Chapter Nine: Metal Forming - Drawing

9.1. Introduction

In the context of bulk deformation, drawing is an operation in which the cross section of a bar, rod, or wire is reduced by pulling it through a die opening, as in Figure 9.1. The general features of the process are similar to those of extrusion. The difference is that the work is pulled through the die in drawing, where as it is pushed through the die in extrusion. Al though the presence of tensile stresses is obvious in drawing, compression also plays a significant role because the metal is squeezed down as it passes through the die opening. For this reason, the deformation that occurs in drawing is sometimes referred to as indirect compression. Drawing is a term also used in sheet metal working. The term ***wire and bar drawing*** is used to distinguish the drawing process discussed here from the sheet metal process of the same name.

The basic difference between bar drawing and wire drawing is the stock size that is processed. ***Bar drawing*** is the term used for large diameter bar and rod stock, while ***wire drawing*** applies to small diameter stock. Wire sizes down to 0.03 mm (0.001 in) are possible in wire drawing. Although the mechanics of the process are the same for the two cases, the methods, equipment, and even the terminology are somewhat different.

Bar drawing is generally accomplished as a ***single-draft*** operation—the stock is pulled through one die opening. Because the beginning stock has a large diameter, it is in the form of a straight cylindrical piece rather than coiled. This limits the length of the work that can be drawn, necessitating a batch type operation. By contrast, wire is drawn from coils consisting of several hundred (or even several thousand) feet of wire and is passed through a series of draw dies. The number of dies varies typically between 4 and 12. The term ***continuous drawing*** is used to describe this type of operation because of the long production runs that are achieved with the wire coils, which can be butt-welded each to the next to make the operation truly continuous.

In a drawing operation, the change in size of the work is usually given by the area reduction, defined as follows:

$$r = \frac{A_o - A_f}{A_o} \qquad (9.1)$$

where r = area reduction in drawing; A_o = original area of work, mm^2 (in^2); and A_f = final area, mm^2 (in^2). Area reduction is often expressed as a percentage. In bar drawing, rod drawing, and in drawing of large diameter wire for upsetting and heading operations, the term draft is used to denote the before and after difference in size of the processed work. The ***draft*** is simply the difference between original and final stock diameters:

$$d = D_o - D_f \qquad (9.2)$$

where d = draft, mm (in); D_o = original diameter of work, mm (in); and D_f = final work diameter, mm (in).

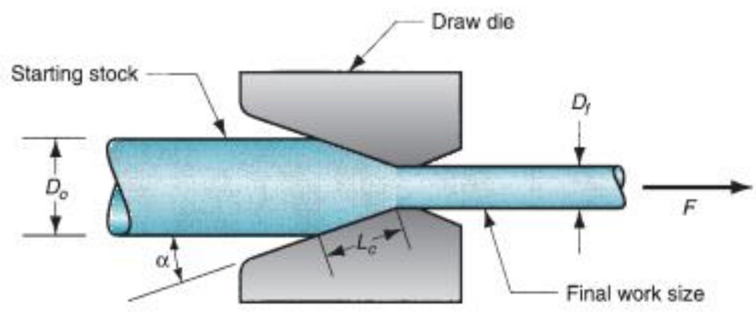

Figure 9.1 Drawing of bar, rod, or wire.

9.2. Analysis of Drawig

In this section, we consider the mechanics of wire and bar drawing. How are stresses and forces computed in the process? We also consider how large a reduction is possible in a drawing operation.

Mechanics of Drawing If no friction or redundant work occurred in drawing, true strain could be determined as follows:

$$\epsilon = \ln\frac{A_o}{A_f} = \ln\frac{1}{1-r} \tag{9.3}$$

where A_o and A_f are the original and final cross-sectional areas of the work, as previously defined; and r = drawing reduction as given by Eq. (9.1). The stress that results from this ideal deformation is given by

$$\sigma = \overline{Y}_f\epsilon = \overline{Y}_f \ln\frac{A_o}{A_f} \tag{9.4}$$

where $\overline{Y}_f = \frac{K\epsilon^n}{1+n}$= average flow stress based on the value of strain given by Eq. (9.3)

Because friction is present in drawing and the work metal experiences in-homogeneous deformation, the actual stress is larger than provided by Eq. (9.4). In addition to the ratio A_o/A_f, other variables that influence draw stress are die angle and coefficient of friction at the work–die interface. A number of methods have been proposed for predicting draw stress based on values of these parameters. We present the equation suggested by Schey:

$$\sigma_d = \overline{Y}_f\left(1 + \frac{\mu}{\tan\alpha}\right)\phi \ln\frac{A_o}{A_f} \quad (9.5)$$

wheres σ_d = draw stress, MPa (lb/in^2); μ = die-work coefficient of friction; α = die angle (half-angle) as defined in Figure 9.1; and ϕ is a factor that accounts for inhomogeneous deformation which is determined as follows for a round cross section:

$$\phi = 0.88 \pm 0.12\frac{D}{L_c} \quad (9.6)$$

where D = average diameter of work during drawing, mm (in); and L_c = contact length of the work with the draw die in Figure 9.1, mm (in). Values of D and L_c can be determined from the following:

$$D = \frac{D_o + D_f}{2} \quad (9.7a)$$

$$L_c = \frac{D_o - D_f}{2\sin\alpha} \quad (9.7b)$$

The corresponding draw force is then the area of the drawn cross section multiplied by the draw stress:

$$F = A_f \sigma_d = A_f \overline{Y}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \phi \ln\frac{A_o}{A_f} \tag{9.8}$$

where F = draw force, N (lb); and the other terms are defined above. The power required in a drawing operation is the draw force multiplied by exit velocity of the work.

Example: Wire is drawn through a draw die with entrance angle = 15°. Starting diameter is 2.5 mm and final diameter = 2.0 mm. The coefficient of friction at the work–die interface = 0. 07. The metal has a strength coefficient K = 205 MPa and a strain-hardening exponent n = 0.20. Determine the draw stress and draw force in this operation.

Solution: The values of D and L_c for Eq. (9.6) can be determined using Eqs. (9.7). D=2.25 mm and L_c = 0.966 mm. Thus,

$$\phi = 0.88 + 0.12\frac{2.25}{0.966} = 1.16$$

The areas before and after drawing are computed as A_o = 4.91 mm^2 and A_f = 3.14 mm^2

.The resulting true straine $\epsilon = \ln\left(\frac{4.91}{3.14}\right) = 0.446$, and the average flow stress in the operation is computed:

$$\overline{Y}_f = \frac{205(0.446)^{0.20}}{1.20} = 145.4 \text{ MPa}$$

Draw stress is given by Eq. (9.5):

$$\sigma_d = (145.4)\left(1 + \frac{0.07}{\tan 15}\right)(1.16)(0.446) = 94.1 \text{ MPa}$$

Finally, the draw force is this stress multiplied by the cross-sectional area of the exiting wire:

$$F = 94.1(3.14) = 295.5 \text{ N}$$

Maximum Reduction Per Pass A question that may occur to the reader is: Why is more than one step required to achieve the desired reduction in wire drawing? Why not take the entire reduction in a single pass through one die, as in extrusion? The answer can be explained as follows. From the preceding equations, it is clear that as the reduction increases, draw stress increases. If the reduction is large enough, draw stress will exceed the yield strength of the exiting metal. When that happens, the drawn wire will simply elongate instead of new material being squeezed through the die opening. For wire drawing to be successful, maximum draw stress must be less than the yield strength of the exiting metal. It is a straightforward matter to deter mine this maximum draw stress and the resulting maximum possible reduction that can be made in one pass, under certain assumptions. Let us assume a perfectly plastic metal (n = 0), no friction, and no redundant work. In this ideal case, the maximum possible draw stress is equal to the yield strength of the work material. Expressing this using the equation for draw stress under conditions of ideal deformation, Eq. (9.4), and setting $\overline{Y}_f = Y$ (because n = 0),

$$\sigma_d = \overline{Y}_f \ln \frac{A_o}{A_f} = Y \ln \frac{A_o}{A_f} = Y \ln \frac{1}{1-r} = Y$$

This means that ln(A_o/A_f) = ln (1/(1-r)=1. That is, $\epsilon_{max} = 1.0$. In order for ϵ_{max} to be zero, then A_o/A_f = ln (1/(1-r)=must equal the natural logarithm base e. Accordingly, the maximum possible area ratio is

$$\frac{A_o}{A_f} = e = 2.7183 \tag{9.9}$$

and the maximum possible reduction is

$$r_{\max} = \frac{e-1}{e} = 0.632 \tag{9.10}$$

The value given by Eq. (9.10) is often used as the theoretical maximum reduction possible in a single draw, even though it ignores (1) the effects of friction and redundant work, which would reduce the maximum possible value, and (2) strain hardening, which would increase the maximum possible reduction because the exiting wire would be stronger than the starting metal. In practice, draw reductions per pass are quite below the theoretical limit. Reductions of 0.50 for s ingle- draft bar drawing and 0.30 for multiple- draft wire drawing seem to be the upper limits in industrial operations.