1. extrusion .

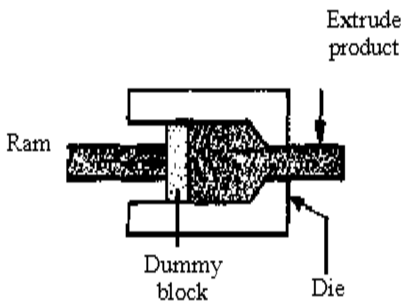


Fig. 1. Direct extrusion

In the **extrusion process** material is forced through a orifice in a closed die (dummy block) which is similar to squeezing toothpaste from a tube (Fig.1), which is similar to squeezing toothpaste from a tube. The cross section of an extrude product is determined by a shape of an orifice. Almost any cross-section may be produced by extrusion. Since the die geometry remains the same throughout the operation, extruded products have a constant cross-section. Depending on the ductility of the material, extrusion may be carried out at room or elevated temperatures. Because a chamber is involved, each billet is extruded individually, and thus extrusion is a batch or semicontinuous process, producing essentially semifinished parts.

Typical products made by extrusion are door and window frames, railings for sliding doors, tubing having various cross-sections, and structural and architectural shapes. Extruded products can be cut into desired lengths, which then become discrete parts, such as door handles, brackets, and gears. Commonly extruded materials are aluminum, copper, steel, magnesium, and lead (lead pipes were made by extrusion in the eighteenth century). Other metals and alloys can be extruded with various levels of difficulty.

Extrusion may be done by various means and is often combined with forging operations, in which case it is generally known as *cold extrusion*.

Drawing is an operation in which the cross-section of solid rod, wire, or tubing is reduced or changed in shape by *pulling* it through a die. Drawn rods are used for shafts, spindles, and small pistons and as the raw material for fasteners such as rivets, bolts, and screws. In addition to round rods, various profiles are also drawn. Drawing is similar to extrusion. However, in drawing, the material is subjected to a tensile force, whereas in extrusion the billet is under compression. The term *drawing* is also used to refer to making cup-shaped parts by sheet forming operations.

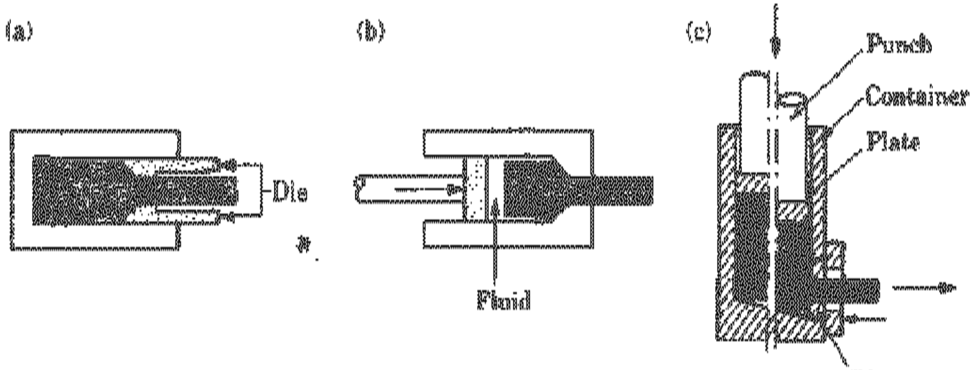


Fig. 2. Types of the extrusion: a – backward extrusion, b – hydrostatic extrusion, c – lateral extrusion

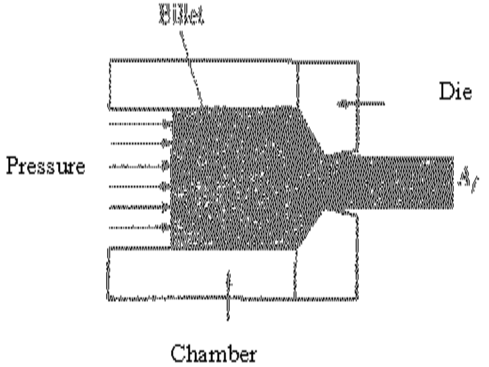
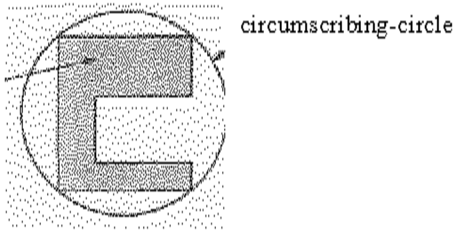


Fig.3. Process variables in direct extrusion: the die angle, reduction in cross-section, extrusion speed, billet temperature, and lubrication

The distinction between the terms rod and wire is somewhat arbitrary, rod being relatively larger in cross-section than wire. In industry, wire is generally defined as a rod that has been drawn through a die at least once. Wire drawing involves smaller diameters than rod drawing.

In the basic extrusion process, called *direct,* or forward, *extrusion,* a round billet is placed in a *chamber* (or container) and forced through a die opening by a hydraulically driven ram. The die opening may be round, or it may have various other shapes. Other types of extrusion are indirect, hydrostatic, and impact extrusion. In *indirect extrusion* (reverse, inverted, or backward extrusion), the die moves toward the billet. In *hydrostatic extrusion*, the billet is smaller in diameter than the chamber, which is filled with a fluid, and the pressure is transmitted to the billet by a ram. Unlike in direct extrusion, there is no friction to overcome along the container walls. Another type of extrusion is *lateral,* or side, *extrusion.*



Method of determining the circumscribing-circle diameter (CCD) of an extruded cross-section

2. Process variables in extrusion

The geometric variables in extrusion are the die angle, α, and the ratio of the cross-sectional area of the billet to that of the extruded product, A_0/A_f, called the extrusion ratio. A parameter describing the shape of the extruded product is the circumscribing-circle diameter (CCD), which is the diameter of the circle into which the extruded cross-section will fit. Thus the CCD for a square cross-section is its diagonal dimension. The complexity of an extrusion is a function of the ratio of the perimeter of the extruded product to its cross-sectional area, and is known as the *shape factor*. You can see that a solid round extrusion has the lowest shape factor. Other extrusion-process variables are the *temperature* of the billet, the *speed* at which the ram travels, and the type of *lubricant* used.

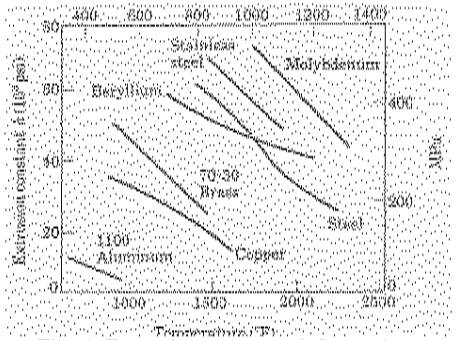


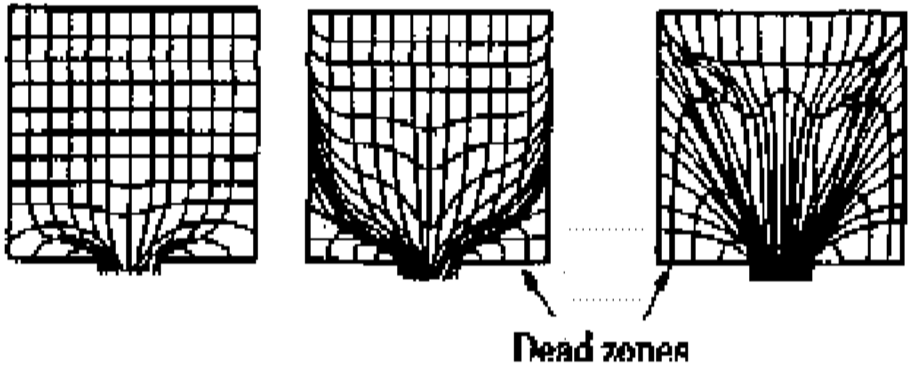
Fig. 4. Extrusion constant *k* for various metals at different temperatures

The force required for extrusion depends on the strength of the billet material, the extrusion ratio, friction in the chamber and die, and process variables such as the temperature of the billet and speed of extrusion. We can estimate the extrusion force *F* from the formula

$$F = A_0 k \ln\left(\frac{A_0}{A_f}\right),$$

where k is the *extrusion constant,* and A_0 and A_f are the billet and extruded product diameters, respectively.

The metal flow pattern in extrusion, as in other forming processes, is important because of its influence on the quality and mechanical properties of the final product. The material flows longitudinally much like fluid flow in a channel, so extruded products have an elongated grain structure (preferred orientation). Improper metal flow during extrusion can produce various defects.



a b c

Fig.5. Types of metal flow in extruding with square dies: a – flow pattern btained with low friction, or in indirect extrusion, b – pattern obtained with high friction in the billet-chamber interfaces, c – pattern obtained with high friction and/or cooling of the outer regions of the billet in the chamber

A common technique for investigating the flow pattern is to section the round billet in half lengthwise and mark one face with a square grid pattern. The two halves are placed in the chamber together and extruded. They are then taken apart and studied. Fig. 5 shows typical flow patterns obtained by this technique in direct extrusion with *square* flies (90° die angle). The conditions under which these different flow patterns occur are described in the figure caption. Note the dead-metal zones in Fig.5, b and Fig.5, c, where the metal at the corners is essentially stationary. This situation is similar to stagnation of fluid flow in channels that have sharp angles and turns.

Extrusion Practice

Because they have sufficient ductility, aluminum, copper, magnesium, and their alloys and steels and stainless steels are extruded with relative ease into numerous shapes. Other metals such as titanium and refractory metals can be extruded but with some difficulty and considerable die wear. Although it is a batch or semicontinuous process, extrusion can be economical for large as well as short production runs. Tool costs are generally low, particularly for producing simple solid cross-sections.

Extrusion ratios usually range from about 10: 1 to 100 :1. They may be higher for special applications (400 :1) or lower for less ductile materials, although they are usually at least 4:1.

Ram-speeds may range up to 0.5 m/s. Generally, slower speeds are preferred for aluminum, magnesium, and copper and higher speeds for steels, titanium, and refractory alloys. Extruded products are usually less than 7.5 m long because of the difficulty in handling greater lengths but have been as long as 30 m.

Most extruded products, particularly those with small cross-sections, require straightening and twisting. This is done by stretching the extruded product, usually in a hydraulic stretcher equipped with jaws. Tolerances in extrusion are usually in the range of +0.25-2.5 mm and increase with increasing cross-section.

The presence of a die angle causes a small portion of the end of the billet to remain in the chamber after the operation has been completed. This piece—called scrap or the *butt end*—is removed by cutting off the extrusion at the die exit. Another billet or a graphite block may be placed in the chamber to extrude the piece remaining from the previous extrusion.

Coaxial extrusion (or *cladding)* is also possible. In this operation, coaxial billets are extruded together when the strength and ductility of the two metals are compatible. An example is copper clad with silver. *Stepped extrusions* are produced by extruding the billet partially in one die, then in one or more larger dies.

Hot extrusion

Extrusion is carried out at elevated temperatures for metals and alloys that do not have sufficient ductility at room temperature — or in order to reduce forces required (Table 1)

EXTRUSION TEMPERATURE RANGES FOR VARIOUS	METALS
	°C
Lead	200-250
Aluminum and its alloys	375-475
Copper and its alloys	650-975
Steels	875-1300
Refractory alloys	975-2200

Die wear can be excessive. Cooling of the hot billet in the cool container can be a problem, resulting in highly nonuniform deformation (Fig. 5). To reduce cooling of the billet and. to prolong die life, extrusion dies may be preheated. Because the billet is hot, it develops an oxide film unless heated in an inert-atmosphere furnace. This film can affect the flow pattern of the material because of its frictional characteristics. It also results in an extruded product that may be unacceptable when good surface finish is important. Lateral extrusion (Fig. 2c) is used for sheathing of wire and coating of electric wire with plastic. In order to avoid formation of oxide films on the extruded product, the dummy block placed ahead of the ram (Fig. 1) is made a little smaller in diameter than the container. After extrusion, a thin cylindrical shell *(skull),* consisting mainly of the oxidized layer, is left in the container and the extruded product is thus free of oxides. This shell is later removed from the chamber.

Die design

Die design (Fig.) requires considerable experience. Square dies (shear dies) are used in extrusion of nonferrous metals, especially aluminum. Square dies develop dead-metal zones, which in turn, form a die geometry along which the material flows in the deformation zone. The dead-metal zones produce extrusions with bright finishes.

Tubing is extruded from a solid or hollow billet to wall thicknesses as small as 1 mm (0.040 in.). For solid billets, the ram is fitted with a mandrel that pierces a hole in the billet. Billets with a previously pierced hole may also be extruded in this way. Because of friction and severity of deformation, thin-walled extrusions are more difficult to produce than thick-walled extrusions. Wall thickness is usually limited to 1 mm for aluminum, 3 mm for carbon steels, and 5 mm for stainless steels.

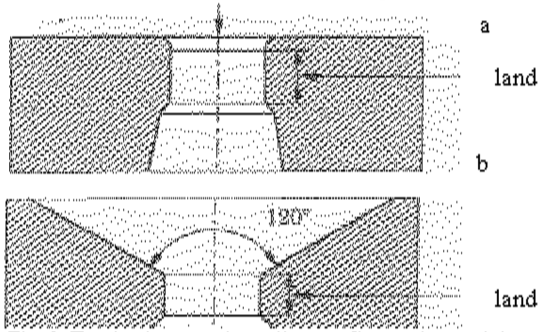
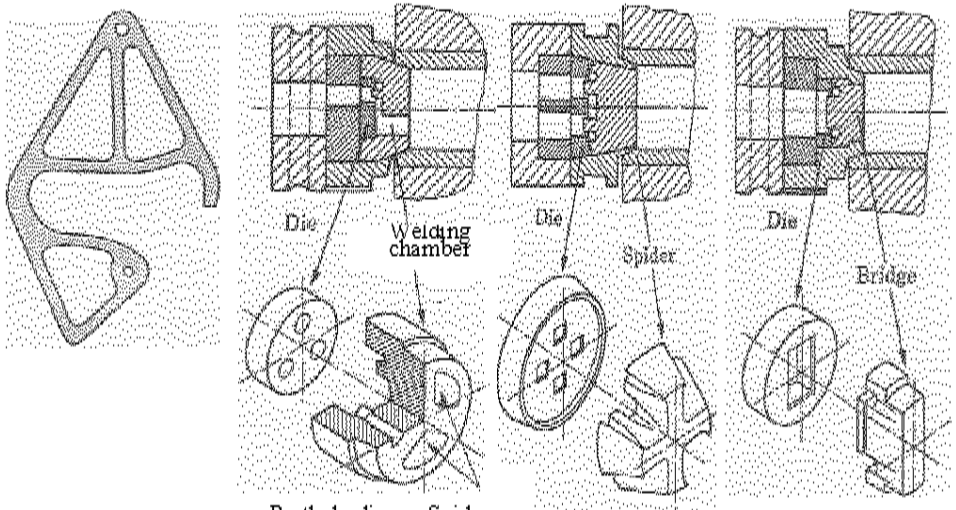


Fig.6. Typical extrusion-die configurations: (a) die for nonferrous metals; (b) die for ferrous

Hollow cross-sections (Fig. 7a) can be extruded by welding-chamber methods and the use of various special dies known as spider dies, **porthole** dies, and **bridge** dies (Fig. 7b). The metal divides and flows around the supports for the internal mandrel into strands. These strands are then rewelded under the high pressures in the welding chamber before exiting through the die. This condition is much like air flowing around a moving car, and rejoining downstream. The welding-chamber process is suitable only for aluminum and some of its alloys because of their capacity for developing a strong weld under pressure. Lubricants cannot be used because they prevent rewelding of the metal in the die.



Porthole die Spider die Bridge die

Fig.7. a – Extruded aluminum ladder lock is 8 mm thick and is sawed from the extrusion. b – components of various dies for extruding intricate hollow shapes

Guidelines for proper die design in extrusion are illustrated in Fig. 8. Note the importance of symmetry of cross-section and the avoidance of sharp corners and extreme changes in dimension within the cross-section.

Die materials for hot extrusion are usually hot-work die steels. Coatings such as zirconia may also be applied to the dies to extend die life. Partially stabilized zirconia dies are also being used for hot extrusion.

Lubrication

Lubrication is important in hot extrusion. Glass is an excellent lubricant for steels, stainless steels, and high-temperature metals and alloys. In a process developed in the 1940s and known as the **Sejournet process,** a circular glass pad is placed at the die entrance. This pad acts as a reservoir of molten glass and supplies it as a lubricant as extrusion progresses. Before the billet is placed in the chamber, its cylindrical surface is coated with a layer of powdered glass to reduce friction at the billet-chamber interface.

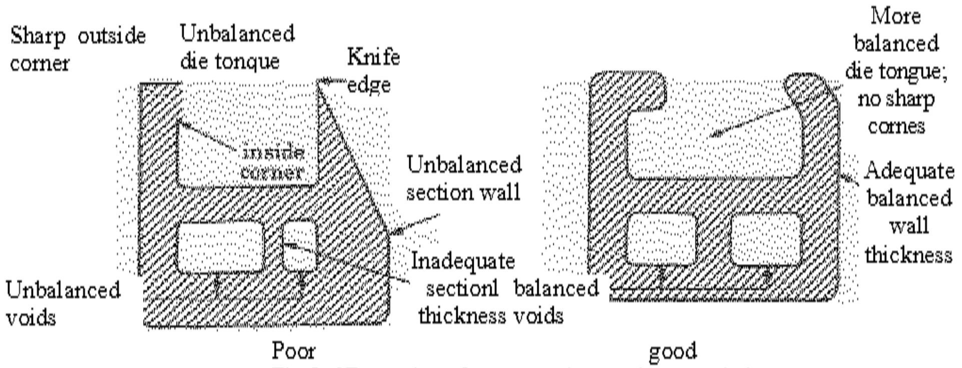


Fig.8. 0Examples of cross-sections to be extruded.

For metals that have a tendency to stick to the container and the die, the billet can be enclosed in a thin-walled container made of a softer, lower strength metal, such as copper or mild steel. This procedure is called jacketing (or *canning).* In addition to acting as a low-friction interface, this jacket prevents contamination of the billet by the environment.

Cold extrusion

Cold extrusion is a general term often denoting a combination of operations, such as direct and indirect extrusion and forging. This process uses slugs cut from cold-finished or hot-rolled bar, wire, or plate. Slugs that are less than about 40 mm in diameter are sheared and their ends are squared by grinding or upsetting. Larger diameter slugs are machined from bars in specific lengths. Although most cold-extruded parts weigh less, parts weighing as much as 45 kg and having lengths of up to 2 m have been made. Powder-metal slugs (preforms) are also cold extruded.

Cold extrusion has the following advantages over hot extrusion:

– Improved mechanical properties resulting from work-hardening, provided that the heat generated by deformation and friction does not recrystallize the extruded metal;

– Good control of tolerances, thus requiring little subsequent machining or finishing operations;

– Improved surface finish, due partly to lack of an oxide film, provided that lubrication is effective;

– Production rates and costs competitive with those of other methods of producing the same part. Some machines are capable of producing more than 2000 parts per hour.

However, the magnitude of the stresses on the tooling in cold extrusion is very high, especially with steel workpieces, being on the order of the hardness of the workpiece material. The punch hardness usually ranges between 60 and 65 *HRC* and 58 and 62 *HRC* for the die. Punches are a critical component, as they must have not only sufficient strength but also toughness and wear and fatigue resistance.

The design of tooling and selection of appropriate tool and die materials is crucial to the success in cold extrusion. Also important is the control of workpiece material with regard to its quality, accuracy of slug dimensions, and surface condition. Lubrication is critical, especially with steels, because of the possibility of sticking *(seizure)* between the workpiece and the tooling if the lubrication breaks down. The most effective means of lubrication is application of phosphate *conversion coatings* on the workpiece, followed by a coating of soap or wax.

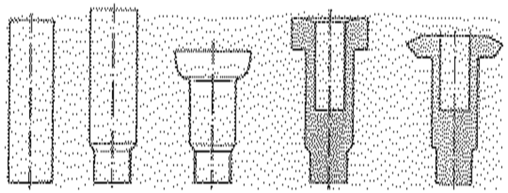
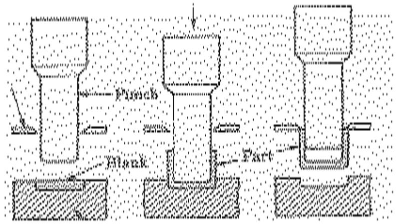


Fig.9. Billet 2. Extrusion 3. Upsetting 4. Backward can extrusion 5 Final Upsetting

Example: The sequence of operations involved in making a bevel-gear shaft by cold extrusion is shown in the accompanying figure. After shearing or cutting off an appropriate length of round stock, the billet is partially extruded to form the small lower end of the shaft. The upper end is then upset to preform it for the next operation, which is piercing the part from the top, whereby the part is backward extruded and a cavity is produced. The final operation is upsetting of the upper section, making it larger in diameter and forming the bevel section. Gear teeth can be produced either by additional forming operations or by machining

Impact Extrusion



Impact extrusion is similar to indirect extrusion and is often included in the cold-extrusion category. The punch descends rapidly on the blank (slug), which is extruded backward. The thickness of the tubular extruded section is a function of the clearance between the punch and the die cavity. The diameter of the parts made can approach 150 mm. Another example is the production of collapsible tubes, such as for toothpaste. Most nonferrous metals can be impact extruded using vertical presses at production rates as high as two parts per second.

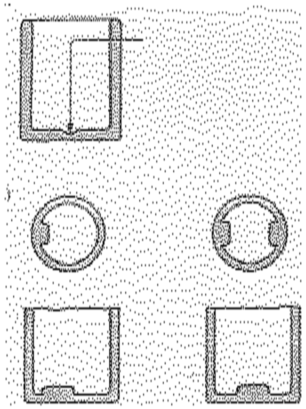


Fig.10Design quidelines for impact extrusion – symmetry keep material flow uniform

Hydrostatic extrusion

In *hydrostatic extrusion* the pressure required for extrusion is supplied through a fluid medium surrounding the billet. (Fig.2b). Consequently, there is no container-wall friction. Pressures are usually about 1400 MPa. The high pressure in the chamber transmits some of the fluid to the die surfaces, thus significantly reducing friction and forces. Hydrostatic extrusion, which was developed in the early 1950s, has been improved by extruding the part into a second pressurized chamber, which is under lower pressure (*fluid-to-fluid extrusion)*. This operation reduces the defects in the extruded product.

Because the hydrostatic pressure increases the ductility of the material, brittle materials can be extruded successfully by this method. However, the main reasons for this success appear to be low friction and use of low die angles and high extrusion ratios. Most commercial hydrostatic-extrusion operations use ductile materials.

Hydrostatic extrusion is usually carried out at room temperature, typically using vegetable oils as the fluid, particularly castor oil because it is a good lubricant and its viscosity is not influenced significantly by pressure. For elevated-temperature extrusion, waxes, polymers, and glass are used as the fluid. These materials also serve as thermal insulators and help maintain the billet temperature during extrusion.

In spite of the success obtained, hydrostatic extrusion has had limited industrial applications, largely because of the somewhat complex nature of tooling.

Extrusion defects

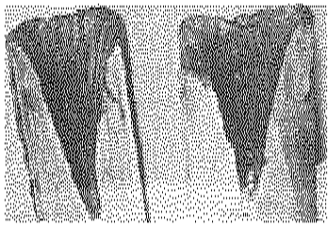
Depending on material condition and process variables, several types of defects can develop in extruded products, which can significantly affect their strength and product quality. There are three principal extrusion defects: surface cracking, pipe, and internal cracking. Some defects are visible to the naked eye.

Surface cracking

If extrusion temperature, friction, or speed is too high, surface temperatures rise significantly, which may cause *surface cracking* and tearing (fir-tree cracking or speed cracking). These cracks are intergranular (along the grain boundaries) and are usually caused by *hot shortness.* These defects occur especially in aluminum, magnesium, and zinc alloys, although they may also occur in high-temperature alloys. This situation can be avoided by lowering the billet temperature and extrusion speed.

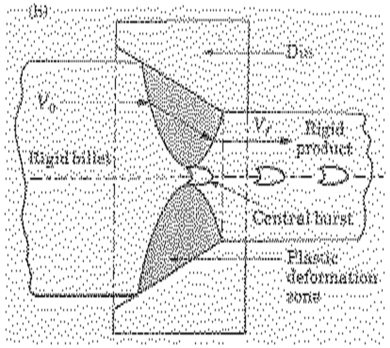
Surface cracking may also occur at lower temperatures. These cracks have been attributed to periodic sticking of the extruded product along the die land. When the product being extruded sticks to the die land, the extrusion pressure increases rapidly. Shortly thereafter the product moves forward again and the pressure is released. The cycle is then repeated continuously, producing periodic circumferential cracks on the surface. Because of its similarity to the surface of a bamboo stem, it is known as **bamboo defect.**

Pipe



The type of metal-flow pattern shown in Fig. 11(c) tends to draw surface oxides and impurities toward the center of the billet, much like a funnel (Fig. 116). This defect is known as pipe defect (also *tailpipe* or *fishtailing).* As much as one third of the length of the extruded product may contain this type of defect and have to be cut off as scrap. Piping can be minimized by modifying the flow pattern to a more uniform one, such as by controlling friction and minimizing temperature gradients. Another method is to machine the billet's surface prior to extrusion so that scale and surface impurities are removed.

Internal cracking



The center of the extruded product can develop cracks, which are variously called center cracking, *center-burst, arrowhead fracture,* or *chevron cracking* (Fig. 12). These cracks are attributed to a state of hydrostatic tensile stress at the centerline in the deformation zone in the die (Fig. 12), a situation similar to the necked region in a tensile-test specimen. The tendency for center cracking increases with increasing die angle and amount of impurities and decreases with increasing extrusion ratio and friction. It usually results from small reduction of nonstrainhardening metals such as severely cold-worked metal, since cold-working reduces the strain-hardening exponent. In multistep operations, chevroning, therefore, usually occurs when a light reduction follows a heavy one.

They are caused by periodic tensile stresses that result from non-homogeneous deformation which requires an abrupt acceleration of the metal in the extrusion die. They occur with relatively small reductions, relatively large die angles, relatively high surface friction, and subsequent to previous severe cold working. These defects can therefore be prevented by (1) increasing the reduction, (2) decreasing the die half-angle, (3) decreasing the friction, and (4) increasing the strainhardening capability of the material by annealing or material selection These cracks have also been observed in tube extrusion and in spinning of tubes, appearing on the inside surfaces of tubes for the same reasons.

Influence of die angle

In addition to probable central-burst formation, there are other limitations in regard to how large a die half-angle α can be used in drawing and/or extrusion in order to obtain sound metal flow. These are (1) dead-zone formation, (2) shaving, and (3) the breaking of the wire or rod on the exit side in case of drawing.

As the die half-angle increases from 0° to the optimal half-angle α, the external friction losses drastically decrease, and the drawing or extruding energy or stress decreases to a minimum at which sound flow of metal occurs. Beyond this point, an increase in the die half-angle causes the drawing or extrusion stress to increase, because the internal shear losses or redundancy increases rather rapidly. This rise in or extrusion stress will not, of course, increase indefinitely, but at some die half-angle called the first critical angle, α_{cr1} dead-zone formation begins as shown in Fig. 13. At this point, internal shearing of the metal next to the die surface occurs forming a dead-metal zone, which no longer participates in the flow process but instead adheres to the surface of the die as a built-up surface and acts much like the extended surface of the die, virtually limiting the size of the die half-angle. The first critical die half-angle is a function of the percent reduction in area and the shear factor. The drawing or extrusion stress remains constant, as shown in Fig. 13 in the dead-zone formation region.

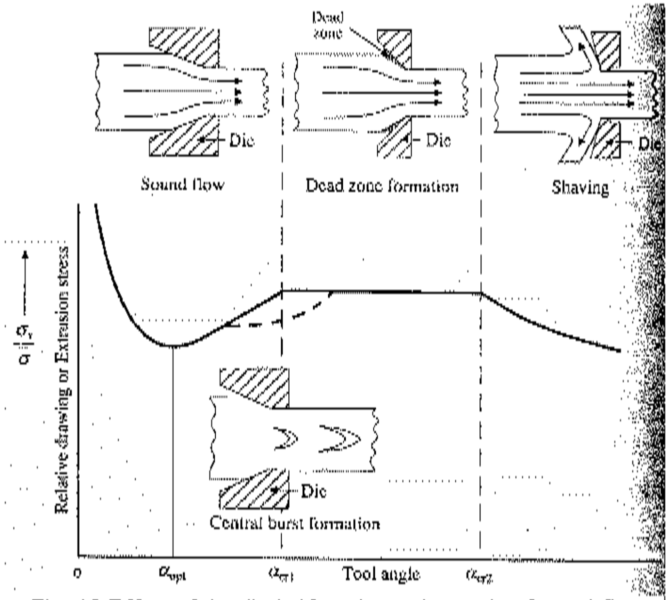


Fig. 13 Effect of the die half-angle on the mode of metal flow and drawing stress

As the die half-angle increases further, the second critical die half-angle *occr-i,* is reached, at which the dead-zone metal ceases to adhere to the die and begins to move backward forming metal chips somewhat the same as one would peel or shave off a chip from a wooden stick, with a knife. As the wire or rod proceeds through the die, the outer surface is shaved off and the core moves through the die without plastic deformation with equal entrance and exit elocities. The drawing or extrusion stress is found to decrease with an increase in α as shown in Fig. 13 in the shaving region. The critical die half-angle for shaving, α_{cr2}, is dependent on the percent reduction in area, the sharpness of the tool and whether or not a built-up edge occurs, and the type of process, i.e., drawing or extrusion.

If conditions are favorable for center-burst formation, as shown in Fig. 7 i3 then at some angle α_{cr1}, as determined by the criterion for central-burst formation, this internal defect will form and, if sufficiently severe, total fracture of the workpiece will result.

Extrusion Equipment

The basic equipment for extrusion is a hydraulic press. These presses are suitable for extrusion because the stroke and speed of the operation can be controlled. They are capable of applying a constant force over a long stroke; thus long billets can be used and the production rate increased. Hydraulic presses with a ram-force capacity as high as 120 MN (14,000 tons) have been built and are used for hot extrusion of large billets.

Vertical hydraulic presses are usually used for cold extrusion. They generally have less capacity than those used for hot extrusion, but take up less floor space. In addition to presses, crankjoint and knucklejoint mechanical presses are also used for cold extrusion and impact extrusion to mass produce small components.

THE DRAWING PROCESS

In drawing, the cross-section typically of a round rod or wire is reduced or changed by pulling it through a die (Fig. 14). The major variables in drawing are similar to those in extrusion, that is, reduction in cross-sectional area, die angle, friction along the die-workpiece interfaces, and speed. The die angle influences the drawing force and the quality of the drawn product. We can show that for a certain reduction in diameter and frictional condition, there is one die angle at which the drawing force is a minimum. However, this does not mean that the process should be carried out at this optimum angle because, as you will see, there are other product-quality considerations.

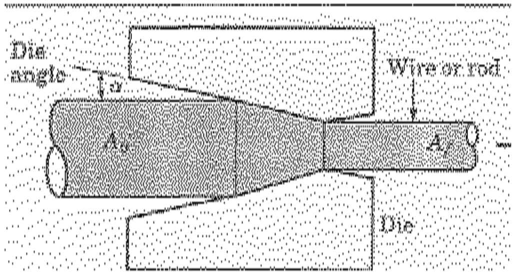


Fig. 14 Drawing

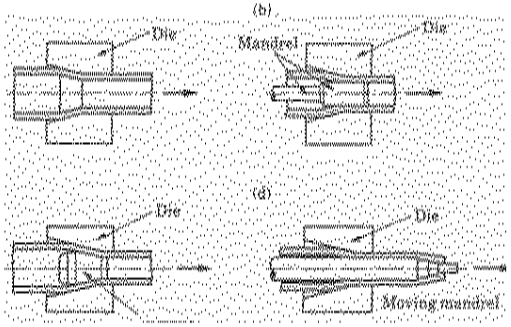


Fig. 15 Tube drawing

Because more work has to be done to overcome friction and to reduce the diameter, the force increases with increasing friction and reduction of cross-sectional area. However, there has to be a limit to the magnitude of the drawing force as reduction increases, because when the tensile stress due to the drawing force reaches the yield stress of the drawn metal, it will simply yield. In that case, the product will undergo further deformation after it leaves the die, which is not acceptable. Ideally, the maximum reduction in cross-sectional area per pass is 63 percent. Thus, for example, a 10-mm diameter rod can at most be reduced to a diameter of 6.1 mm in one pass.

Drawing of other shapes

As in extrusion, various solid cross-sections can be produced by drawing through dies with various profiles (Fig. 15). The initial cross-section is usually round or square. Proper die design and the selection of reduction sequence per pass require considerable experience to ensure proper material flow in the die in order to reduce defects and improve surface quality

The wall thickness, diameter, or shape of tubes produced by extrusion or other processes can be reduced by tube drawing processes (Fig. 15.21). Tubes as large as 0.3 m (12 in.) in diameter can be drawn by these techniques. Mandrels of various profiles are available for these operations.

In drawing flat strips, the dies are wedge shaped. This process, although not of major industrial significance, is the fundamental deformation process in *ironing,* which is used extensively in making aluminum beverage cans

Drawing Practice

As in all metalworking processes, successful drawing operations require careful selection of process parameters and consideration of many factors. The procedure and sequence used to make wire are shown schematically in Fig. 15.22.

Drawing speeds depend on the material and cross-sectional area. They may range from 1 m/s to 2.5 m/s (200 ft/min to 500 ft/min) for heavy sections to as much as 50 m/s (10,000 ft/min) for very fine wire, such as that used for electromagnets. Because it does not have sufficient time to dissipate, temperature can rise substantially at high drawing speeds and can have detrimental effects on product quality.

Reductions in cross-sectional area per pass range from near zero to about 45 percent. Usually, the smaller the cross-section is to begin with, the smaller will be the reduction per pass. Fine wires are usually drawn at 15-25 percent reduction per pass, and larger sizes at 20-45 percent. Reductions of more than 45 percent may result in lubrication breakdown and surface-finish deterioration. Drawing large solid or hollow sections can be done at elevated temperatures.

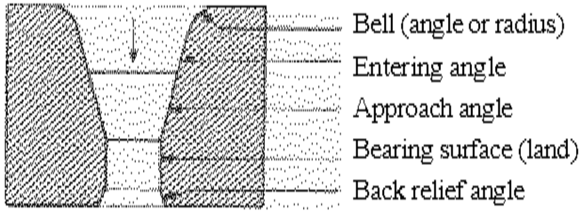
A light reduction—called a sizing pass—may also be taken on rods to improve surface finish and dimensional accuracy. However, because they basically deform the surface layers, light reductions usually produce highly nonuniform deformation of the material and its microstructure. Consequently, the properties of the material vary with location in the cross-section.

Because of work hardening, intermediate annealing between passes may be necessary to maintain sufficient ductility during cold drawing. Drawn copper and brass wires are designated by their temper, such as 1/4 hard, 1/2 hard, etc.

High-carbon steel wires for springs and musical instruments are made by heat treating, or patenting the drawn wire, whereby the microstructure obtained is fine pearlite. These wires have ultimate tensile strengths as high as 5 GPa (700 ksi) and tensile reduction of area of about 20 percent.

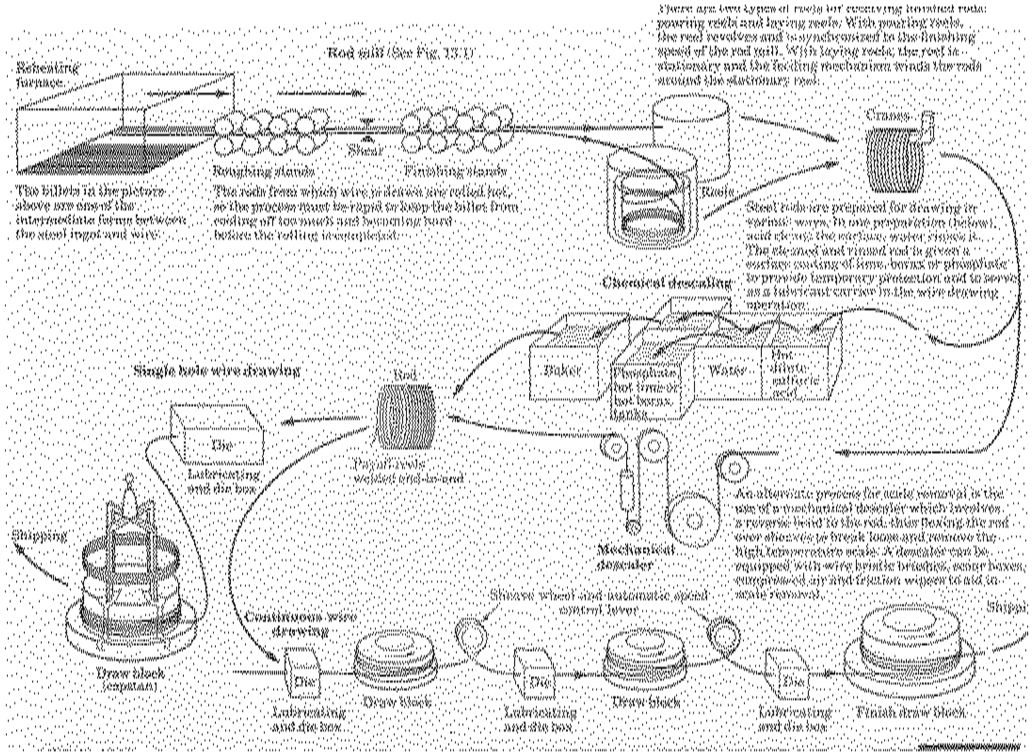
Die design

The characteristic features of a typical die design for drawing are shown in Fig. 16. Die angles usually range from 6° to 15°. Note, however, that there are two angles (entering and approach) in a typical die. This shape is arrived at through experience. The purpose of the land is to set the final diameter of the product, called *sizing*. Also, when the worn die is reground, the land maintains the exit dimension of the die opening.

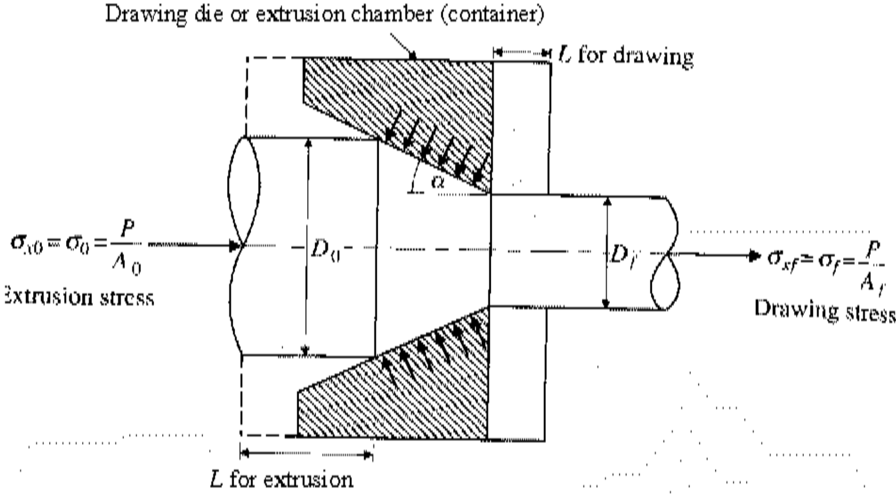


A set of dies is required for profile drawing for various stages of deformation (see Fig. 15.20). Designing these dies requires considerable experience in order to produce defect-free products. The dies may be made in one piece or, depending on the complexity of the profile, with several segments held together in a ring. Computer-aided design techniques are being implemented to design dies that smooth material flow through the dies and minimize defects.

A set of idling rolls is also used in drawing rods or bars of various shapes (Fig. 15.24). This arrangement *(Turk's head)* is more versatile than that of ordinary



The different common processes by which a bar (or wire) might be



reduced by flow through a converging die are bar and wire drawing, direct or forward extrusion, indirect or backward extrusion, hydrostatic extrusion, and impact extrusion. All of these processes may be classified as indirect compression processes, in which the major forming stress results from the compressive stresses as a result of the direct tensile or compressive stresses exerted in drawing or extrusion as shown in Fig. 7.1 for drawing and for direct or forward extrusion. Here, the converging die surface in the form of a truncated cone is used, but die surfaces of other geometries might also be used. An important distinction of these metal-working processes is that the plastic deformation may be done by hot-, warm-, or coldworking. Prototypes of the direct, indirect, and impact or backward extrusion processes are shown in Fig. 7.2. A drawing of the die assembly for the Pressure-to-pressure hydrostatic extrusion process is shown in Fig. 7.3. Methods extruding hollow shapes using internal and spider mandrels are shown in Figs. 7.4 and 7.5. Tube thinning and elongation by drawing with internal support provided by a moving mandrel, a plug, and a floating plug; and without internal support by sinking is shown in Fig. 7.6.

FIGURE 7.1
Composite drawing showing the indirect compressive stresses generated in drawing and extrusion through a converging die.

The existing solutions for calculating the drawing or extrusion stress or pressure may be divided into the four groups: (1) analytical, (2) numerical, (3) semiempirical, and (4) empirical.

Exact analytical solutions for metalworking problems such as extrusion are very difficult to obtain because of the complexity of the problems. A number of simplifying assumptions must be made. As mentioned previously, exact or complete solutions must satisfy the following requirements:

1. Equilibrium conditions, i.e., must satisfy the three equilibrium equations
2. Continuity of flow, in which the material is incompressible and no voids are formed, etc., i.e., it must satisfy the equations of compatibility
3. Stress-strain relations and the yield criterion used
4. Boundary conditions, including the effect of friction

For analytical upper- and lower-bound solutions, for example, some of the above conditions are relaxed for the process being considered. For example, a von Mises material may be used as a good approximation, which is a rigid (nonelastic), homogeneous, isotropic, nonstrainhardening continuum, that obeys the von Mises yield criterion.

One would expect a blending of the theoretical and empirical solutions to provide semiempirical solutions. Pragmatically, the proponents of the theoretical solutions attempt to fit them to practical, every-day production problems, and the technologists who rely on empirical equations or formulas based on experimental and production data attempt to utilize theoretical solutions for the purpose of simplification and rationalization in an effort to understand the process and to place it on a sound foundation.

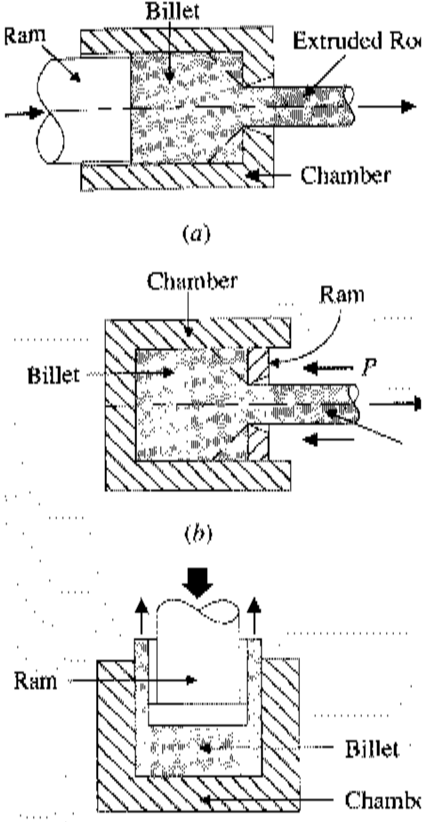


FIGURE 7.2 Prototypes of extrusion processes (a) Direct extrusion with a flat-faced die; *(b)* indirect extrusion with a flat-faced die; and (c) impact extrusion with a flat ram.

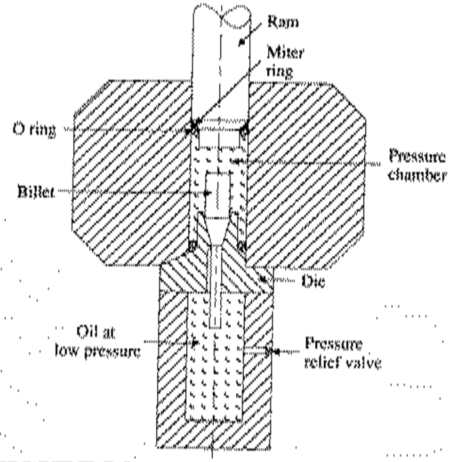
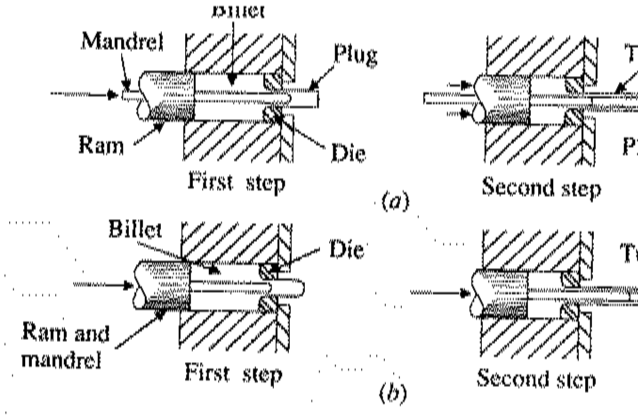
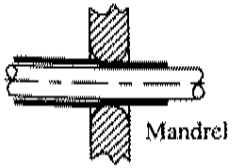


FIGURE 7.3
Schematic drawing of a ram-type extrusion chamber for the pressure-to-pressure hydrostatic extrusion process [7.3].





rlUUKt, 7.4
Two methods of extruding hollow shapes using internal mandrels [8.6J.

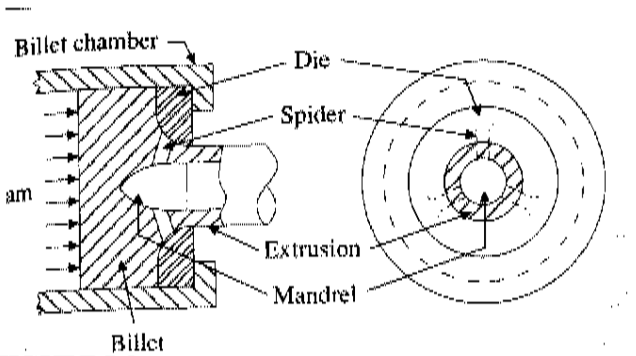


FIGURE 7.5
Extrusion of a hollow shape using a spider mandrel [8.6].

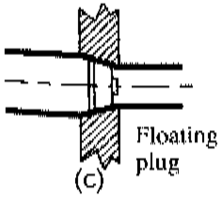
for die angles above the optimal amount commonly used in practice. Consequently the

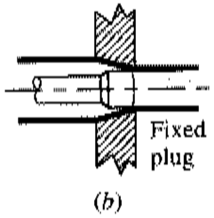
(7.2)

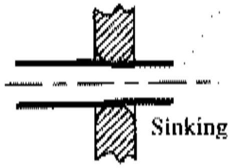
solutions predict drawing and extrusion stresses or pressures that are below those actually required and may therefore represent lower-bound solutions. All the important factors are taken into consideration in the computer design of flat-face die extrusion to be

(7.3)

discussed later.







(a)
FIGURE 7.6
Tube thinning and elongation by drawing with internal support provided by (a) a moving mandrel, (ft) a plug, and (c) a floating plug; and *(d)* without internal support by sinking [7.1].

(7.4)

other form of curve-fitting. These methods would include the various graphical methods that have been proposed to predict the drawing or extrusion pressures

After a brief discussion of the energy required for homogeneous deformation and for the various losses, the application of the above approaches to the solution of converging-die drawing and extrusion problems will now be illustrated as examples of their application to metalworking problems.

7.2. DRAWING AND EXTRUSION OF ROUND BARS AND FLAT STRIPS

From the standpoint of the state of stress causing deformation, bar drawing and forward

(7.1)

extrusion with conical dies are quite similar and will be discussed here together.

If external friction and internal shearing losses are excluded, the stress required for drawing or extrusion is simply that required for homogeneous deformation:

$$\sigma = \bar{\sigma} \ln \frac{A_0}{A_f} = \bar{\sigma} \ln \left(\frac{1}{1-r} \right)$$

where <r = drawing or extrusion stress or pressure *Ao* = entry or
initial area *Af* = exit or final area
r= fractional reduction in area *(Ay-A)/Ay*
(T = flow stress for a nonstrainhardening material or the mean true flow stress *o-fn, for*
a strainhardening material as is shown in Fig. 3.8

To correct for external friction and internal shearing redundancy losses, the above value for the drawing stress may be divided by the efficiency $rJ=Wh/^{w}t$, or multiplied by two correction factors, one to compensate for the external friction loss *Cf(cx),* which is a function primarily of the die half-angle *a,* and the other to compensate for the internal shear redundancy loss C,(o', r), which is a function not only of the die half-angle *a,* but also of the fractional reduction of area r. The correction factors also depend on the process, i.e., drawing, extrusion, etc. The die half-angle *a* is the angle that the die surface makes with the axis of the workpiece.

The above equations may therefore be written as

$$\sigma = C_f(\alpha) C_i(\alpha, r) \bar{\sigma} \ln \frac{A_0}{A_f}$$

and

$$\sigma = C_f(\alpha) C_i(\alpha, r) \bar{\sigma} \ln \left(\frac{1}{1-r} \right)$$

If the fractional reduction in area, r, and the lubrication practice are fixed, a graph showing schematically for a limited range of *a,* the variation of the various relative stress and work terms, is shown in Fig. 7.7. As stated previously the total work per unit volume is given as

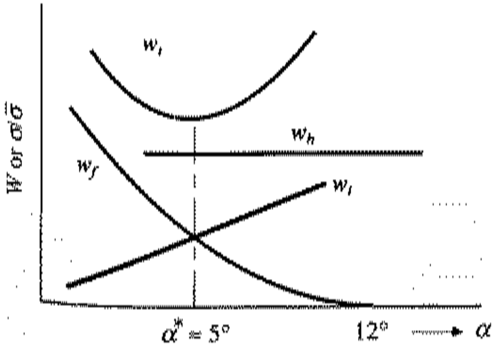
$$w_t = w_h + w_f + w_i$$

The homogeneous deformation *w,,* is not a function of *a* and is therefore constant. The optimal die half-angle is given by *a**. To the left of the minimum of *w, on* the graph, i.e., of a*, external friction predominates. A very large stress and much work would be theoretically required to draw or extrude a workpiece through a very long die with a very small *a* and consequently with a very large surface area. As *a* is increased, ny decreases and *w,* increases until it predominates. During extrusion, as the die half-angle is increased a dead zone may develop, which essentially limits the value of *a,* as will be discussed later. As external friction increases to the extreme of sticking, a*, the optimal die half-angle, also increases. Friction is high in hot-working operations, and *a* is made larger than the optimal value to ensure better surface quality and safe tool loading. The optimal die half-angle a* increases with the amount of reduction from about 3° for about 10 percent reduction to 8° for a 45 percent reduction.

Once the equation for the total drawing or extrusion stress or the total work is written in terms of the die half-angle, the optimal angle may be found by differentiating the equation and equating to zero.

As shown in Fig. 7.7, if one calculates only the relative drawing or extrusion stress or the work of deformation *W,,* while neglecting the external friction and redundancy losses, appreciable error may occur. One of the next stages in the development, therefore, is to determine a drawing or extrusion stress equation in which external friction is included in the analysis, but redundancy is neglected, that is, *w,* = *0.* This is one of the oldest approaches to drawing and extrusion. The freebody equilibrium or slab approach for the drawing of a cylindrical bar with a conical die will be used here as a typical example of the equilibrium solution. In this case *a,* /A, and *a* will be assumed to be constant. The extension of the resulting equation to forward extrusion and tube drawing will then be discussed.

FIGURE 7.7
Schematic curves showing the effect of die half-angle on the relative drawing or extrusion stress and work balance for a constant reduction ratio and lubrication condition, a* is the optimal die half-angle.



7.3 FREEBODY, SLAB, OR EQUILIBRIUM APPROACH TO DRAWING AND EXTRUSION

Figure 7.8 shows a cylindrical rod being drawn through a conical die and a freebody equilibrium diagram of an element of the rod in the process of beine reduced.

The sum of the forces in the axial (and in the radial) direction should be zero. If the freebody is in static equilibrium, the axial components of the forces in the *x* direction consist of those due to the following stresses:

(7.6a)
(7.6ft)

1. **Longitudinal** stress, o,.
2. Die pressure, *p,* that is, normal pressure at the die surface
3. Frictional drag, *p,* on the extrusion chamber, die surface, and/or die land *L,* as shown in Fig. 7.1, where /A is the Coulomb coefficient of friction

(7.5)

Summing the forces in the *x* direction, one obtains

$$\sum F = (\sigma_x + d\sigma_x)\frac{\pi}{4}(D+dD)^2 - \sigma_x\frac{\pi}{4}D^2$$

$$+\, p\left(\pi D\cdot\frac{dx}{\cos\alpha}\right)\sin\alpha + \mu p\left(\pi D\frac{dx}{\cos\alpha}\right)\cos\alpha = 0$$

where *D* is any cone diameter and *a* is the die half-angle as shown in Fig. 7.8.

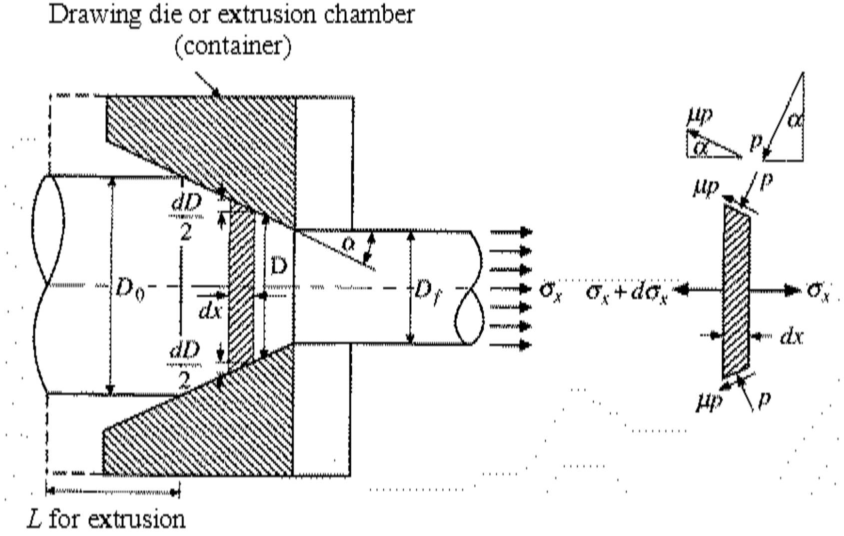


FIGURE 7.8
Cylindrical rod being drawn through a conical die and a freebody equilibrium diagram at an element in the reduced section [7.1].

Tf one ignores the products of the infinitesimal quantities and simplifies, one obtains

$$D\,d\sigma_x + 2[\sigma_x + p(1+\mu\cot\alpha)\,dD] = 0$$

$$2r\,dr\,\sigma_x + r^2\,d\sigma_x + 2pr\,dr + \frac{2r\,dr\,\tau}{\tan\alpha} = 0$$

where T = the friction shear stress = *mcr/\f3.*

Likewise, summing the forces in the radial direction, one obtains the radial or die-breaking stress *cr,*

$$\sum F_r = \sigma_r(\pi D\,dx) + \left(\pi D\frac{dx}{\cos\alpha}\right)\cos\alpha - \mu p\left(\pi D\frac{dx}{\cos\alpha}\right)\sin\alpha = 0$$

and

$$\sigma_r = -p(1-\mu\tan\alpha)$$

For small angles, /A tan *a* may be ignored, and o-,. = -*p* [7.1].

By combining the yield criterion with Eq. (7.6) for the axial force, letting B = *fJi* cot *a,* integrating the resulting differential equation, and simplifying, one obtains the following equation for the average drawing stress:

(7.9)

$$\frac{\sigma_x}{\bar{\sigma}}=\frac{1+B}{B}\left[1-\left(\frac{D_f}{D_0}\right)^{2B}\right]$$

where o- is the mean flow stress, B is equal to /A cot *a,* and Do and Dy are the original and final diameters.

The same approach can be used to yield equations of essentially the same form for such similar operations as drawing of a wide strip through a wedge-shaped die, mandrel and plug drawing and sinking (drawing with no internal support) of tubing (Fig. 7.6), and extrusion of bars and strips.

For frictionless drawing and extrusion, where *p.* = 0, both external friction and redundancy are neglected, so the equation for homogeneous deformation must be used.

The following is a listing of other similar slab or equilibrium equations for drawing and extrusion, which excludes the effect of friction and redundancy:

1. Drawing of a strip through a wedge-shaped die in plane strain [7.1]:

$$\frac{\sigma_x}{S}=\frac{1+B}{B}\left[1-\left(\frac{h_f}{h_0}\right)^{B}\right]$$

where 5=2/\/3oo or 1.15o-o and is the yield (flow) stress in a plane-strain compression test according to the von Mises criterion and o-o is the yield stress in uniaxial tension, and *hy* and *hf* are the initial and final thickness.

2. Close-pass plug and straight mandrel drawing with a conical die as in pji 7.6(a), *(b),* and (c):

cr, l+B*f *[hA -JM-k-j* J I

$$B^* \quad \frac{\mu_1 \pm \mu_2}{\quad} \quad \frac{\sigma_x}{S}= \quad B^* \left[1-\left(\frac{h_f}{h_0}\right)^{B^*}\right]$$

UiU7 2 where B = and5 =—=0-0

as above

tan a —tan *p*√3

(The plus sign is used for plug drawing and the minus sign fo mandrel drawing.) a = outside die half-angle /3 = inside die half-angle

/i = coefficient of friction at the die-workpiece interface *IJi-t* = coefficient of friction at the plug or mandrel-workpiece interfaci *hf* = final tube thickness *ho* = initial tube thickness

In mandrel drawing, if ,1 = /A, the equation (7.1) for homogeneous deforma tion applies. If > *i,* the drawing stress for mandrel drawing may be les; than for frictionless drawing for the same reduction in area.

3. Tube sinking (tube drawing with no internal support) as in Fig. *7.6(d):*

o-, l+JSf /DA$^{8'}$)

$$\frac{\sigma_x}{1.1\sigma_0}=\frac{\quad}{B}\left[1-\left(\frac{D_f}{D_0}\right)^{B}\right]$$

4. Round-bar extrusion through a conical die

$$\frac{\sigma_x}{\sigma_0}=\frac{1+B}{\quad}\left[1-\left(\frac{D_0}{\quad}\right)^{2B}\right]$$

lii-ffl f7.13) o ***B* L *\Df)***

where o-**x** = extrusion pressure on the end of the billet B = *IJL* cot *a*

Note that the entry and exit conditions for extrusion versus drawing inverts the diameter ratio.

5. Extrusion of flat strip through constant angle dies:

SBLWJ

$$\frac{\sigma_x}{\quad}=\frac{1+B}{\quad}\left[1-\left(\frac{h_x}{h_f}\right)^{B}\right]$$

As the above simple solutions represent lower-bound solutions, the next stage in the development is to consider upper-bound solutions.

As applied to hot forward extrusion through conical dies, one can convert equation (7.5) by expansion, simplification, and manipulation to the form

$$-\sigma_{x0}=\bar{\sigma}\ln\left(\frac{A_0}{A_1}\right)+\frac{\tau\ln(A_0/A_1)}{\sin\alpha\cos\alpha}$$

where ~*xo* = pressure at the extrusion end of the die ln(Ao/Ai)=21n(ro/ri) *Ay* and *A-i* = cross-sectional area of the billet and of the extrusion respectively,

iro and r, = their radii, respectively a = die half-angle

The first term of Eq. (7.15) represents the homogeneous deformation or lossless work, and the second term the external friction loss [7.2].

S CENTRAL-BURST FORMATION AND SHAVING IN EXTRUSION

^{n} forward extrusion the primary mode of failure is *center-burst* or *chevron J°rmation,* also called *cupping.* Although this defect does not occur with great Jequency, it is insidious because it is usually not visible from the surface but, scause of its seriousness, 100 percent nondestructive testing such as by **x**-ray •'adiography or ultrasonic testing may be required. Central bursts, or chevrons,

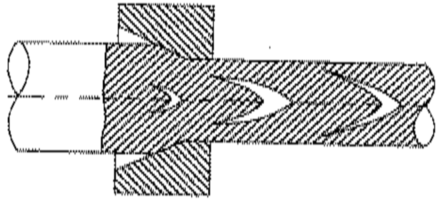
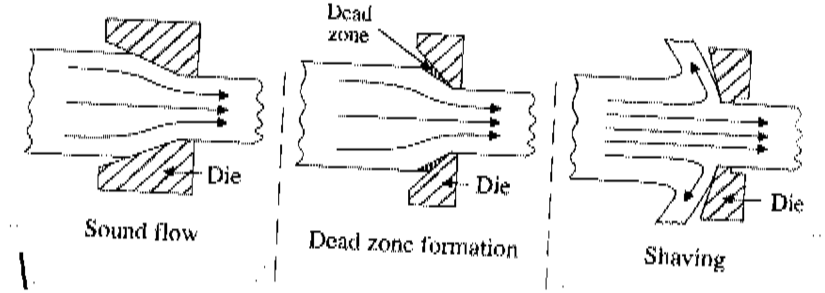


FIGURE 7.11
(a) Sketch showing central bursts or chevrons in the process of formation in cold extrusion. (6) Photograph of center bursts formed in forward cold extrusion of steel, *(a)* [7.3]. *(b) (Courtesy of Bethlehem Steel Corp.)*

are internal defects that appear on the longitudinal cross section of the workpiece as arrowhead- or chevron-shaped voids that point in the direction of metal flow, as seen in Fig. 7.11. It usually results from small reduction of nonstrainhardening metals such as severely cold-worked metal, since cold-working reduces the strain-hardening exponent. In multistep operations, chevroning, therefore, usually occurs when a light reduction follows a heavy one.



They are caused by periodic tensile stresses that result from non-homogeneous deformation which requires an abrupt acceleration of the metal in the extrusion die. They occur with relatively small reductions, relatively large die angles, relatively high surface friction, and subsequent to previous severe cold working. These defects can therefore be prevented by (1) increasing the reduction, (2) decreasing the die half-angle, (3) decreasing the friction, and (4) increasing the strainhardening capability of the material by annealing or material selection. The foregoing criteria for the prevention of central bursting is summarized in Fig. 7.12 [7.5], where /3 gives the prorated slope of the true stress-true strain curve of a rigid, linearly strainhardening material in the plastic range or the tangent to the *cr-s* curve of a nonlinearly strainhardening metal. The true stress-true strain curve or a segment in the plastic range may be defined by the relationship [7.6]:

$$\sigma = \sigma_n(1+\beta\varepsilon_n) \tag{7.19}$$

(r=(1+J (7.18)

If the stresses at e, and £2 are o-i and o-;,, the solution of the above equations simultaneously for /3 yields

$$\beta = \frac{\sigma_2-\sigma_1}{\sigma_1(\varepsilon_2-\varepsilon_1)}$$

FIGURE 7.12
Graph summarizing the criteria for the occurrence of central bursts for drawing and forward extrusion on the basis of die half-angle *a,* percent reduction, friction factor *m,* and material strainhardening capability /3. The area to the left or above any curve represents a safe zone for the conditions indicated by that curve. For example, for r=40% and m =0, an *a* of 18° can be used safely. [4.10], [7.5].

In Fig. 7.12, m is the friction shear factor. The region to the left of any curve represents the safe zone in which no central bursting is expected for the conditions indicated by the particular curve. Arrows show that central-bursting is expected for the conditions indicated by the particular curve. Arrows show that central-bursting may be prevented by either reducing the die half-angle or increasing the percent reduction. Sound metal flow therefore does not occur for all combinations of die angle, percent reduction, and friction values.

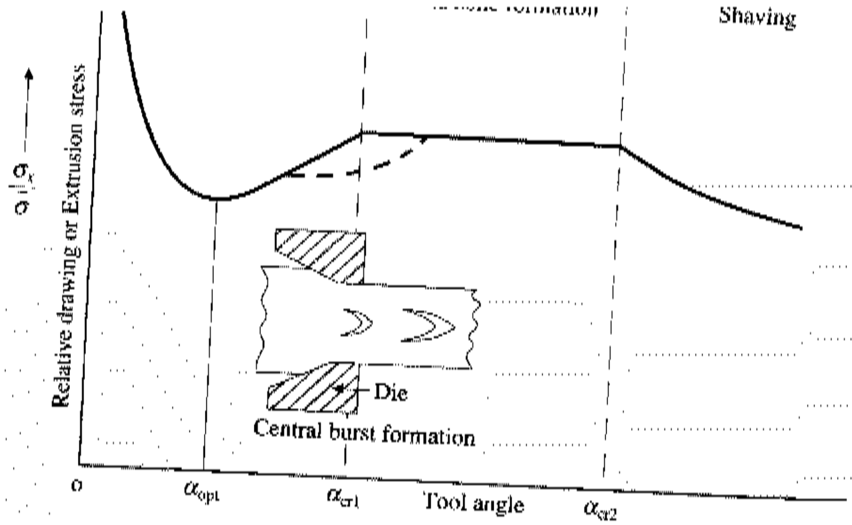
In addition to probable central-burst formation, there are other limitations in regard to how large a die half-angle *a* can be used in drawing and/or extrusion in order to obtain sound metal flow. These are (1) dead-zone formation, (2) shaving, and (3) the breaking of the wire or rod on the exit side in case of drawing.

As shown in Fig. 7.10, as the die half-angle increases from 0° to the optimal half-angle *a**, the external friction losses drastically decrease, and the drawing ^{or} extruding energy or stress decreases to a minimum at which sound flow of ®etal occurs. Beyond this point, an increase in the die half-angle causes the drawing or extrusion stress to increase, because the internal shear losses or dundancy increases rather rapidly as shown in Fig. 7.10. This rise in the drawing

_- _.,,.,,,. m l-KOCESSE

FIGURE

(7.20)



7.13

SS'S--eoe.a.a.on at the exit of the die [7.31, f7.51 wlng stress s0 as to Aviate necking and fracture

7.6 CAUSE OF CENTRAL-BURST FORMATION

An explanation of the cause of central-burst or chevron formation in wire drawing and extrusion and the limitations placed on these processes has been presented by Avitzur [7.5].

For his upper- and lower-bound solutions, Avitzur included a term in the upper-bound theorem that involved a surface of tangential velocity discontinuity, and he divided the metal in the vicinity of the die into three zones as shown in Fig. 7.14(a), as follows: zone I, in which the velocity vector of the metal flow is parallel to the longitudinal axis of the workpiece and equal to the ram velocity, Uo; zone II, in which the direction of the velocity vector is toward the apex of the cone of the die; and zone III, in which the direction of the velocity vector is again parallel to the longitudinal axis of the workpiece. The two transition regions between zones I and II and between zones II and III, in which the direction of flow changes gradually, have been successfully replaced by two spherical boundaries B] and *B, of* tangential velocity discontinuities, with their centers at the apex of the die angle and with radii *ry* and *r,* respectively. During deformation, as soon as a material point reaches the first boundary, a change in the direction of metal flow occurs as it starts to move faster and faster toward the apex of the die. As the material point reaches the second boundary, a change in the direct metal flow occurs once again, restoring it to its original direction parallel to the longitudinal axis. The tangential discontinuities in velocities parallel to the surfaces B] and *B* and of the magnitude *Vy* sin *0* and ty sin *0,* result. [These velocity discontinuities result in the shear losses mentioned in conjunction with Eq. (7.17).] The velocity components tangent to the boundary surfaces cause a shear stress over the surfaces. It should be emphasized that to preserve constancy of volume, no discontinuity of velocity occurs normal to the surfaces, where the normal components of velocity are continuous, as shown in Fig. 7.14(b).

In zone II, the material point near the center of the rod moves somewhat 'aster than a corresponding point closer to the surface in order to preserve constancy of volume, i.e.,

$$\frac{v_0}{v_f} = \frac{V_f}{V_0} = \left(\frac{R_f}{R_0}\right)^2 = \left(\frac{D_f}{D_0}\right)^2$$

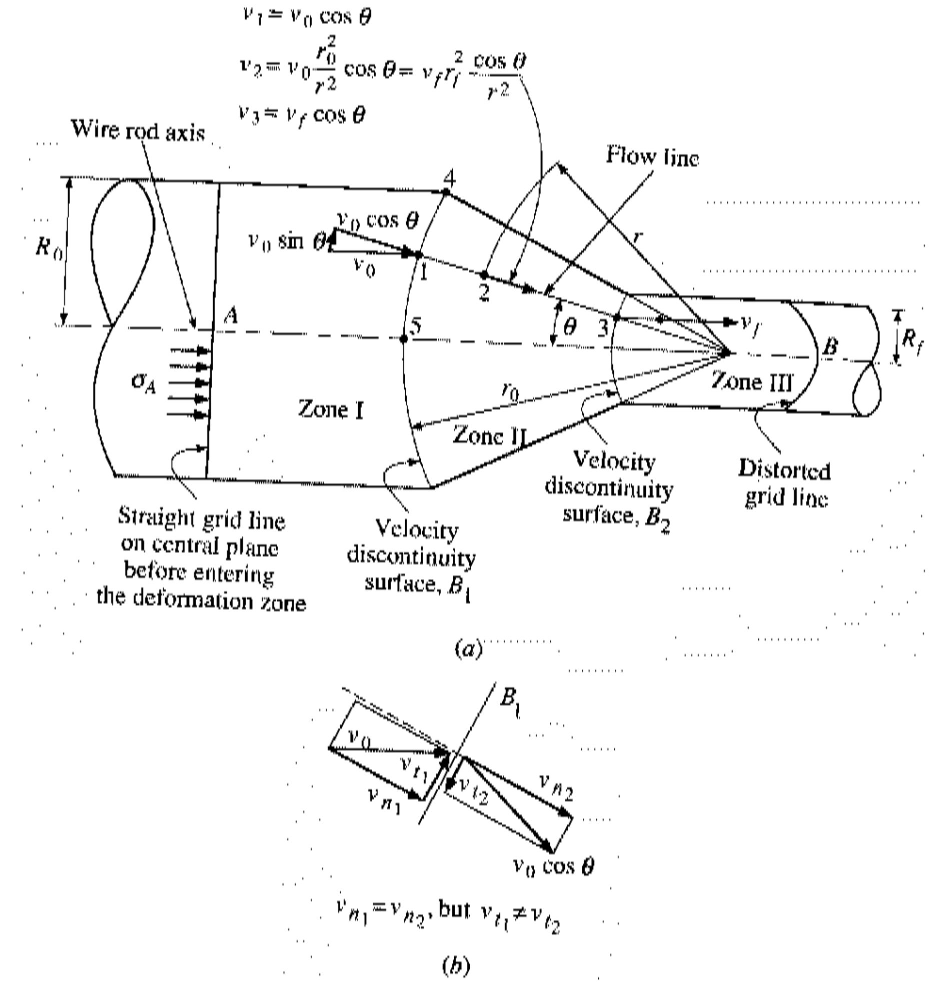


FIGURE 7.14

SS awntmuow, "————ally admissible velocity field for of the deformation zo, and ?4 S 'H 3(? T end lines (surfaces) oundaries and final deformed meta respec iveT (h\ t ,f ""deformed metal, the deformation region, but not in the normalvl F(3 are S y. polygon showing a •"y i" the tange'ntial ciuuiyana u are

used here mterchangeably with *v) [7.3].*
spheribnTareTu TT the plastic zone (zone n) at the of the ram end 7is th1 eq o , where *v0 is* the initia1 locity or that
angle *6* vTrieTzSo posltlon of the point from the <erlL. The velocity ofh aa nolr1" to *a* at the surface of the die, s0 that the ., toatSJZt-1"

As the material point travels through the deformation zone (zone II) from boundary Bi toward boundary .82 along a flow line, its angular position *6* does not change; however, its radial distance *r* from the apex decreases. As r decreases, the velocity *v* increases, so as again to preserve the constancy of volume since the flow cavity is narrowing. The velocity of the material point along the flowline in zone II is given by

$$v_2 = v_0\left(\frac{r_0}{r}\right)^2 \cos\theta = v_f\left(\frac{r_f}{r}\right)^2 \cos\theta$$

as shown in Fig. 7.14(a). A straight transverse grid line in the diametral plane through the longitudinal axis of the workpiece will distort as shown in Fig. 7.14(a) on moving from point *A* to point *B*. This distortion will increase as a increases, and for high values of a (a > 30°) will extend back into zone **I,** which indicates that the internal shear loss or redundancy increases with a.

The central burst may be explained by means of the distortion of the spherical velocity field as shown in Fig. 7.15(a) and (b). This distorted deformation zone is also compatible with the formation of grid patterns with double maxima as is represented in Fig. 7.15 and discussed in the section on visioplasticity. Undistorted deformation zones will have grid patterns with only a single maximum, as shown in Fig. 7.14(a).

The boundaries of velocity discontinuities Bi and *B,* which are spherical for optimal die half-angles, tend to distort as the die half-angle increases and tend to approach each other. For some drawing or extrusion conditions, they touch each other and their area ofcontact expands. Since the exit velocity ly is greater than the entrance velocity *Vy,* a velocity discontinuity normal to a plane occurs. An internal crack or burst initiates along the centerline, and grows until . departs from the die. Nonsteady-state flow occurs, and the sequence of crack •nitiation, crack growth, and the departure of a single crack or burst from the die cavity becomes a periodic event yielding a series of central bursts or chevrons along the centeriine of the drawn or extruded rod as shown in Fig. 7.16. The periodic variation of the drawing or extrusion stress and the velocity of flow are also shown schematically in the foregoing figure. Note how the front pull stress *a* and the velocity at exit of the die *v* vary below and above the mean velocity, respectively, with the initiation, growth, and departure of a single central-burst defect.

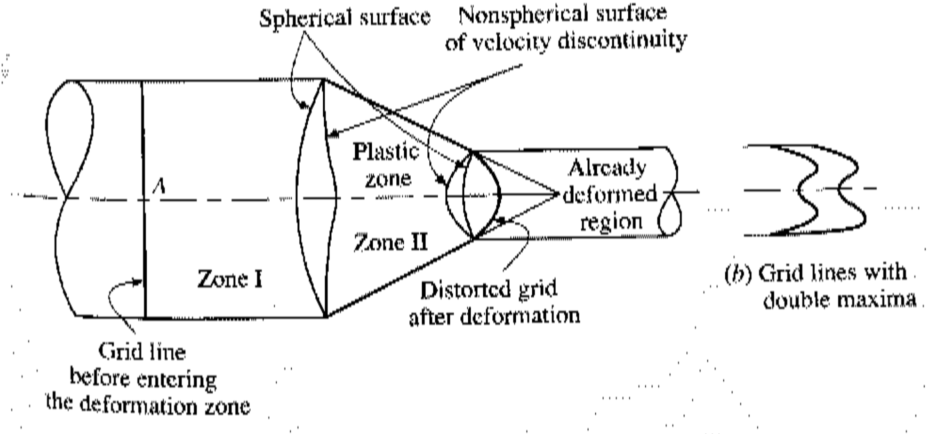
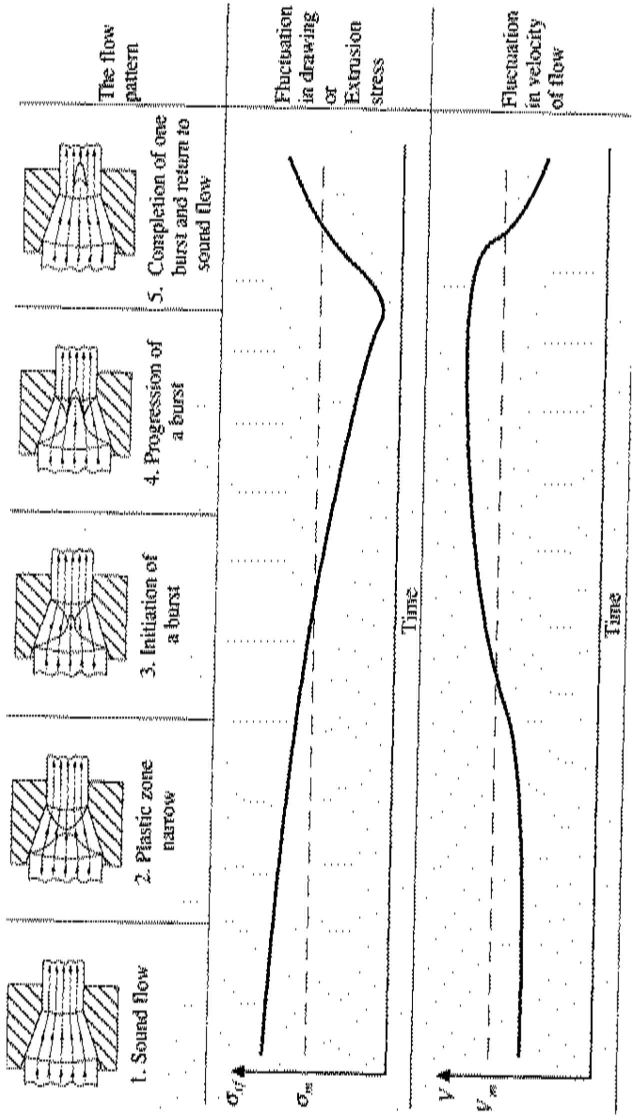


FIGURE 7.15 (") Schematic representation of distorted nonspherical surfaces of horizontal velocity discontinuities, and *(b)* schematic grid lines showing double maxima [7.5].



The material characteristics that cause susceptibility to central bursting will be discussed by use of the slip-line field method, after its use is illustrated for determination of the extrusion pressure for backward and forward extrusion.

Drawing is an operation in which the cross-section of solid rod, wire, or tubing is reduced or changed in shape by *pulling* it through a die. Drawn rods are used for shafts, spindles, and small pistons and as the raw material for fasteners such as rivets, bolts, and screws. In addition to round rods, various profiles are also drawn. Drawing is similar to extrusion. However, in drawing, the material is subjected to a tensile force, whereas in extrusion the billet is under compression. The term *drawing* is also used to refer to making cup-shaped parts by sheet forming operations.

The distinction between the terms rod and wire is somewhat arbitrary, rod being relatively larger in cross-section than wire. In industry, wire is generally defined as a rod that has been drawn through a die at least once. Wire drawing involves smaller diameters than rod drawing. Wire and wire products cover a wide range of applications, such as electrical and electronic wiring, cables, screens, tension-loaded structural members, welding electrodes, springs, paper clips, spokes for bicycle wheels, and string musical instruments.