approach has some advantages and shortcomings, and until a perfect approach is available, they all complement and assist each other. With further progress, and as each approach gets closer to the exact solution, they also get closer to each other to the extent that some initially thought to be conflicting rival approaches turn out to be identical. The upper- and lower-bound solutions for some metal forming processes, for example, disc and strip forging (Avitzur, 1983) are so close that when plotted together, both curves are almost overlapping. The expressions for drawing in plane strain, obtained by the upper bound are identical to those obtained by a force equilibrium on a rigid triangular element (Westwood, 1960). The same similarities can be observed between the upper bound and slipline solutions to other problems in plane strain. The popular slipline technique identifies surfaces within the workpiece, along which shear stress is at its peak. Thus, the material along these surfaces shears producing plastic flow and the shaping of the workpiece. The slip line technique, based on the stress equilibrium approach, identifies surfaces along which maximum shear stress prevails. In a comparable manner the upper bound approach, based on deformation patterns, offers the stream line technique and the associated stream function. See Talbert and

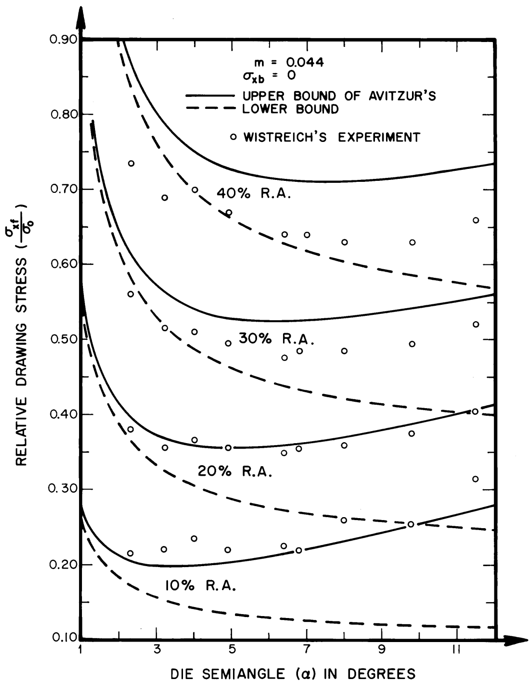

FIG. 37. Relative drawing stress versus semicone angle and percentage reduction in area during wire drawing.

Avitzur (1996). Here a flow line along the path of a particle through the deformation region determines a function $f(x, y, z \text{ and } \varepsilon)$ = Constant, where x, y, and z are coordinates in space, and ε identifies each specific flow line. When this function and its derivatives are set to conform to the geometrical boundary conditions imposed by the tooling, a stream function is derived. Such a stream function leads to the determination of the strains and strain rate components and to the derivation of an upper bound solution for the energy required. In practice this method is applied to two-dimensional conditions. Although this method is applicable to non-steady state flow, it is more easily applied to steady state flow.

In the free slug equilibrium approach bulk elements of the workpiece are considered and the forces acting on them are set in equilibrium. As has been shown, with proper adaptation, the free slug approach provides the following expression for the relative drawing stress in wire drawing, which is very close to the upper bound solution presented in Fig. 38.

$$\frac{\sigma_{xf}}{\sigma_0} = \frac{\sigma_{xb}}{\sigma_0} + 2\ln\left(\frac{R_0}{R_f}\right) + \frac{2}{\sqrt{3}} m \cot\alpha \ln\frac{R_0}{R_f} + \frac{4}{3\sqrt{3}}\tan\alpha$$

(Avitzur, 1980).

With the computer revolution, several numerical methods emerged as computational tools to study metalforming. In the procedures described next the workpiece is divided into a finite number of elements. Each element experiences a continuous plastic deformation pattern, which may also be a rigid body motion. The elements also experience sliding motion with respect to each other and along their contact surfaces with the tools. The elements are bordered (restricted) by each other, and by the surfaces of the tools, or they are free, exposed surfaces. The total energy required to impose plastic flow of the entire workpiece is calculated piece by piece as the sum of energies expended in each of the elements and along their surfaces.

The numerical methods mentioned can be compiled into three major groups, i.e., the "Upper Bound Elemental Technique" (UBET), its offspring, the "Spatial Elementary Rigid Region" (SERR) Method, and the "Finite Element Method" (FEM). UBET was introduced by Prof. Kudo (1960, 1961) as an extension to his analytical upper bound solutions to fundamental elementary shapes. Any workpiece of complex shape undergoing plastic deformations can be constructed as an assembly of a number of the elementary shapes. The UBET computerized procedure then determines the total deformation energy. The initial UBET procedures were restricted to axisymmetric and plain strain deformations. The basic elements were rings and cylinders of rectangular and triangular cross-sections.

The extension to three-dimensional problems by the SERR method was made by the introduction of the Tetrahedral element that undergoes a linear rigid body motion. A workpiece of any shape can be constructed from an assembly of tetrahedral elements where the curved surfaces interfacing the tools are approximated by plane surfaces. The plastic deformation of the workpiece is then accommodated by the sliding of the elements, one with respect to each other, and along the surfaces of the tool. See Avitzur (1993), Azarkhin and Richmond (1992), and Prafulla Kumar Kar (1998). The tetrahedrons themselves act as rigid bodies and consume no energy of deformations. Energy is consumed only along the surfaces of the tetrahedral elements where sliding occur.

The potential for the SERR method is unlimited. The linear rigid body motion of the elements may eventually be allowed to experience the more general rigid body rotational motion where the plane surfaces of the tetrahedral element are replaced by more complex curved surfaces. Any shape of the workpiece will be automatically divided to a minimal number of tetrahedral elements, and the motion of each element will be automatically determined. Better precision will be reached when each large element will be subdivided automatically to (twelve) smaller ones.

Today the most popular of the numerical methods is the FEM, which proved itself in other fields such as electricity, heat transfer, and fluid flow. In the FEM the workpiece is divided into a finite number of elements that may undergo plastic deformations. In one approach, for each element the differential equations of equilibrium of the stresses are replaced by an equilibrium on a set of finite differences of the stresses.

Material properties may be introduced in any complexity desired to reflect real behavior. The procedure to obtain flow patterns and tool loads is iterative in nature. The more complex the geometry and the material, the longer the time it takes; and larger computers are then required for a single solution. There is no doubt that with the advancement in computer technology and better finite element procedures more and more of the tooling design for metal forming will be assigned to the FEM method.

D. Pros and Cons of the Different Modeling Procedures

The construction of production tools for large components may be rather expensive. Ideally, the first tool for a new product should be the best one possible. In practice, however, the first tool may fail to perform as expected, resulting in a defective product or a fractured tool. The possible modes of failure are numerous, and some of them are most common. Modeling by scaling down, by modeling materials, and by mathematical models makes the road to the choice of best production tooling shorter. Comparisons and guidelines for the choice of the most suitable modeling method for each circumstance will be attempted.

In comparing experimental procedures of small-scale or material modeling on the one hand with mathematical modeling on the other hand, one notes that the development of a mathematical model is much more time-consuming. In the study of flow through conical converging dies (Fig. 39), many flow patterns are observed that lead to failure. The choices of die angle, reduction, and friction that lead to those failures are presented by the inserts. For example, the development of the criterion for the prevention of central burst took about 18 months. This derivation was based on years of work in the general area of flow through conical converging dies and the application of the upper bound approach to metal-forming processes in general. Such work requires a specialized expertise, which is quite scarce at present. Furthermore, the original criteria, although useful, may need further study.

The specific problem that prompted the central-burst study (Avitzur, 1968) could have been solved by a trial-and-error, experimental procedure in a few weeks or months by personnel without an analytical background. As a matter of fact, experimental procedures were employed successfully for the elimination of central burst, when discovered, prior to the development of the criteria. Every new appearance of the phenomenon called for a new study, but the resolution of the problem did not add to the understanding of the causes of the defect or to a solution to the problem when it appeared again. The analytical criterion, on the other hand, is universal; it applies anywhere and to any material. When an analytical solution is applied successfully to a new problem, the technique itself advances further, making the next solution for another problem easier and more reliable. The potential for the application of analytical methods is unlimited.

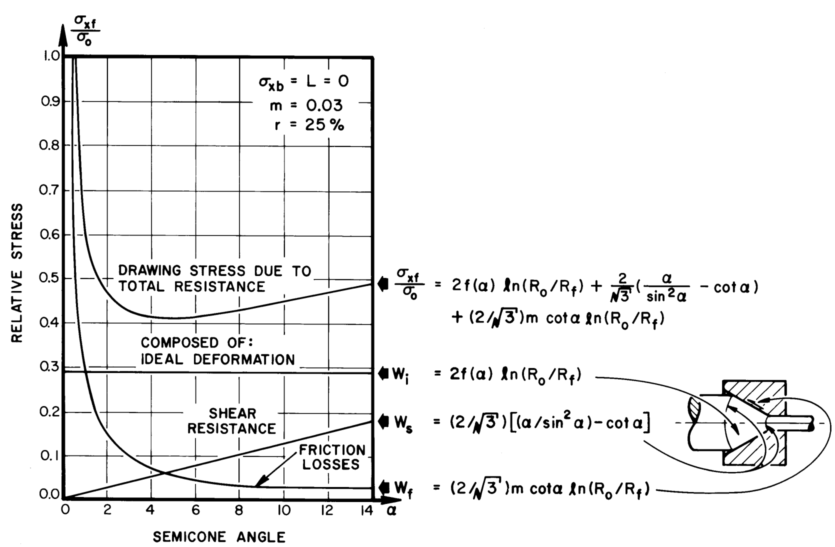

FIG. 38. Upper-bound solution to flow through conical converging dies.

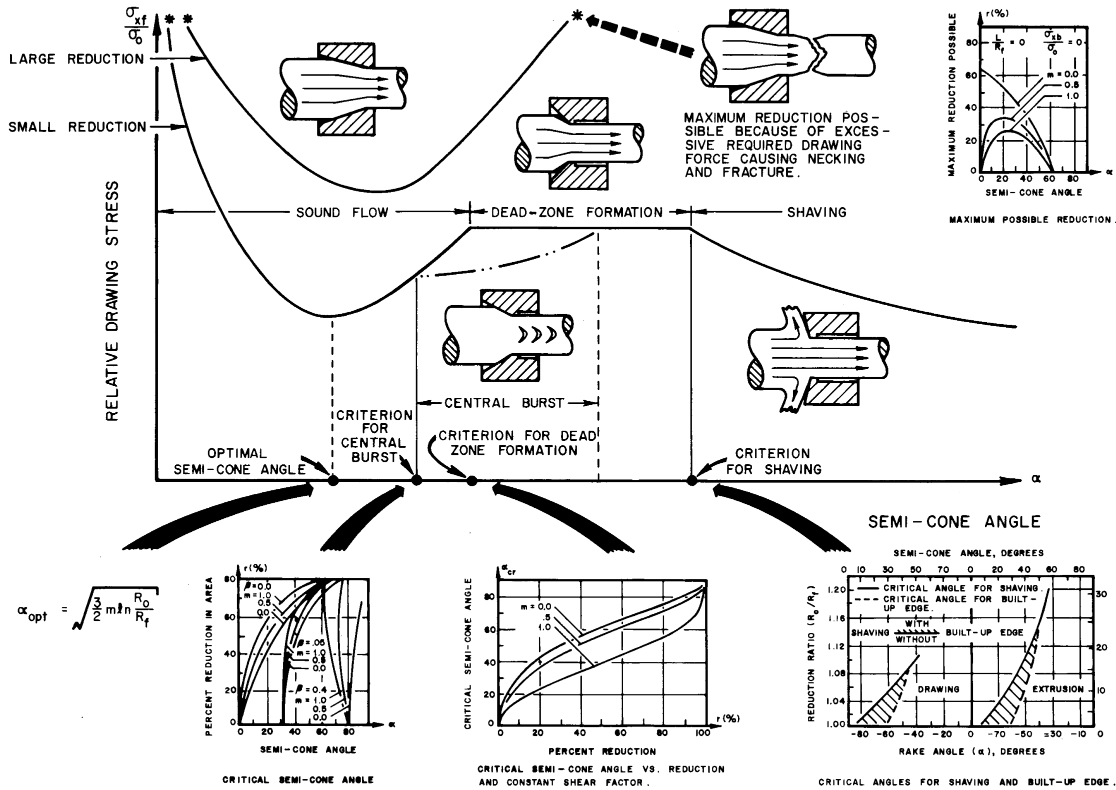

FIG. 39. Criteria for failure in flow through conical convergine dies.

However, when a specific problem arises, the pressure of time may dictate experimental methods. For example, the study of flow patterns for complex forging may one day be conducted analytically or by numerical procedures. At present, however, experimental work is the only practical solution. For the study of die design to prevent unfilled corners and cracks due to folding, modeling materials are most helpful. On the other hand, complex deep-drawing studies cannot be made with plasticine, wax, or lead but can be conducted successfully on a scaled-down model using the real material. Also, studies to determine tool life have not yet been conducted mathematically or through modeling materials; even scaled-down models are not very useful. Die design, including the choice of die material, is only improved through practice on the production line with full-scale equipment.

VII. Summary

The desire to make large parts, take large reductions, use high-strength materials, work to net shape (precision flashless closed die forging), and use cold forming to obtain certain physical properties all require high forming forces. These forces may be larger than the capacity of existing machinery. Some possible solutions are:

1. design larger machines,
2. use inertia forces to allow smaller machines to do the job,
3. take many small reductions, as in superimposition of ultrasonic vibrations,
4. impart localized deformations,
5. use high-energy-rate forming, such as explosive forming, and
6. use modeling methods to identify the optimal condition to minimize forming forces.

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