2 METAL FORMING

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2.1 OVERVIEW OF METAL FORMING

Definitions

Plastic Deformation Processes

Operations that induce shape changes on the workpiece by plastic deformation under forces applied by various tools and dies.

Bulk Deformation Processes

These processes involve large amount of plastic deformation. The cross-section of workpiece changes without volume change. The ratio *cross-section area/volume* is small. For most operations, hot or warm working conditions are preferred although some operations are carried out at room temperature.

Sheet-Forming Processes

In sheet metalworking operations, the cross-section of workpiece does not change—the material is only subjected to shape changes. The ratio *cross-section area/volume* is very high.
Sheet metalworking operations are performed on thin (less than 6 mm) sheets, strips or coils of metal by means of a set of tools called punch and die on machine tools called stamping presses. They are always performed as cold working operations.

Material considerations

Material Behavior

In the plastic region, the metal behavior is expressed by the flow curve:

$$\sigma = K\varepsilon^n$$

where K is the strength coefficient and n is the strain-hardening (or work-hardening) exponent. K and n are given in the tables of material properties or are calculated from the material testing curves.

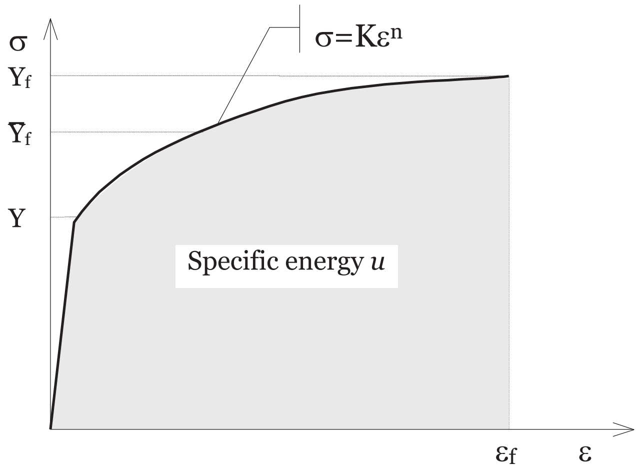
Flow stress

For some metalworking calculations, the flow stress Yf of the work material (the instantaneous value of stress required to continue deforming the metal) must be known:

$$Y_f = K\varepsilon^n$$

Average (mean) flow stress

In some cases, analysis is based not on the instantaneous flow stress, but on an average value over the strain-stress curve from the beginning of strain to the final (maximum) value that occurs during deformation:



Stress-strain curve indicating location of average flow stress $\bar{Y}_f$ in relation to yield strength Y and final flow stress Y_f

The mean flow stress is defined as

$$\bar{Y}_f = \frac{K\varepsilon_f^{\ n}}{1+n}$$

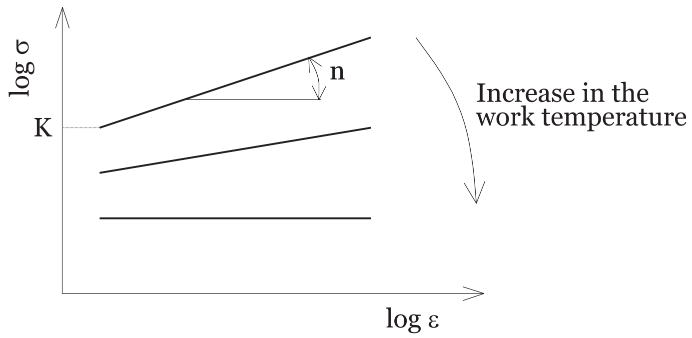
here ε_f is the maximum strain value during deformation.

Work-hardening

It is an important material characteristic since it determines both the properties of the workpiece and process power. It could be removed by annealing.

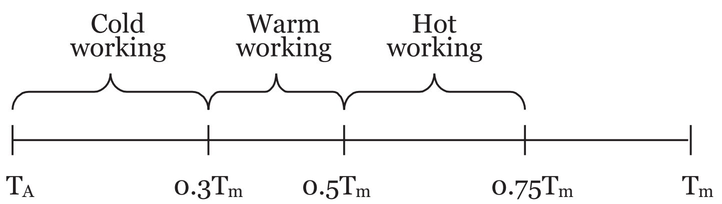
Temperature in metal forming

The flow curve is valid for an ambient work temperature. For any material, K and n depend on temperature, and therefore material properties are changed with the work temperature:



True stress-strain curve showing decrease in strength coefficient K and strain-hardening exponent n with work temperature

There are three temperature ranges-cold, warm, and hot working:



Temperature range for different metal forming operations. T_A is the ambient (room) temperature, and T_m is the work metal melting temperature

Cold working is metal forming performed at room temperature.

Advantages: better accuracy, better surface finish, high strength and hardness of the part, no heating is required.
Disadvantages: higher forces and power, limitations to the amount of forming, additional annealing for some material is required, and some material are not capable of cold working.

Warm working is metal forming at temperatures above the room temperature but bel-low the recrystallization one.

Advantages: lower forces and power, more complex part shapes, no annealing is required.
Disadvantages: some investment in furnaces is needed.

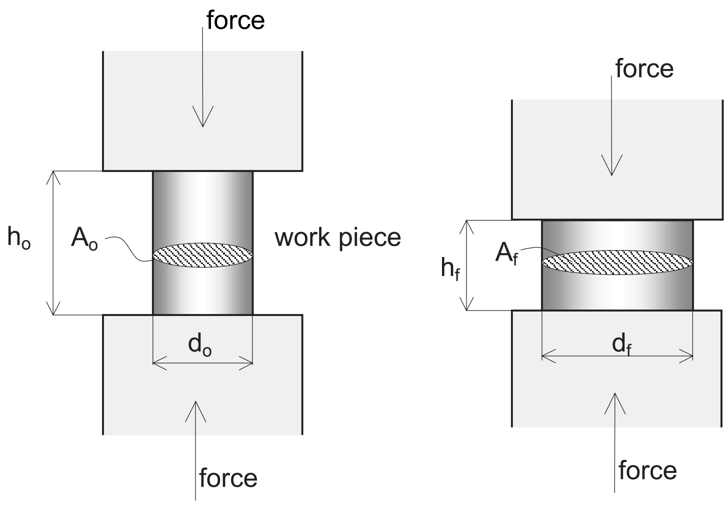
Hot working involves deformation of preheated material at temperatures above the re-crystallization temperature.

Advantages: big amount of forming is possible, lower forces and power are required, forming of materials with low ductility, no work hardening and therefore, no additional annealing is required.
Disadvantages: lower accuracy and surface finish, higher production cost, and shorter tool life.

Friction effects

Homogeneous Deformation

If a solid cylindrical workpiece is placed between two flat platens and an applied load P is increased until the stress reaches the flow stress of the material then its height will be reduced from initial value of h_o to h_1. Under ideal homogeneous condition in absence of friction between platens and work, any height reduction causes a uniform in-crease in diameter and area from original area of A_o to final area A_f.



Homogeneous deformation

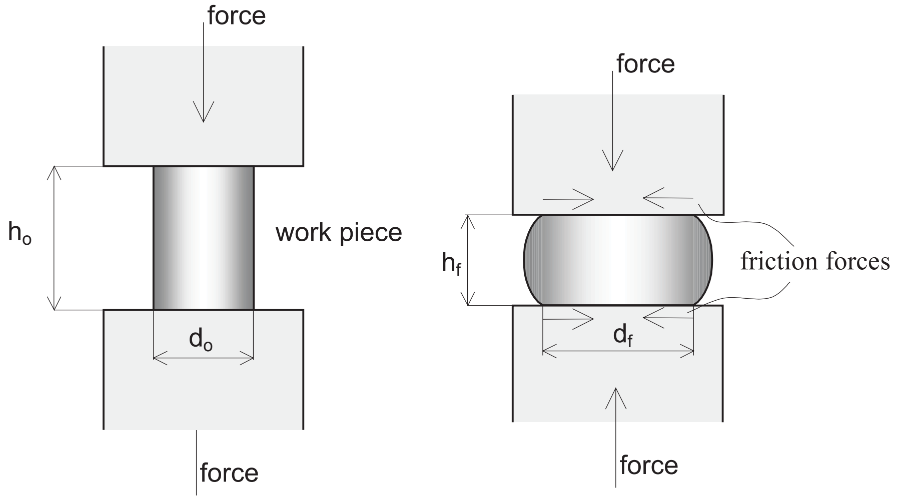
The load required, i.e. the press capacity, is defined by

$$P = Y_f A_f$$

Inhomogeneous deformation

In practice, the friction between platens and workpiece cannot be avoided and the latter develops a "barrel" shape. This is called inhomogeneous deformation and changes the load estimation as follows

$$P = Y_f k_s A_f = Y_f\left(1 + \frac{\mu d_o}{3h_o}\right)A_f$$

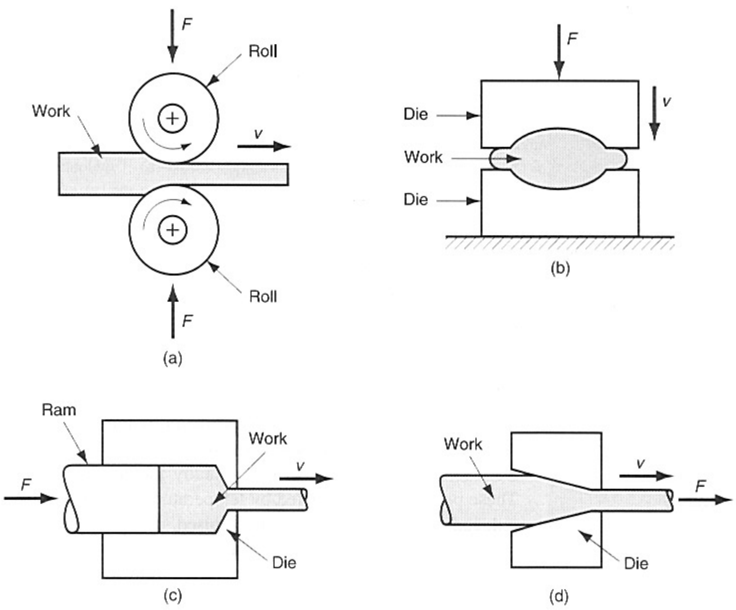


Inhomogeneous deformation with barreling of the workpiece

where μ is the frictional coefficient between workpiece and platen, and k_s is the shape factor.

2.2 BULK DEFORMATION PROCESSES

Classification of Bulk Deformation Processes



Basic bulk deformation processes
(a) rolling, (b) forging, (c) extrusion, (d) drawing

Rolling: Compressive deformation process in which the thickness of a plate is reduced by squeezing it through two rotating cylindrical rolls.

Forging: The workpiece is compressed between two opposing dies so that the die shapes are imparted to the work.

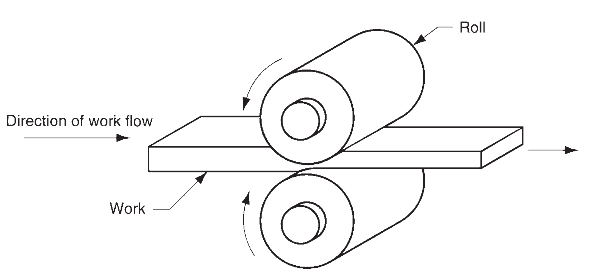
Extrusion: The work material is forced to flow through a die opening taking its shape

Drawing: The diameter of a wire or bar is reduced by pulling it through a die opening (bar drawing) or a series of die openings (wire drawing)

Rolling

Definition

Rolling is a Bulk Deformation Process in which the thickness of the work is reduced by compressive forces exerted by two opposing rolls:



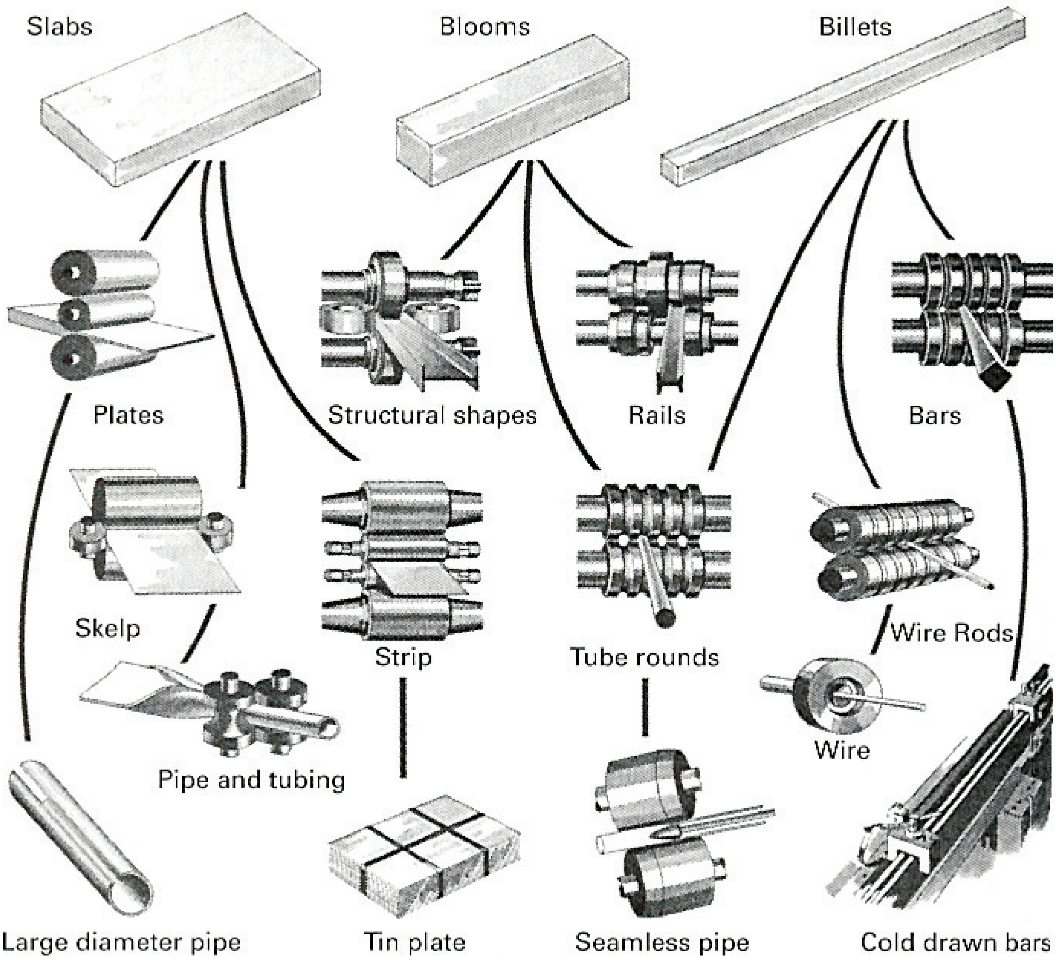
The process of flat rolling

Steps in rolling

The preheated at 1200 °C cast ingot (the process is known as *soaking*) is rolled into one of the three intermediate shapes called *blooms*, *slabs*, or *billets*.

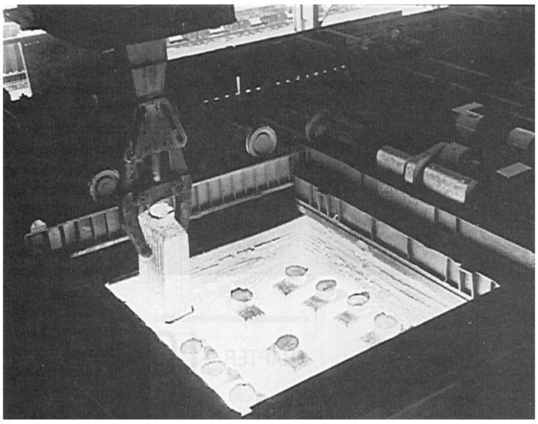
- ***Bloom*** has a square cross section of 150/150 mm or more
- ***Slab*** (40/250 mm or more) is rolled from an ingot or a bloom
- ***Billet*** (40/40 mm or more) is rolled from a bloom

These intermediate shapes are then rolled into different products as illustrated in the figure:

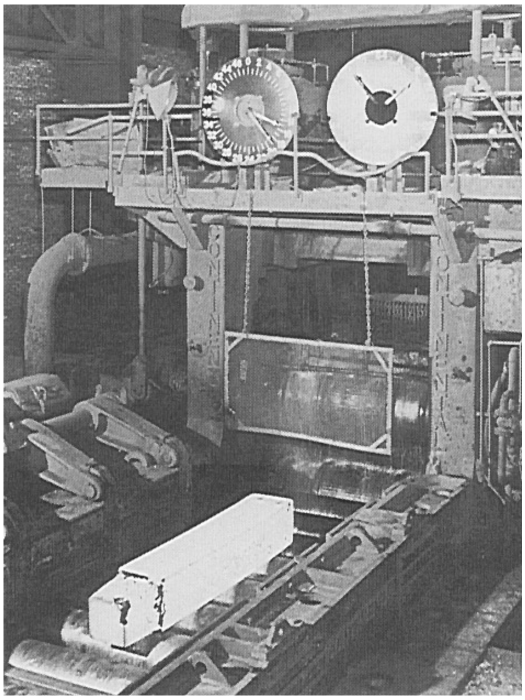


Production steps in rolling

Next pictures show some production steps in flat and shape rolling:



Powerful tongs lift an ingot from the soaking pit where it was thoroughly heated to the rolling temperature

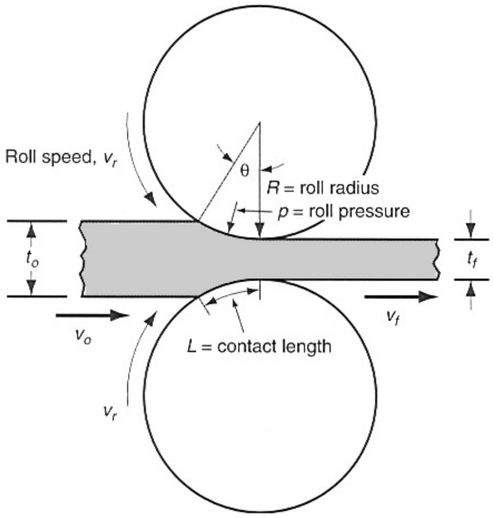


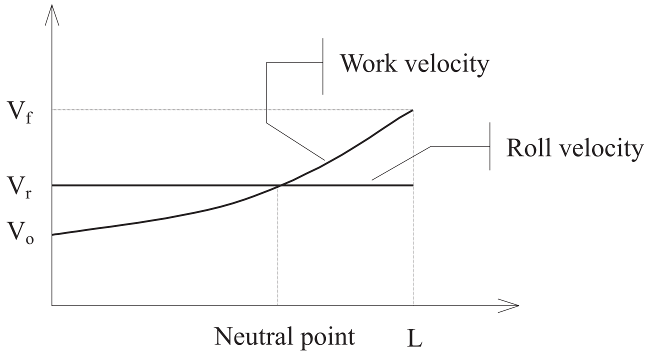
Steel bloom enters the rolling mill

Structural shapes are rolled from blooms on mills equipped with grooved rolls

Hot saw cuts rolled shapes to customer length after delivery from the finishing rolling mill

Flat rolling





Side view of flat rolling and the velocity diagram indicating work and roll velocities along the contact length L

The work is squeezed between two rolls so that it thickness is reduced by an amount called the *draft*, d

$$d = t_o - t_f$$

If the draft is expressed as a fraction of the starting block thickness, it is called *reduction*, r:

$$r = d/t_o$$

Rolling increases the work width from an initial value of w_o to a final one of w_f, and this is called *spreading*.

The inlet and outlet volume rates of material flow must be the same, that is,

$$t_o w_o v_o = t_f w_f v_f$$

where v_o and v_f are the entering and exiting velocities of the work. The point where roll velocity equals work velocity is known as the *no-slip point* or the *neutral point*.

The true strain and the mean flow stress are defined by

$$\text{true strain } \varepsilon = \ln\frac{t_o}{t_f} \text{ , and mean flow stress } \bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

Friction occurs with a certain coefficient of friction μ on either sides of no-slip point. Both friction forces act in opposite directions and are not equal. The entrance force is bigger so that the resulting force pulls the work through the rolls. The maximum possible draft d_{max} depends on μ and roll radius R and is given by

$$d_{max} = \mu^2 R$$

The *rolling force* F is estimated as

$$F = \bar{Y}_f wL$$

where L is the contact length, approximately

$$L = \sqrt{R(t_o - t_f}$$

The *power* P required to drive each roll is

$$P = 2\pi NFL$$

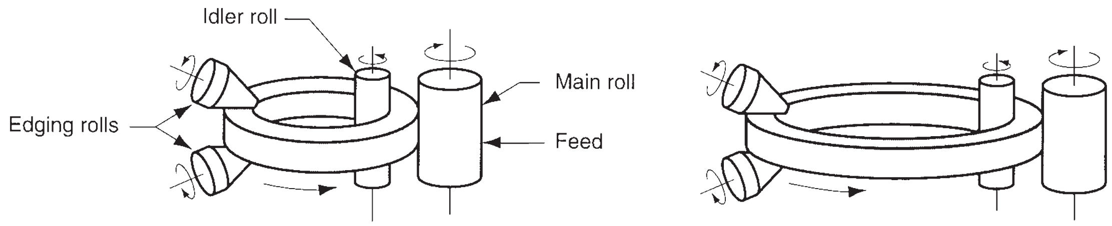
where N is the rotational speed of the roll.

Shape rolling

The work is deformed by a gradual reduction into a contoured cross section (I-beams, L-beams, U-channels, rails, round, squire bars and rods, etc.).

Ring rolling

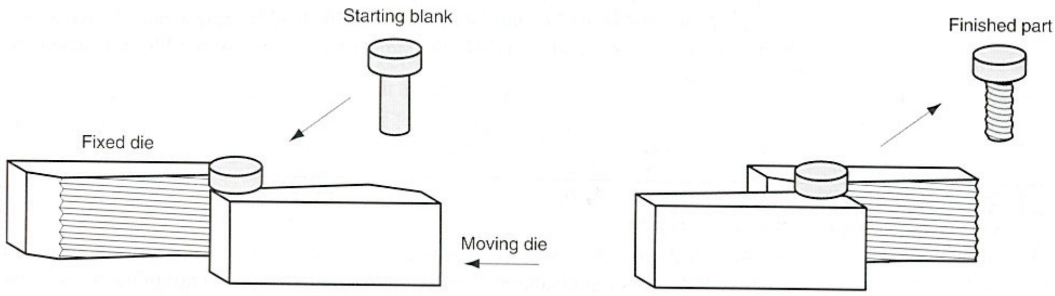
Thick-walled ring of small diameter is rolled into a thin-walled ring of larger diameter:



Ring rolling used to reduce the wall thickness and increase the diameter of a ring

Thread rolling

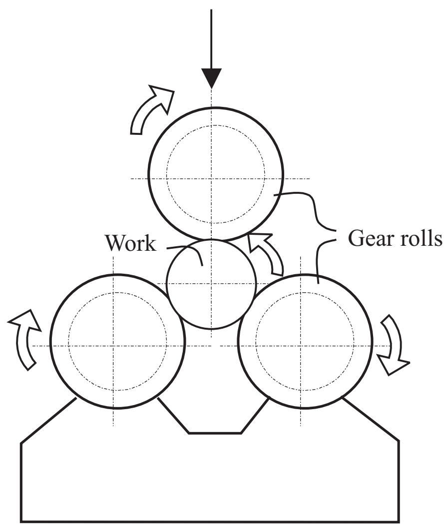
Threads are formed on cylindrical parts by rolling them between two thread dies:



Thread rolling with flat dies

Gear rolling

Gear rolling is similar to thread rolling with three gears (tools) that form the gear profile on the work.



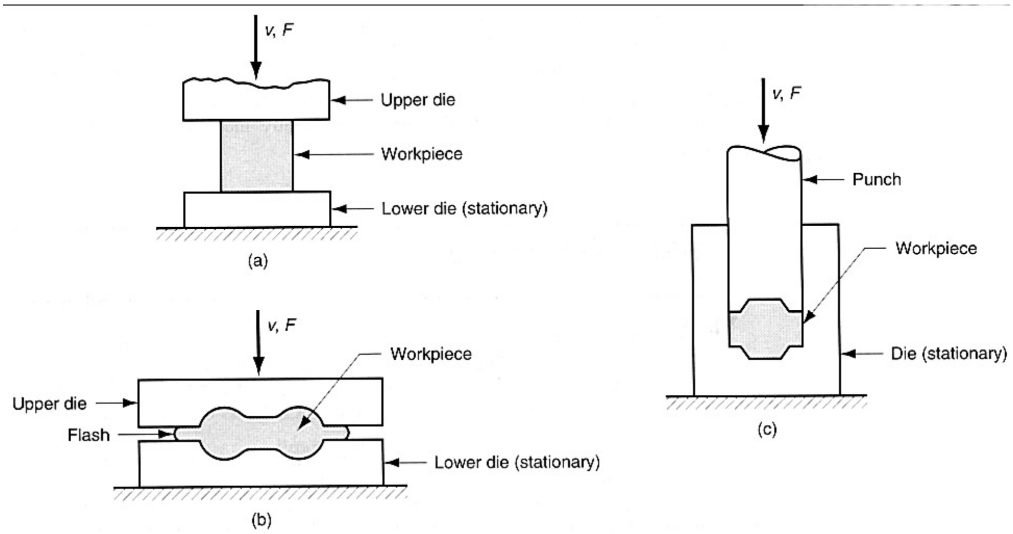
Gear rolling between three gear roll tools

Forging

Definition

Forging is a Bulk Deformation Process in which the work is compressed between two dies. According to the degree to which the flow of the metal is constrained by the dies there are three types of forging:

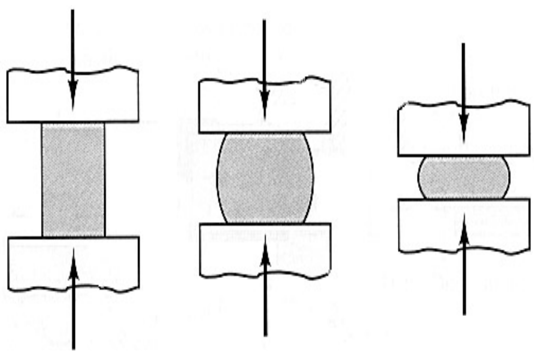
1. Open-die forging
2. Impression-die forging
3. Flashless forging



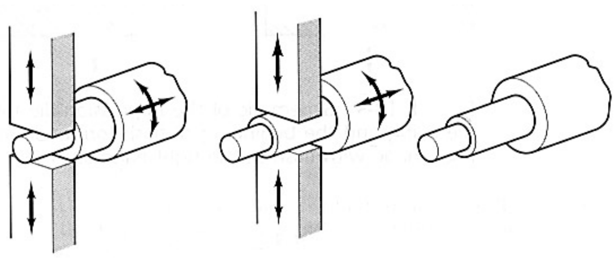
Three types of forging: (a) open-die forging, (b) impression die forging, and (c) flashless forging

Open-die forging

Known as *upsetting*, it involves compression of a work between two flat dies, or platens. Force calculations were discussed earlier.



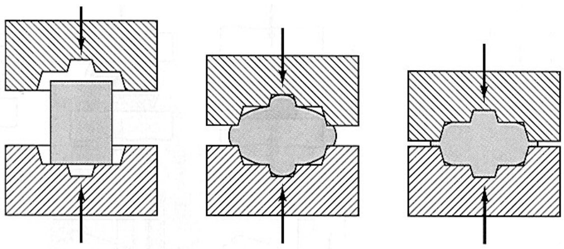
Sequence in open-die forging illustrating the unrestrained flow of material. Note the barrel shape that forms due to friction and inhomogeneous deformation in the work



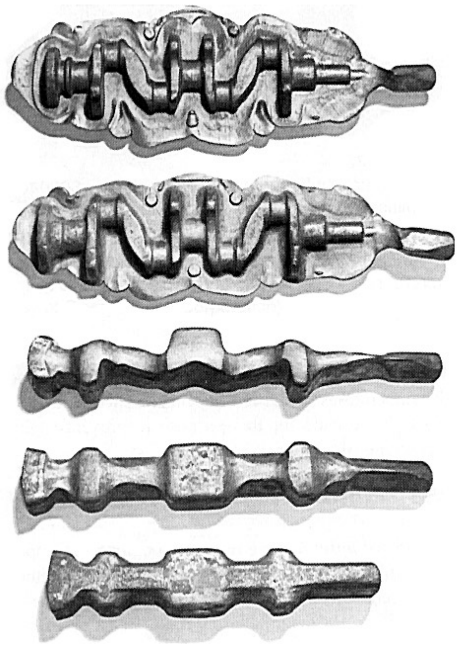
Open-die forging of a multi diameter shaft

Impression-die forging

In impression-die forging, some of the material flows radially outward to form a flash:



Schematics of the impression-die forging process showing partial die filling at the beginning of flash formation in the center sketch, and the final shape with flash in the right-hand sketch



Stages (from bottom to top) in the formation of a crankshaft by hot impression-die forging

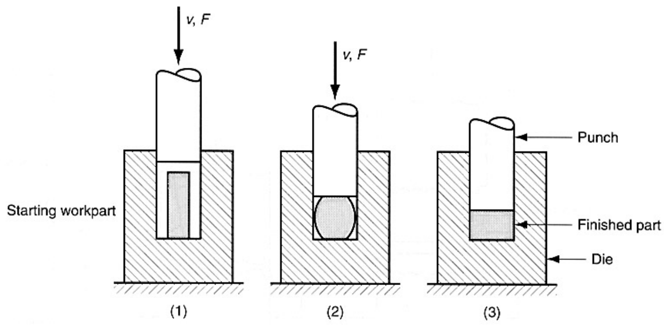
Estimation of the maximum force F can be approximately done by

$$F = K_f Y_f A$$

where K_f is the shape factor ranging from 6 to 10, bigger for more complex shapes, Y_f is the yield strength of the material at work temperature, A is the projected area of the part, including flash.

Flashless forging

The work material is completely surrounded by the die cavity during compression and no flash is formed:

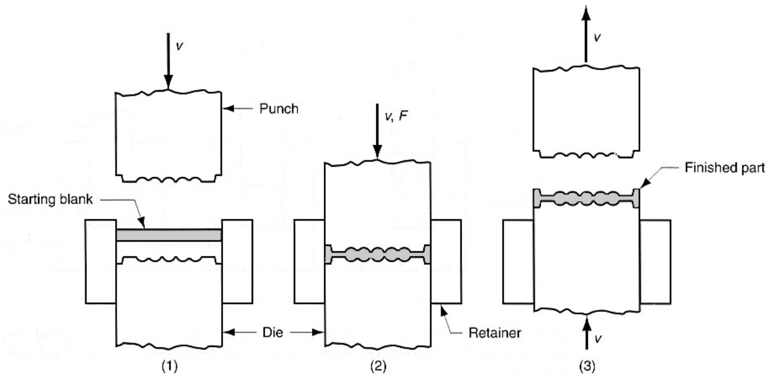


Flashless forging: (1) just before initial contact with the workpiece, (2) partial compression, and (3) final push and die closure. Symbol v indicates motion, and F - applied force.

Most important requirement in flashless forging is that the work volume must equal the space in the die cavity to a very close tolerance. For force estimation, the same equation as in impression-die forging is applied.

Coining

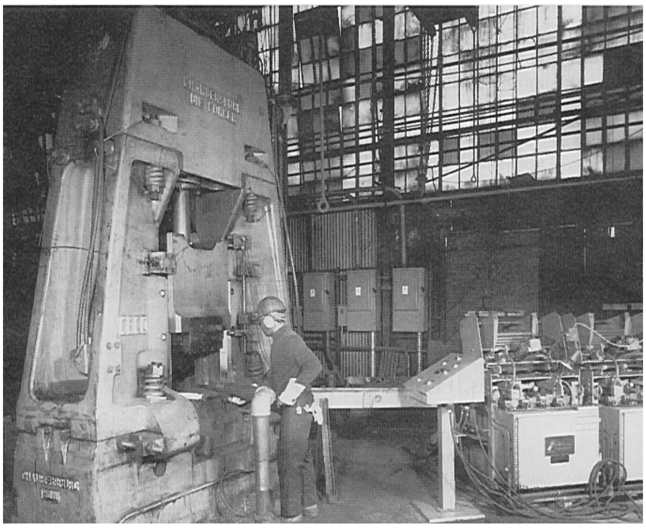
Special application of flashless forging in which fine detail in the die are impressed into the top and bottom surfaces of the workpiece. There is a little flow of metal in coining.



Coining operation: (1) start of cycle, (2) compression stroke, and (3) ejection of finished part

Forging machines

The next figures show some examples of the common forging machines-hammers and presses:



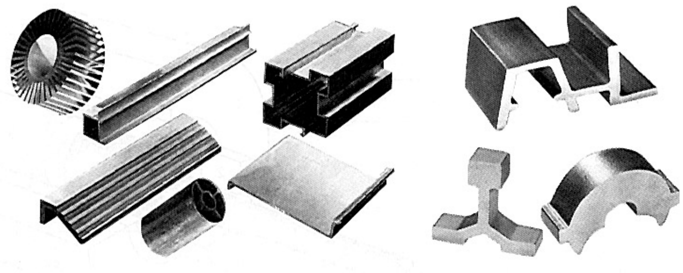
Drop forging hammer, fed by conveyor and heating unit at the right of the scene.

A 35 000-ton forging press. In the foreground is a 120-kg, 3-m aluminum part that has forged on this press.

Extrusion

Definition

Extrusion is a Bulk Deformation Process in which the work is forced to flow through a die opening to produce a desired cross-sectional shape.

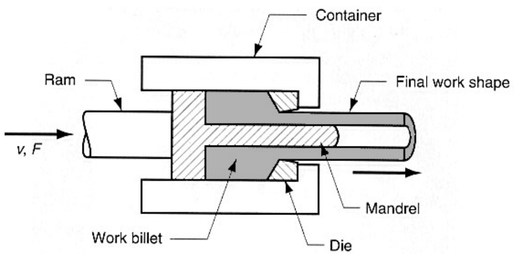


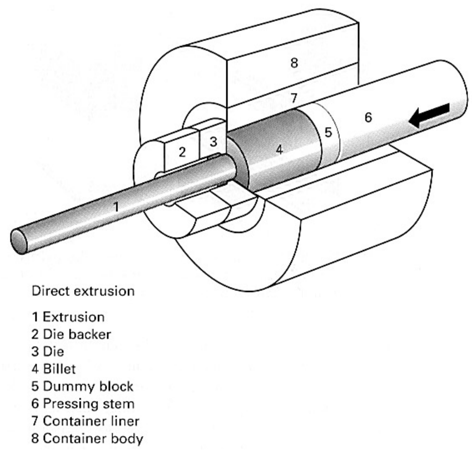
Typical shapes produced by extrusion

Extrusion is performed in different ways therefore different classifications are available:

- Direct and indirect extrusion
- Hot and cold extrusion
- Continuous and discrete extrusion

Direct and indirect extrusion





(Left) Direct extrusion to produce hollow or semihollow cross section. (Right) Direct extrusion to produce solid cross section. Schematic shows the various equipment components.

Force and power analysis in extrusion

The ram force, F, is estimated as

$$F = p\,A_o$$

where A_o is the billet cross-sectional area, and p is the ram pressure,

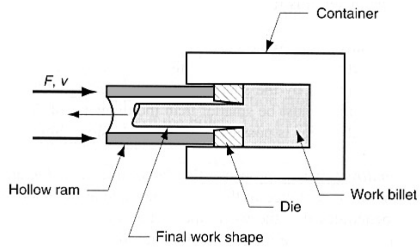
$$p = \overline{Y}_f\left(\varepsilon_x + \frac{2L}{D_o}\right)$$

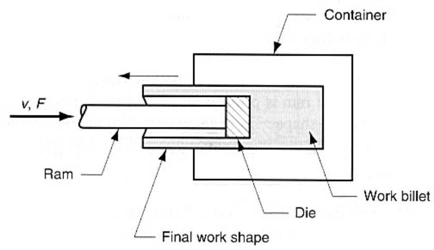
where D_o is the original diameter of the billet, L is the length of the billet in the die, and ε_x is the extrusion strain,

$$\varepsilon_x = a + b\ln(A_o/A_f),$$

a and b being the empirical constants, usually a=0.8 and b=1.2~1.5.

Power required is calculated as $P = Fv$, where v is the ram velocity.



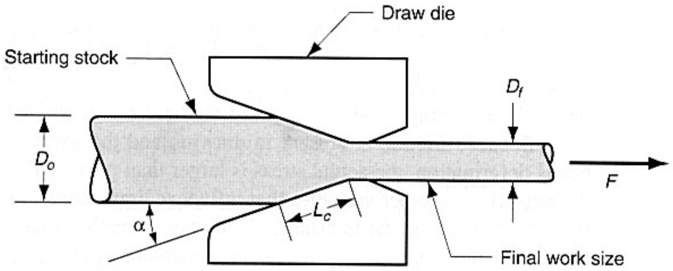


In indirect extrusion (backward, inverse extrusion) the material flows in the direction opposite to the mo-tion of the ram to produce a solid (top) or a hollow cross section (bottom).

Wire and Bar Drawing

Definition

Wire and Bar Drawing is a Bulk Deformation Process in which the cross-section of a bar, rod or wire is reduced by pulling it through a die opening, as in the next figure:



Drawing of a rod, bar, or wire

Bar drawing is a single-draft operation. By contrast, in wire drawing the wire is drawn through a series of dies, between 4 and 12.

The draft, d, is defined as

$$d = D_o - D_f$$

and reduction, r, is given by

$$r = d/D_o$$

Force and power analysis in drawing

The draw force F is calculated as a product of the drawn cross-section area A_f and the draw stress σ_d

$$F = A_f \sigma_d$$

The draw stress σ_d is defined as

$$\sigma_d = \bar{Y}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \phi \ln \frac{A_o}{A_f}$$

where ϕ is the factor, that accounts for inhomogeneous deformation, usually around 1.0.