Extrusion

Is a compression process in which the work metal is forced to flow through a die opening to produce a desired cross-sectional shape. The process can be likened to squeezing toothpaste out of a toothpaste tube. Extrusion as an industrial process was invented around 1800 in England, during the Industrial Revolution. There are several advantages of the modern process:

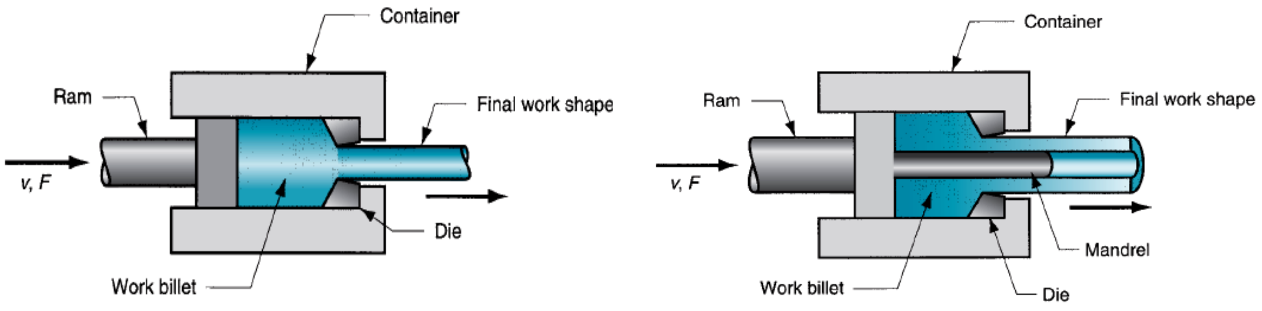
(1) A variety of shapes are possible, especially with hot extrusion.
(2) Fairly close tolerances are possible, especially in cold extrusion.
(3) In some extrusion operations, little or no wasted material is created.
(4) Grain structure and strength properties are enhanced in cold and warm extrusion.

Types of extrusion

Extrusion is carried out in various ways. One important distinction is between direct extrusion and indirect extrusion. Another classification is by working temperature: cold, warm, or hot extrusion. Finally, extrusion is performed as either a continuous process or a discrete process.

1- Direct extrusion

Also called forward extrusion is illustrated in Figure (1). A metal billet is loaded into a container, and a ram compresses the material, forcing it to flow through one or more openings in a die at the opposite end of the container. As the ram approaches the die, a small portion of the billet remains that cannot be forced through the die opening. This extra portion, called the butt, is separated from the product by cutting it just beyond the exit of the die. One of the problems in direct extrusion is the significant friction that exists between the work surface and the walls of the container as the billet is forced to slide toward the die opening. This friction causes a substantial increase in the ram force required in direct extrusion. In hot extrusion, the friction problem is aggravated by the presence of an oxide layer on the surface of the billet. This oxide layer can cause defects in the extruded product. To address these problems, a dummy block is often used between the ram and the work billet. The diameter of the dummy block is slightly smaller than the billet diameter, so that a narrow ring of work metal (mostly the oxide layer) is left in the container, leaving the final product free of oxides. Hollow sections (e.g., tubes) are possible in direct extrusion by the process setup in Figure (1b).



(a) (b)

FIGURE (1) Direct extrusion to produce (a) a solid cross section and (b) a hollow cross

FIGURE (2) Direct extrusion to produce a hollow or semi-hollow cross

The starting billet in direct extrusion is usually round in cross section, but the final shape is determined by the shape of the die opening. Obviously, the largest dimension of the die opening must be smaller than the diameter of the billet.

2- In indirect extrusion.

Also called backward extrusion and reverse extrusion, Figure (3), the die is mounted to the ram rather than at the opposite end of the container. As the ram penetrates into the work, the metal is forced to flow through the clearance in a direction opposite to the motion of the ram. Since the billet is not forced to move relative to the container, there is no friction at the container walls, and the ram force is therefore lower than in direct extrusion. Limitations of indirect extrusion are imposed by the lower rigidity of the hollow ram and the difficulty in supporting the extruded product as it exits the die.

Indirect extrusion can produce hollow (tubular) cross sections, as in Figure (3b). In this method, the ram is pressed into the billet, forcing the material to flow around the ram and take a cup shape. There are practical limitations on the length of the extruded part that can be made by this method. Support of the ram becomes a problem as work length increases.

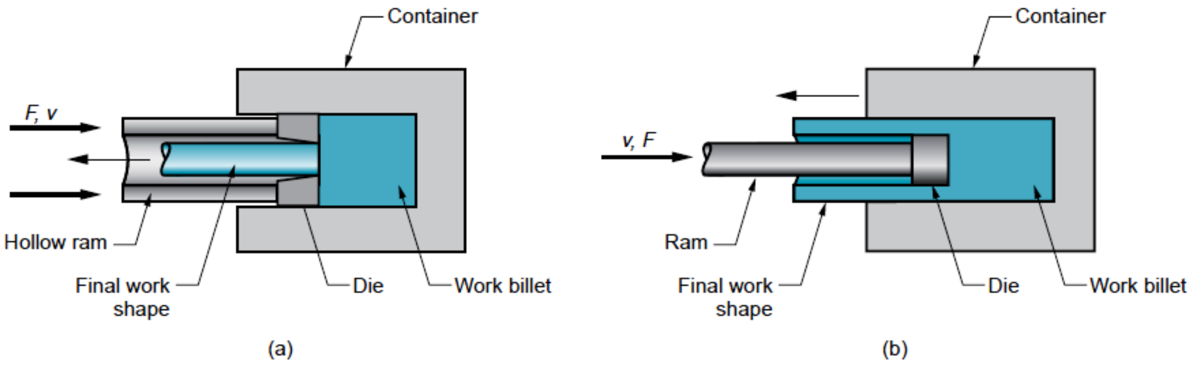


FIGURE (3) Indirect extrusion to produce (a) a solid cross section and (b) a hollow cross

Analysis of extrusion

Let us use Figure (4) as a reference in discussing some of the parameters in extrusion. The diagram assumes that both billet and extrudate are round in cross section. One important parameter is the extrusion ratio, also called the reduction ratio. The ratio is defined:

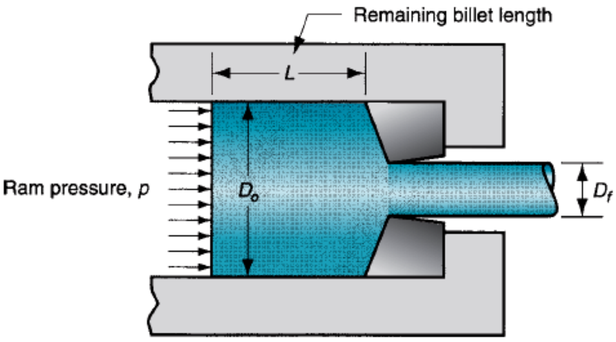


FIGURE (4) Pressure and other variables in direct extrusion

$$r_x = \frac{A_o}{A_f} \quad \text{……….1}$$

where r_x: extrusion ratio, A_o: cross-sectional area of the starting billet,mm2 and A_f : final cross-sectional area of the extruded section,mm2. The ratio applies for both direct and indirect extrusion. The value of r_x can be used to determine true strain in extrusion, given that ideal deformation occurs with no friction and no redundant work:

$$\epsilon = \ln r_x = \ln \frac{A_o}{A_f} \quad \text{………2}$$

Under the assumption of ideal deformation (no friction and no redundant work), the pressure applied by the ram to compress the billet through the die opening depicted in our figure can be computed as follows:

$$p = \overline{Y}_f \ln r_x \quad \text{…………….3}$$

where Y_f average flow stress during deformation, MPa

In fact, extrusion is not a frictionless process, and the previous equations grossly underestimate the strain and pressure in an extrusion operation. Friction exists between the die and the work as the billet squeezes down and passes through the die opening. In direct extrusion, friction also exists between the container wall and the billet surface. The effect of friction is to increase the strain experienced by the metal. Thus, the actual pressure is greater than that given by Eq. (3), which assumes no friction.

Various methods have been suggested to calculate the actual true strain and associated ram pressure in extrusion. The following empirical equation proposed by Johnson for estimating extrusion strain has gained considerable recognition:

$$\epsilon_x = a + b \ln r_x \quad \text{…………..4}$$

where ϵ_x : extrusion strain; and *(a)* and (*b*) are empirical constants for a given die angle. Typical values of these constants are: ***a*** = 0.8 and ***b*** = 1.2 to 1.5. Values of ***a*** and ***b*** tend to increase with increasing die angle.

The ram pressure to perform indirect extrusion can be estimated based on

Johnson's extrusion strain formula as follows:

$$p = \overline{Y}_f \epsilon_x \text{ ....5}$$

where Y_f is calculated based on ideal strain from Eq. (2), rather than extrusion strain in Eq. (4).

ram pressure in direct extrusion:

$$p = \overline{Y}_f \left(\epsilon_x + \frac{2L}{D_o} \right) \text{ ....6}$$

where the term *2L/Do* accounts for the additional pressure due to friction at the container–billet interface. *L* is the portion of the billet length remaining to be extruded, and *Do* is the original diameter of the billet.

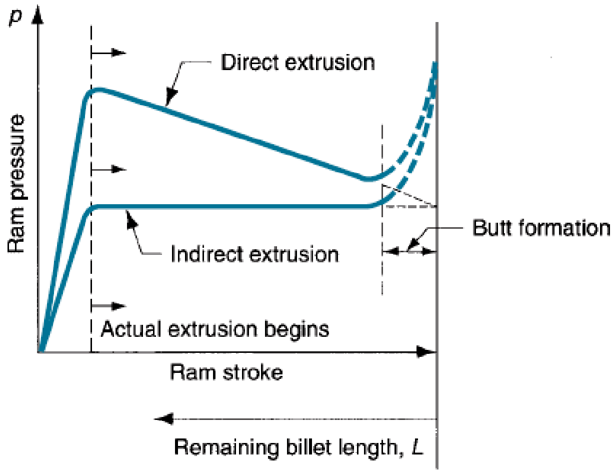


FIGURE (5) Typical plots of ram pressure versus ram stroke (and remaining billet length) for direct and indirect extrusion. The higher values in direct extrusion result from friction at the container wall. The shape of the initial pressure buildup at the beginning of the plot depends on die angle (higher die angles cause steeper pressure buildups). The pressure increase at the end of the stroke is related to formation of the butt.

Ram force in indirect or direct extrusion is simply pressure p from Eq. (6), multiplied by billet area *Ao*:

$$F = pA_o \text{ ....7}$$

where *F* : ram force in extrusion, *(N)* . Power required to carry out the extrusion operation is simply

$$P = Fv \text{ ....8}$$

where *P* : power (J/s) ; *F* : ram force (*N*) ; and *v* : ram velocity (m/s).

Example

A billet 75 mm long and 25 mm in diameter is to be extruded in a direct extrusion operation with extrusion ratio $r_x = 4.0$. The extrudate has a round cross section. The die angle (half-angle) = 90°. The work metal has a strength coefficient = 415 MPa, and strain-hardening exponent = 0.18. Use the Johnson formula with $a = 0.8$ and $b = 1.5$ to estimate extrusion strain. Determine the pressure applied to the end of the billet as the ram moves forward.

Solution: Let us examine the ram pressure at billet lengths of $L = 75$ mm (starting value), $L = 50$ mm, $L = 25$ mm, and $L = 0$. We compute the ideal true strain, extrusion strain using Johnson's formula, and average flow stress:

$$\epsilon = \ln r_x = \ln 4.0 = 1.3863$$

$$\epsilon_x = 0.8 + 1.5(1.3863) = 2.8795$$

$$\overline{Y}_f = \frac{415(1.3863)^{0.18}}{1.18} = 373 \text{ MPa}$$

$L = 75$ mm: With a die angle of 90°, the billet metal is assumed to be forced through the die opening almost immediately; thus, our calculation assumes that maximum pressure is reached at the billet length of 75 mm. For die angles less than 90°, the pressure would build to a maximum as in Figure as the starting billet is squeezed into the cone-shaped portion of the extrusion die. Using Eq. ( ),

$$p = 373\left(2.8795 + 2\frac{75}{25}\right) = 3312 \text{ MPa}$$

$$L = 50 \text{ mm: } p = 373\left(2.8795 + 2\frac{50}{25}\right) = 2566 \text{ MPa}$$

$$L = 25 \text{ mm: } p = 373\left(2.8795 + 2\frac{25}{25}\right) = 1820 \text{ MPa}$$

$L = 0$: Zero length is a hypothetical value in direct extrusion. In reality, it is impossible to squeeze all of the metal through the die opening. Instead, a portion of the billet (the "butt") remains unextruded and the pressure begins to increase rapidly as L approaches zero. This increase in pressure at the end of the stroke is seen in the plot of ram pressure versus ram stroke in Figure . Calculated below is the hypothetical minimum value of ram pressure that would result at $L = 0$.

$$p = 373\left(2.8795 + 2\frac{0}{25}\right) = 1074 \text{ MPa}$$

This is also the value of ram pressure that would be associated with indirect extrusion throughout the length of the billet.