Friction and Lubrication in Bulk Metal-Forming Processes

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The type of lubrication regime which occurs in a metal forming operation has a strong influence on the frictional conditions as well as on other important factors such as product surface finish and tooling wear rate. The characteristics of the different types of regimes which can occur are reviewed, together with what is known about their incidence in drawing, extrusion, rolling, and upsetting operations. In the light of this information it is evident that the commonly used methods of characterizing friction can often lead to erroneous results. Suggestions for improved methods of characterizing friction are made.

Lubrication is vitally important in many bulk metal forming processes. In most cases reduction of friction has a beneficial effect by lowering the forces required for a given operation. This reduces the stresses imposed on tooling and may allow the use of smaller and less costly equipment. Alternatively, larger changes in shape can be achieved for a given force level. This may reduce the number of stages required to make the final part. In some cases, such as rolling and forging, carefully controlled friction levels are required to optimize metal flow. In these cases too little friction can be as bad as too much and careful design of lubrication systems to achieve suitable friction levels is required.

Effective lubrication can improve product quality by eliminating surface defects such as scoring or cracking through the reduction of metal-to-metal contact and avoiding harmful residual stresses and internal defects through promoting more homogeneous deformation conditions. Tooling life can be extended by the presence of a lubricant film which will prevent wear and may act as a thermal insulating shield between the tooling and a hot workpiece.

Despite the importance of lubrication, workers involved in the design and analysis of metal forming processes are usually relatively uninformed about the subject. It is not uncommon to find that little or no attention has been given to lubrication in the design of a process, or that sophisticated plasticity theory is combined with naive assumptions about frictional conditions. The object of the present review is to present a concise description of the mechanics of the processes involved in lubricating bulk metal forming processes. It is hoped that it will be useful to those involved in the design and analysis of these processes.

The reader should understand that there is some controversy regarding the relative importance of different effects in metal working lubrication. The present paper is based on the research work of the author and represents a particular personal viewpoint of the topic.

1. REGIMES OF LUBRICATION

The most important feature of lubrication in metal forming is that a variety of different types of lubrication

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ISSN 0162-9700/79/0701-0007$00.75/0

regimes can be associated with a given process. In each regime different physical and chemical factors control lubrication. Different regimes can occur as a result of slight changes in lubricant and workpiece properties, speed, temperature, geometry, or surface roughnesses. Furthermore, several regimes can co-exist at different locations in the workpiece-tooling interface or succeed each other at a given location as the process proceeds.

The four main regimes involved are described below and illustrated in Fig. 1. The main factor which distinguishes the regimes is the lubricant film thickness relative to the surface roughness.

1.1 Thick Film Lubrication

In the thick film regime the surfaces are separated by a continuous film of lubricant which is much thicker than either the roughness of the surfaces involved or the molecular size of the lubricant. For normal engineering systems, this occurs when the mean lubricant film thickness is greater than about ten times the RMS roughnesses of the surfaces involved. Thus, the lubricant can be modeled as a continuum between smooth surfaces.

In the thick film regime, friction is decided by the physical properties of the lubricant under the conditions at the interface. As will be discussed later, the idea of a coefficient of friction is of little validity in this regime but, as a rough guide, measured values of the coefficient of friction are usually less than 0.1 and often less than 0.05.

Since the surfaces are completely separated by the lubricant film, wear in the thick film regime is unlikely. However, wear can occur due to corrosion or erosion by cavitation or foreign particles in the lubricant.

In the thick film regime the tooling surface has little constraining influence on the deformation of the workpiece surface as these are separated by the highly compliant lubricant film. Thus, the workpiece surface roughness will increase to the level which would occur at a free surface under the same strain conditions. This roughening of the surface is often used as an indication that the system is operating in the thick film regime. It may result in a product with a surface which is unacceptable for certain applications.

1.2 Thin Film Regime

When the mean lubricant film thickness is between approximately three and ten times the RMS surface roughnesses of the surfaces, the system is in the thin film regime. In this regime the surface roughness can have an important influence on the lubrication process. However, in the thin film regime the film thickness is almost everywhere larger than the lubriant molecular size. In other words "contacts" between individual roughness elements (asperities) carry a negligible fraction of the total load between the surfaces.

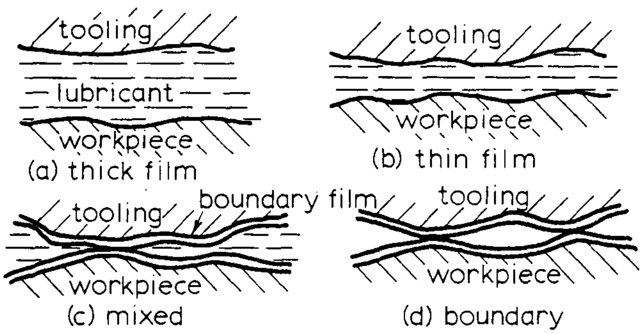

Fig. 1—Regimes of lubrication.

Frictional behavior in the thin film regime is similar to that in the thick film regime except that the surface roughness can affect the friction level. Wear is usually slight.

Workpiece surface roughening can occur in the thin film regime but it is also possible for the workpiece roughness to remain essentially constant or even to decrease during the deformation process. Changes in surface roughness are especially significant in the thin film regime because of the influence of roughness on the lubrication process.

1.3 Mixed Lubrication Regime

If the mean film thickness is reduced much below about three times the RMS roughness of the surfaces a significant fraction of the load between the surfaces will be carried by contacts between asperities. If part of the load is still carried by the pressure in the lubricant film around the asperity contacts, the system is in the mixed lubrication regime.

If the lubricant is properly formulated it will contain compounds which react chemically with the surfaces, forming tightly adhering "boundary" lubricant films. Even though these films typically have thicknesses of the order of the lubricant molecular size, they can prevent direct metal-to-metal contact, welding and galling at asperity collisions.

A good model for the mixed lubrication regime must combine considerations of the completely different types of processes active at the asperity valleys and peaks. In the valleys the films are relatively thick and a modified version of thin film lubrication theory can be used. However, at the peaks, chemical and surface physics effects become important and an approach based on continuum mechanics alone will have serious limitations. For this reason the mixed lubrication regime is very difficult to model adequately.

In the mixed regime friction coefficients can range from the levels of less than 0.05 associated with thick film lubrication to values of 0.4 or greater associated with poor boundary lubrication. Both the physical and chemical properties of the lubricant are important in deciding the friction level. Small changes in process conditions can result in large changes in friction levels.

Workpiece surface roughness tends to be decreased when working in the mixed lubrication regime. However, if the thin boundary films are disrupted, workpiece asperities may weld to the tooling and be torn from the workpiece surface. These can then cause appreciable scoring of the workpiece with a consequent increase in surface roughness.

Asperity interactions can also result in removal of material from the tooling. Thus, significant wear is possible in the mixed regime. The level of wear is dependent on the fraction of the load carried by asperity contacts, the relative strengths of the surfaces, and the effectiveness of the boundary films.

1.4 Boundary Lubrication Regime

If all the load between the surfaces is carried by the asperity contacts the system is in a purely boundary lubrication regime. In the boundary regime the mechanics of local deformation of the asperities as well as the surface physics and chemistry of the boundary films are the important factors. Comprehensive quantitative models for the boundary lubrication regime are yet to be developed.

In the boundary regime the idea of a constant coefficient of friction is more useful than in the regimes previously discussed. Under ideal conditions coefficients of friction of about 0.1 can be obtained with boundary lubrication. However, under the severe conditions found in metal forming processes, coefficients of friction are usually larger than 0.1 and values of 0.4 or higher can result if conditions are sufficiently severe to disrupt the boundary films.

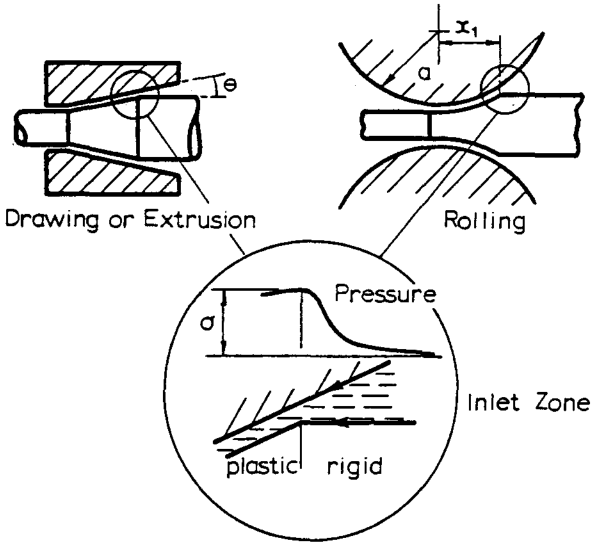

Fig. 2—Inlet zones.

As in the mixed regime, relatively high wear levels occur in the boundary regime. If effective boundary films are present, decreases in workpiece surface roughness are likely, but if the films break down, extensive surface roughening usually occurs.

1.5 Comparison of the Regimes

It is obvious that the thick and thin film lubrication regimes (often collectively called the full film regime) are very desirable from the point of view of reducing friction and wear. A wide variety of metal forming processes are regularly operated in these regimes. However, the necessity of maintaining small surface roughness means that many processes must operate in the mixed or boundary lubrication regimes. Even when surface roughening is not a problem, it may be difficult or uneconomic to achieve full film lubrication at all locations in the workpiece tooling interface at all stages in the forming process. If full film lubrication conditions are not feasible then the mixed lubrication regime will result in lower friction and wear than the purely boundary regime. The lubricant in the roughness valleys not only directly supports part of the load between the surfaces but also provides a fresh supply of active material to replace boundary films as they are worn away.

Any of the lubrication regimes can occur in a given process. It is important to be able to predict what regimes will occur under different conditions. Since the deciding factor is the thickness of the lubricant film present in the contact, the study of the mechanics by which lubricant films are entrained or entrapped at the workpiece-tooling interface provides the key to the problem of what lubrication regimes are present in a given situation.

2. ENTRAINMENT OR ENTRAPMENT OF LUBRICANT FILMS

Lubricant films are entrained by "wedge" action in steady processes such as rolling, drawing, and extrusion, and are entrapped by "squeeze" action in unsteady processes such as upsetting. Furthermore, both liquid and solid lubricant films are of interest in each case. The various possibilities are discussed in detail below. Most of the published work deals with the thick film regime since this is much better understood than the other regimes.

2.1 Entrainment of Liquid Films in Steady Processes

In liquid lubricated, steady processes such as rolling and drawing the film thickness is decided in the inlet zone shown in Fig. 2. As the workpiece and tooling surfaces converge, the pressure in the lubricant film builds up until it is sufficiently high to cause yield of the workpiece.

In the thick film regime, if the surfaces are rigid in the inlet zone and the lubricant has a constant viscosity μ then it can be shown[1] that the entrained film thickness h_0 is given by

$$h_0 = \frac{6\mu\bar{U}}{\sigma \tan\theta} \qquad [1]$$

where $\bar{U}$ is the mean surface speed in the inlet, σ is the workpiece yield strength, and θ is the angle between the converging surfaces. In drawing and extrusion θ is the die semi-angle, while in rolling it is the nip angle given by

$$\sin\theta = x_1 / a \qquad [2]$$

where x_1 is the length of the arc of contact and a is the roll radius. Thus, the film thickness tends to be increased by the use of high viscosity lubricants, high speeds, and with low strength workpiece materials. Small die angles (in drawing or extrusion) or large rolls and small reductions (in rolling) tend to promote the formation of thick films.

Snidle, Parsons, and Dowson[2] showed that the rigid surface assumption used above is usually valid since elastic deflections have a small effect. However, the work of Eichinger and Lueg[3] suggests that plastic rounding of the workpiece surface as it passes into the work zone may result in much thicker films being entrained. Tsao and Sargent[4] note that it is important to correct for the bulk elastic deflection of the rolls in calculating the nip angle in rolling.

In most bulk metal forming processes the pressures are sufficiently high to increase significantly the lubricant's viscosity. It is customary to assume that the lubricant viscosity μ at pressure p is given by

$$\mu = \mu_0 e^{\gamma p} \qquad [3]$$

where μ_0 is the viscosity at zero pressure and γ is the pressure coefficient of viscosity.

If the pressure-viscosity effect is taken into account[3,5,6] Eq. [1] becomes

$$h_0 = \frac{6\mu_0\gamma\bar{U}}{\tan\theta\,(1 - e^{-\gamma\sigma})} \qquad [4]$$

The film thicknesses given by Eq. [4] are much larger than those given by Eq. [1]. Furthermore, since the term $e^{-\gamma\sigma}$ is usually small, the pressure-viscosity effect makes the film thickness almost insensitive to workpiece strength.

In processes such as hydrostatic extrusion where the lubricant upstream of the inlet zone is under pressure q, Eq. [4] must be modified

$$h_0 = \frac{6\mu_0\gamma e^{\gamma q}}{\tan\theta\,(1 - e^{-\gamma\sigma})} \qquad [5]$$

The term $e^{\gamma q}$ allows for the pressure induced viscosity increase in the container and explains the excellent lubrication which is often found in hydrostatic extrusion. A similar effect exists in conventional extrusion but, in this case, the force on the billet end tends to reduce the effectiveness of the lubrication system.[7]

The viscosity of most lubricants not only increases with pressure but also decreases with temperature. With high viscosity lubricants, or at high speeds the viscous shearing in the lubricant film increases its temperature, reduces its viscosity and decreases the amount of lubricant entrained. This effect can be allowed for by multiplying the film thickness given by isothermal theory by thermal correction factor C_t. For example, in a drawing operation the film thickness given by Eq. [4] must be multiplied by a correction factor

$$C_t = (1 + 0.56\, G^{0.38} L^{0.8})^{-1} \qquad [6]$$

where

$$G = \gamma\sigma \qquad [7]$$

$$L = \mu_0 \alpha \bar{U}^2 / k \qquad [8]$$

and k is the lubricant's thermal conductivity. In this the lubricant viscosity μ at temperature T and pressure p is assumed to be given by

$$\mu = \mu_0 e^{-\alpha (T - T_0) + \gamma p} \qquad [9]$$

where T_0 is the workpiece and tooling inlet temperature and α and γ are the temperature and pressure coefficients of viscosity respectively.

Thermal correction factors have also been derived for

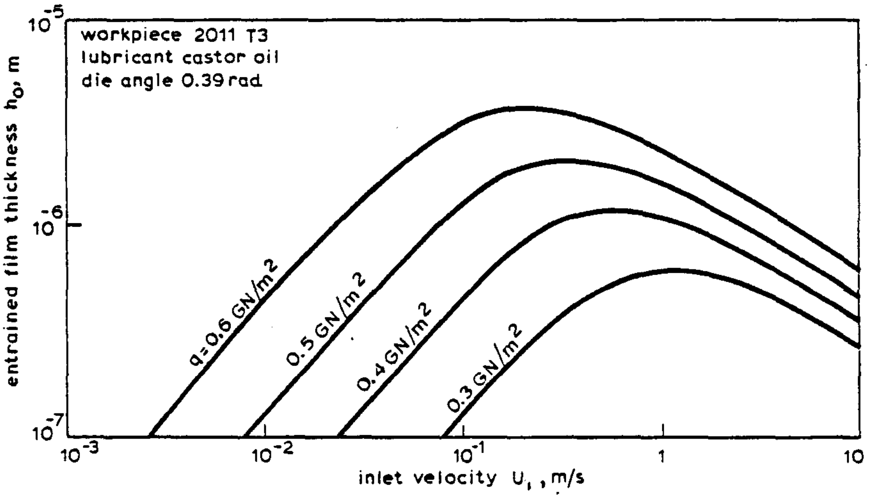

Fig. 3—Film thickness entrained in a hydrostatic extrusion operation.[9]

rolling[8] and for hydrostatic extrusion.[9] In the latter case the correction factor given by Eq. [6] can be applied to Eq. [5] but the parameter L must be redefined

$$L = \mu_0 e^{\gamma q} \alpha \bar{U}^2 / k \qquad [10]$$

where the extra term $e^{\gamma q}$ accounts for the increase in viscosity due to the extrusion pressure.

Figure 3 shows the theoretically predicted variation of entrained film thickness h_0 with extrusion pressure q and workpiece inlet speed U_1 for a particular hydrostatic extrusion system. At low speeds the film thickness increases linearly with increasing speed according to isothermal theory Eq. [5]. At higher speeds thermal effects become important and after going through a maximum, the film thickness decreases with further increase in speed. This means that not only low speeds but also very high speeds are ineffective in generating thick film conditions. The effect of increasing the extrusion pressure is to raise the film thickness curve and to move its peak towards lower speeds. This is a result of the pressure induced viscosity increase enhancing lubricant entrainment but also increasing the thermal effect.

Experimental measurements[9] of film thickness in the system shown in Fig. 3 have established the validity of the theory over the speed range of from about 10 mm/s to about 35 m/s where the system is in the thick film regime. At speeds above or below this window surface damage characteristic of mixed lubrication conditions was observed.

Despite the low sensitivity of film thickness to workpiece strength predicted by the theories described above, there is some indication that it is practically very difficult to generate thick films when drawing high strength materials. This may be due to the inability of the lubricant film to withstand the very high shear stresses involved with such conditions.[10]

All the analyses described above is for the thick-film regime. A recent paper by Tsao and Sargent[11] makes the first attempt at modeling the influence of surface roughness on the entrainment process in rolling. Their results can be expressed in terms of a roughness correction factor C_r which is applied to the film thickness calculated from thick film theory. Figure 4 shows the variation of the factor C_r with the angle β between the roughness lay direction and the rolling direction and the ratio R given by

$$R = r/h_0 \qquad [11]$$

where r is the RMS roughness of the surfaces and h_0 is the film thickness calculated from isothermal theory. The correction factor increases with the angle β so that a roughness lay across the rolling direction results in an increase in film thickness while a roughness lay parallel

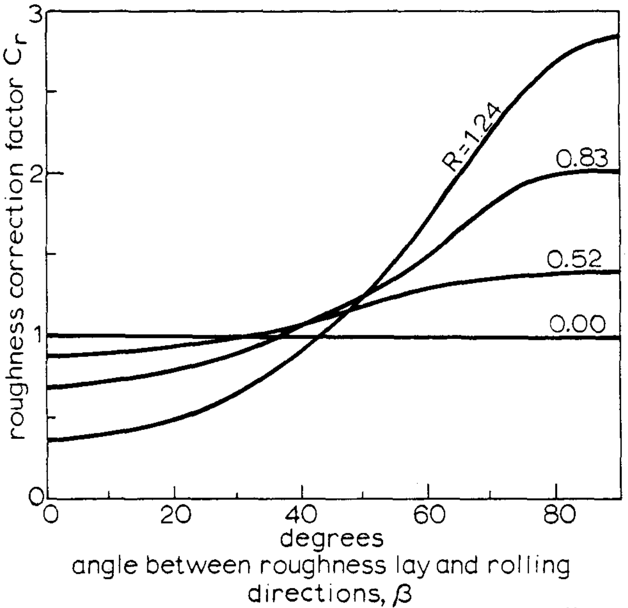

Fig. 4—Effect of roughness on entrained film thickness.[11]

to the rolling direction decreases the film thickness. The roughness effect increases with the roughness ratio R.

The method used by Tsao and Sargent has some deficiencies. It does not apply in the mixed regime nor does it take account of which surface is rough or which surface is moving faster. More sophisticated methods show these to be important factors.

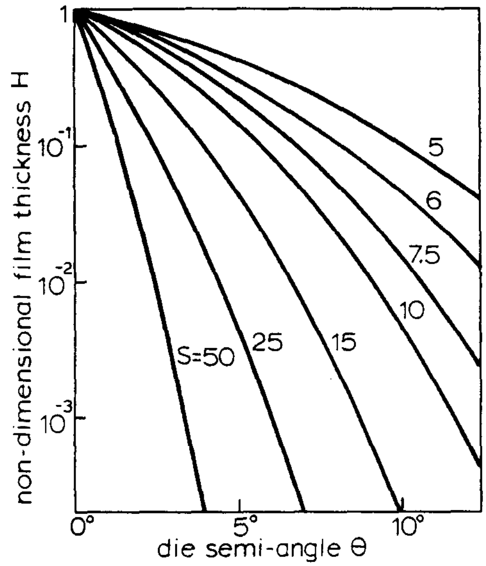

Fig. 5—Solid lubricant film thickness entrained under optimum conditions.[12]

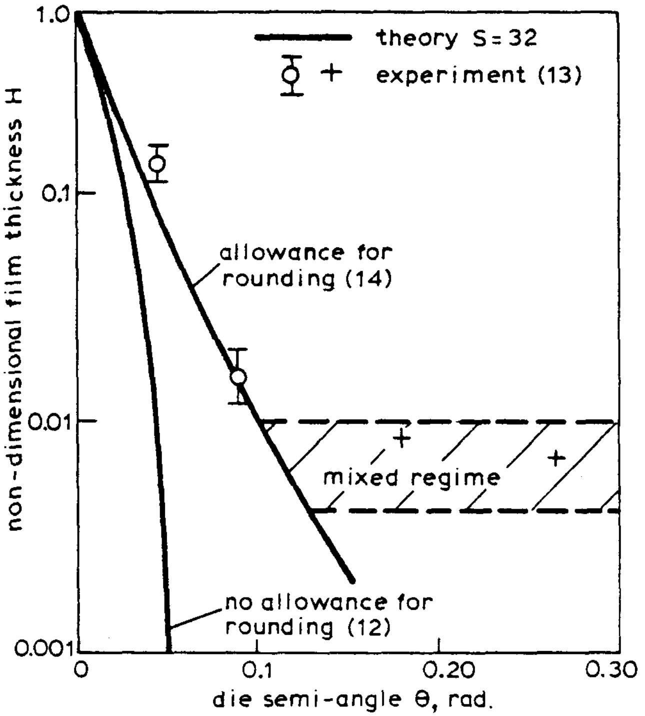

Fig. 6—Comparison of film thickness entrained in wax-lubricated strip drawing with theory.

2.2 Entrainment of Solid Films in Steady Processes

Solids such as soaps, waxes, polymers, soft metals, and other inorganic materials are widely used as lubricants in heavily loaded low speed processes. The entrainment of such materials has been modeled by treating them as viscous liquids with viscosities which vary with speed or temperature. However, this approach fails to represent the essentially plastic behavior of these materials at low speeds.

The upper-bound method of plasticity has been used to model the entrainment of a rigid-plastic lubricant coating in a drawing process.[12] It was found that the entrained film thickness was independent of speed and proportional to the applied coating thickness. The entrained film thickness decreased sharply with increasing die angle and with an increase in the ratio S of the workpiece to lubricant strength. Increasing the adhesion between the coating and the workpiece and decreasing the friction between the coating and the die increases the entrained film thickness.

The results for the ideal case with perfect adhesion to the workpiece and zero friction with the die are shown in Fig. 5 and can be expressed by the semi-empirical equation

$$H = \exp A\theta^{B} \qquad [12]$$

where

$$A = -66.1 \exp(0.01944S) \qquad [13]$$

$$B = 1.05 + (4.32/S) \qquad [14]$$

for the ratio H of the entrained film thickness to the applied coating thickness. This relationship has been corrected for an error which resulted in the erroneous doubling of the values of S in the original paper.

While the theory showed similar trends to experimental measurements[13] of the thickness of wax and soap films entrained in aluminum strip drawing it underestimated the measured thickness. This has been shown[14] to be due to the plastic rounding effect described by Eichinger and Lueg.[3] Figure 6 compares theory with and without an allowance for rounding with experimental measurements with wax coatings. It is evident that the theory with rounding is in good agreement with the experiments at the smaller die angles. At larger die angles the system enters the mixed regime and the entrained film thickness is approximately equal to the surface roughness of the workpiece. Similar results have been obtained in hydrostatic extrusion.[15]

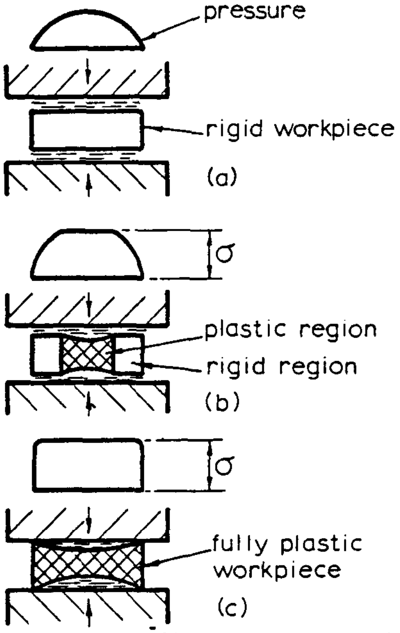

Fig. 7—Entrapment of lubricant film in upsetting.

Solid lubricants do not display the fall off in film thickness at low speeds shown by liquid lubricants. This explains their use under low speed conditions. However, under high speed conditions there is evidence that thermal softening may reduce the film thickness with solid lubricants in the same way that thermally induced viscosity changes reduce the effectiveness of liquid lubricants. This effect has yet to be accounted for in the analysis of solid film entrainment.

2.3 Entrapment of Liquid Films in Unsteady Processes

The only unsteady process in which lubricant entrapment has been extensively studied is liquid lubricated upsetting with flat dies. The entrapment process is shown in Fig. 7. As the dies approach the workpiece, the pressure required to squeeze the lubricant out increases. Eventually the pressure is high enough to cause yield at the center of the workpiece. Once the workpiece yields, the pressure gradients are reduced in the film adjacent to the plastic zone and the lubricant is essentially trapped. The plastic zone spreads until it reaches the edge of the workpiece where the film thickness is reduced to zero.

The film thickness h_0 at the center of contact is given by[16,17]

$$h_0 = \left(\frac{3\mu_0 V x_1^2}{\sigma}\right)^{\frac{1}{3}} \qquad [15]$$

for the isoviscous case and by

$$h_0 = \left(\frac{3\mu_0 \gamma V x_1^2}{1 - e^{-\gamma\sigma}}\right)^{\frac{1}{3}} \qquad [16]$$

for the pressure dependent viscosity case, where V is the rate of approach of the dies and x_1 is the radius of the cylindrical workpiece in the axisymmetric case or the half width of the prismatic workpiece in plane-strain. As in steady processes the film thickness increases with speed or viscosity. However, the film thickness here only increases as the cube root of these variables rather than linearly as in the steady processes. The film thickness also increases as the two-thirds power of the workpiece size and the sensitivity to workpiece strength is small if pressure viscosity effects are important.

A thermal correction must also be applied to Eqs. [15] and [16] to allow for thermally induced viscosity changes. The correction factor C_t is given by[18]

$$C_t = (1 + 0.16\, L^{*0.56})^{-1} \qquad [17]$$

where

$$L^* = \frac{\mu_0 \alpha V^2}{k} \left(\frac{x_1 \sigma}{3\mu_0 V}\right)^{\frac{2}{3}} \qquad [18]$$

This correction process has been verified[19] by experimental measurements of central film thickness in the upsetting of aluminum alloy workpieces lubricated with castor oil and a variety of silicone oils.

As in steady processes the film thickness is upsetting at first increases with speed then passes through a maximum and decreases. For a particular workpiece and material combination, the maximum film thickness occurs at an approach speed V in upsetting which is much lower than the corresponding workpiece speed U_1 in rolling or drawing. This is due to the aggravation of the thermal effect due to the "squish" action in upsetting. This is reflected in the theory by the difference between the parameters L and L^*.

To date there seems to be no published work which attempts to apply thin film theory to an unsteady process like upsetting.

2.4 Entrapment of Solid Lubricants in Unsteady Processes

The lower bound method of plasticity has been used[20] to show that the film thickness h_0 of a rigid-plastic lubricant trapped at the center contact in a plane-strain upsetting operation is given by the smaller of

$$h_0 = h_a \qquad [19]$$

or

$$h_0 = \frac{2kx_1}{\phi\sigma} \qquad [20]$$

where h_a is the applied coating thickness, k is the lubricant shear strength, x_1 is the workpiece half width and ϕ is a redundant work factor.

Figure 8 compares some experimental measurements of the thickness of lead films entrapped during forging aluminum alloy workpieces with the theoretical results. At low values of h_a all the film is entrapped and Eq. [19] applies. At large values of h_a the entrapped film thickness h_0 is given approximately by Eq. [20]. However, in the intermediate range, the theory tends to underestimate the entrapped film thickness. The reasons for this are not currently understood.

3. TRANSPORT OF LUBRICANT FILMS IN WORK ZONES

After the lubricant film has been entrained into or entrapped at the workpiece-tooling interface, it is smeared around by the motion of the workpiece and tooling and thins down as the workpiece surface stretches during plastic deformation. The initial entrainment or entrapment of an adequate lubricant film is no guarantee that lubrication will be effective at some other location or stage in the process. Thus, understanding and modeling the lubricant transport processes in work zones (zones of the workpiece-tooling interface adjacent to regimes of plastic deformation) is of great practical importance.

In work zones the analysis of lubricant flow is facilitated by the fact that the pressures in the lubricant film are largely controlled by the plasticity of the deforming workpiece. This usually means that the pressure gradients in the lubricant film are relatively small and have a negligible influence on the lubricant flow.

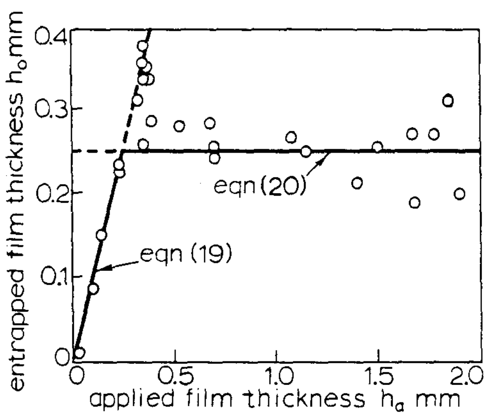

Fig. 8—Comparison of entrapped film thickness in lead lubricated upsetting theory.[20]

3.1 Transport of Liquid Films in Steady Processes

In a steady thick-film isothermal regime, if the pressure gradient does not affect the flow, the lubricant film will be carried at the mean speed $\bar{U}$ of the surfaces. If the lubricant is incompressible, continuity demands that in a plane strain process

$$h\bar{U} = C_1 \qquad [21]$$

and that in an axisymmetric process

$$rh\bar{U} = C_2 \qquad [22]$$

where h is the local film thickness, r the local radius from the axis of symmetry and C_1 and C_2 are constants which can be evaluated from the conditions at the edge of the inlet zone. Equations [21] and [22] imply that the film thickness will decrease as the local workpiece velocity increases in passing through the workzone in rolling, drawing, and extrusion, and this relationship has been used in almost all the analyses of the processes.

If the heat of plastic deformation raises the temperature of the workpiece surface above that of the adjacent workpiece surface, then the lubricant film thickness would tend to increase towards the outlet. In some cases, particularly in drawing and extrusion, this can lead to thicker films at the inlet to the work zone than at the outlet. These effects have been incorporated in analyses of hydrostatic extrusion[9] and rolling.[8,21]

3.2 Transport of Solid Films in Steady Processes

There has been little quantitative work in this area. However, observations of interrupted extrusion operations indicate a thinning of solid lubricant films as the workpiece passes through the work zone. This suggests that solid films may obey Eqs. [21] and [22] or some close relative.

3.3 Transport of Liquid Films in Unsteady Processes

For an unsteady, plane-strain, isoviscous process, the equation governing the lubricant flow (the Reynolds' equation) can be written

$$\frac{\partial}{\partial x}\left(\frac{h^3}{12\mu}\frac{\partial p}{\partial x}\right) = \frac{\partial}{\partial x}(\bar{U}h) + \frac{\partial h}{\partial t} \qquad [23]$$

where x is the distance along the lubricant film, h the local film thickness, μ the lubricant viscosity, p the local pressure, $\bar{U}$ the mean surface speed along the film and t

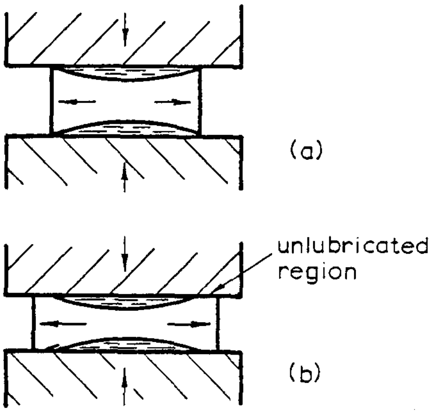

Fig. 9—Breakdown of lubricant film in upsetting.

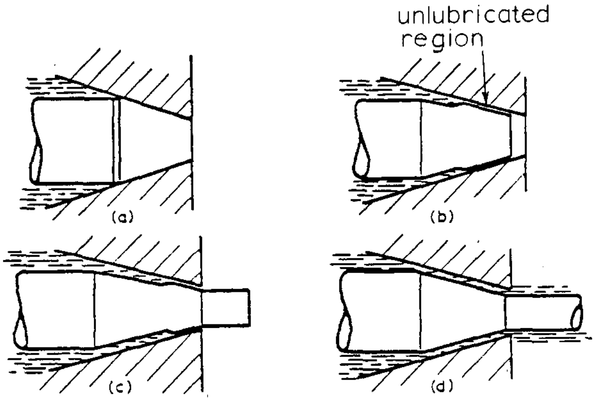

Fig. 10—Breakdown of lubricant film in extrusion.

the time variable. In work zones the term on the left hand side of Eq. [23] is negligible. The remaining part may be decomposed by Lagrange's method to yield two simultaneous ordinary differential equations

$$\frac{dx}{dt} = \bar{U} \qquad [24]$$

and

$$\frac{dh}{dt} = -h\frac{\partial \bar{U}}{\partial x} \qquad [25]$$

Physically, Eq. [24] means that, as in steady processes, the lubricant film tends to be carried around at the mean speed of the surfaces. Equation [25] allows for the thinning of the film as the surface stretches.

In an upsetting operation, since the dies have no component of velocity along the film, after the film is entrapped it tends to be carried outward at half the outward speed of the workpiece.[17] Thus, the film cannot keep up with the outward motion of the workpiece, and if the dies overhang the workpiece, a region in which thick film lubrication is impossible is formed. This process is illustrated in Fig. 9. In practice, thermal effects are important in the transport process.[22] As the workpiece heats up due to plastic deformation the lubricant film tends to become uncoupled from the workpiece and the rate of outward transport is progressively reduced. This results in the formation of a wider "unlubricated" region. An analytical model which allows for this effect is in excellent agreement with experimental measurements of the width of the "unlubricated" regions on aluminum workpieces forged at low speeds with silicone oil lubricants.

The use of active additives in a mineral oil lubricant does not affect the extent of the "unlubricated" region.[23] However, some additives are very effective in reducing forming loads, presumably by providing improved boundary lubrication in the outer part of the contact where thick film lubrication is impossible.

If the workpiece is rougher than the die (either as a result of workpiece preparation[24] or roughening during deformation[25]) the rate of outward transport of the lubricant film is increased with a consequent reduction of the "unlubricated" width.

A similar type of lubrication breakdown to that in upsetting is present during the start of extrusion[1,26] as shown in Fig. 10. As the billet enters the die it draws a lubricant film in with it. However, the lubricant film cannot keep up with the motion of the billet nose. The resulting breakdown in lubrication is responsible for the peak in extrusion pressure as the billet just fills the die which is often noticed in practice.

3.4 Transport of Solid Films in Unsteady Processes

Although relatively little has been done in modeling the transport of solid lubricants in unsteady processes, it is known that solid films break down in a similar way to liquid films in upsetting.[27] However, since solid films are usually less sensitive to temperature they generally yield narrower "unlubricated" regions. As with liquid lubricants roughening the workpiece tends to increase the rate of transport of solid lubricants and decrease the width of the unlubricated region. However, the relationships between surface topography and transport rate appear to be much more complex in the case of solid lubricants than with liquid lubricants.[28]

4. CHARACTERIZATION OF FRICTION

In most metal forming processes, friction between the workpiece and the tooling has an important effect on the mode of deformation and the required force levels. It is important to have some method of characterizing the frictional stresses at the interface in building an analytical model for a given process. The most commonly used methods will be described together with their main deficiencies and some more sophisticated methods of characterizing friction will be discussed.

4.1 Commonly Used Methods

The most commonly used method of characterizing friction in any contact, lubricated or not, is through the use of a constant coefficient of friction μ. In the present context the friction stress τ_f is assumed to be given by

$$\tau_f = \mu p \qquad [26]$$

where p is the local interface pressure. The coefficient of friction is usually assumed to be a property of the workpiece and the tooling materials, and the lubricant, and to be independent of the process geometry and sliding speed at the interface. Almost all scientists and engineers erroneously accept the validity of this method of characterization without question, probably as a result of their early training in mechanics. The idea of a constant coefficient of friction is so pervasive that the terms "friction" and "coefficient of friction" are often used interchangeably and frictional data are quoted in terms of coefficients of friction whether they obey Eq. [26] or not. In fact, the use of a constant coefficient of friction is only really justified under conditions of boundary lubrication where the pressures are relatively small and these conditions are rarely found in bulk metal forming operations.

An alternative method of characterizing friction in metal forming operations is the use of a friction factor m such that the friction stress τ_f is given by

$$\tau_f = m\tau_w \qquad [27]$$

where τ_w is the shear strength of the workpiece material (usually a mean value allowing for strain hardening).

As with the coefficient of friction, the friction factor is usually assumed to be a property of the workpiece and tooling materials and lubricant and independent of other parameters. This model is based on the idea that the interface can withstand a limited shear stress which is independent of pressure. This is the case if the surfaces are completely separated by a continuous film of an ideal plastic solid lubricant, in which case the friction factor m is the ratio of the shear strength of the lubricant to that of the workpiece.

The friction factor has an important advantage over the coefficient of friction as far as metal forming analyses are concerned. With the former characterization, the friction stress at a point is independent of the local pressure and this greatly facilitates analysis, particularly if the upperbound approach is to be used.

Some other simple characterizations of friction have been used in metal forming analyses. However, their advantages, if any, are usually limited to a narrow range of conditions in a particular process and the coefficient of friction and friction factor methods account for the vast majority of existing analyses.

4.2 Problems with the Commonly Used Methods

It is important to understand what is required of frictional characterizations. At the lowest level of sophistication it is useful to have relatively simple models of forming processes which relate "dependent variables" such as forming force to "independent variables" such as material flow strength, tool geometry, and the general level of friction stress at the tooling-workpiece interface. In such analyses, the simple constant coefficient of friction or constant friction factor are usually adequate. However, even at this level of sophistication these characterizations may fail to be useful. A good example of this is in cold rolling where it is common to roll with "negative forward slip." This is a condition where the strip is moving everywhere at lower speed than the rolls. For this case, analyses using either a constant coefficient of friction or a constant friction factor yield meaningless results.

A more serious criticism of the commonly used methods is that in real processes the "independent variables" are often related in a complex manner. For example, in order to predict the real effect of a change in tooling geometry on forming force, it is necessary to include the effect of geometry on friction. Since the commonly used methods of characterizing friction disregard the effect, they often will result in misleading predictions as to the effect of geometric changes on a forming operation.

As mentioned earlier, the idea of different lubrication regimes is of vital importance in analyses of friction and lubrication. Not surprisingly, the biggest failures of the commonly used methods are associated with their inability to provide appropriate models for the different regimes. Particularly serious problems occur when the system is in transition from one regime to another or when more than one regime is present at the workpiece-tooling interface.

Tooling geometry can have an important influence on the amount of lubricant entrained or entrapped at the workpiece-tooling interface which, in turn, can decide the lubrication regime and the level of friction. This is illustrated by Fig. 11 which shows the influence of changes in die semi-angle θ on the "coefficient of fric-

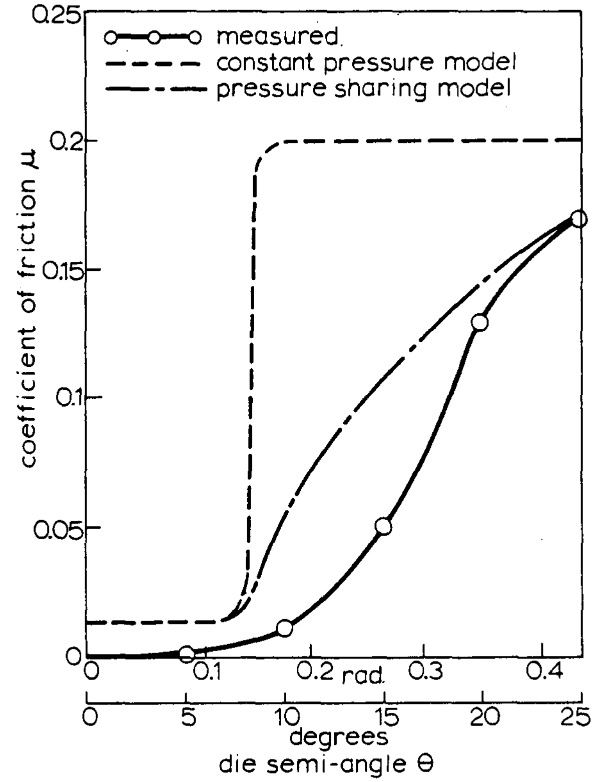

Fig. 11—Friction in wax-lubricated strip drawing.[29]

tion" in the drawing of wax lubricated aluminum strips.[29] The conditions match those for the film thickness measurements shown in Fig. 6. As the die angle is increased, the amount of lubricant entrained is reduced and the system undergoes a transition from the thick-film regime via the thin-film and mixed regimes to an almost completely boundary regime. As this transition proceeds the "coefficient of friction" increases from the very low values characteristic of effective thick-film lubrication to the much larger values typical of boundary lubrication. Since the coefficient of friction increases by a factor of about 30 over the range of die angle studied, the use of a constant coefficient of friction is obviously inadequate for this system. Since the die pressures do not vary much with die angle, a constant friction factor also fails completely to fit the experimental data.

As discussed earlier, not only the process geometry but also the surface roughnesses, speed, and workpiece and lubricant properties can affect the entrained film thickness and, hence, the possibility of a transition from one lubrication regime to another.

The use of a constant coefficient of friction or friction factor may also be inappropriate in processes where different lubrication regimes exist in different parts of the workpiece-tooling interface. The formation of boundary lubricated regimes in otherwise thick-film lubricated extrusion[1] or upsetting[17] will result in this situation.

4.3 Improved Methods

Significant progress has recently been made in predicting frictional conditions in liquid lubricated steady processes operating in the thick film regime. The more refined models[8,9,30–33] indicate that friction levels will be very low under these circumstances. However, these models offer a much more realistic characterization of friction and the influence of process parameters on it than is obtainable via the commonly used methods. A good example of this is in rolling where thick film theory can readily deal with the problem of rolling with negative forward slip and even predict the onset of skidding.[21]

In processes where the thick film regime co-exists with the boundary regime, thick film theory can be used for the appropriate part of the interface, and friction in the other part can be modeled by using a constant coefficient of friction or friction coefficient. In such a combination the extent of the respective regions is decided by thick or thin film lubrication mechanics. This type of approach has been used for extrusion[1] and upsetting.[17] It yields valuable information on changes in friction which occur as a process progresses or as a result of geometrical changes.

It is also possible to use even more generalized methods of characterizing friction. These are usually models for friction in the mixed lubrication regime which can extend to the special cases of thick film lubrication in one direction, and to boundary lubrication in the other. There are two simple possibilities for such a model; a constant pressure model; and a pressure sharing model.

The constant pressure approach adopted by Tsao and Sargent[34,35] for liquid lubricated strip rolling uses thick film theory to calculate the local mean lubricant film thickness in the workpiece-tooling interface. Using information on the roughness height distributions of the surfaces, the fractional area of contact a can then be calculated and the friction estimated from a weighted average of friction in the thick film and boundary regimes.

The pressure sharing approach assumes that once the boundary regime is entered the mean film thickness is equal to the combined roughness of the surfaces. Thick film theory is then used to calculate the pressure which the thick film regime is capable of carrying. From the known required pressure, the fraction b of the interface pressure carried by boundary contact can be calculated and the friction estimated from a weighted average as before.

Figure 11 includes calculated friction curves based on the constant pressure and pressure sharing methods.[36] The uncorrected versions of Eqs. [12], [13], and [14] were used to model the solid lubricant entrainment process. This is roughly equivalent to making an allowance for inlet rounding. The friction coefficient μ was calculated from

$$\mu = a\mu_b + (1 - a)\mu_t \qquad [27]$$

for the constant pressure method and from

$$\mu = b\mu_b + (1 - b)\mu_t \qquad [28]$$

for the pressure sharing method. In both cases the coefficient of friction μ_b in the boundary regime was assumed to be 0.2 and the coefficient of friction μ_t in the thick-film regime was estimated from lubricant shear strength measurements as 0.016.

The constant pressure model predicts a much more rapid transition between regimes than actually occurs. The pressure sharing model yields predictions which are in better agreement with the experiments. However, the transition to the boundary regime as the die angle is increased is still less rapid than the prediction. This is probably due to the beneficial effect of surface roughness on lubricant entrainment in the thin film regime. Both models overpredict friction at small die angles when the system is in the thick film regime. This can be partly explained by the effect of redundant work. The remainder of the error may be due to thermal softening of the wax lubricant.

As more is learned about the thin film and mixed regimes it will be possible to develop even better frictional models for the difficult cases where transitions from the thick film to boundary regime occur in the range of interest. In the case of liquid lubrication the recent work of Patir and Cheng[37] could form the basis for such a model.

CONCLUSION

Four main lubrication regimes can occur at the workpiece-tooling interface in bulk metal forming processes: the thick film regime; the thin film regime; the mixed regime; and the boundary regime. The characteristics of friction and lubrication are different in each regime and it is important to recognize these differences when attempting to develop realistic mathematical models of bulk metal forming processes.

The particular regime or regimes which occur in a given situation are largely decided by the mechanics of lubricant entrainment entrapment but the subsequent transport and stretching of the lubricant film can also be important.

The commonly used methods of characterizing friction such as the use of a constant coefficient of friction or a constant friction factor are inadequate in many cases. In particular they fail to reflect the influence of process geometry, speed, surface roughnesses and workpiece and lubricant properties on the local frictional conditions. Their failure is particularly severe in cases where a transition from one regime to another occurs or where more than one regime coexist in a given process.

More effective frictional models for liquid lubricated systems in the thick film regime are already in use and these can be combined with conventional methods in cases where the thick film regime coexists with the boundary regime. However, the most generalizable frictional characterizations are models for the mixed regime which can be used over the range from thick film to full boundary lubrication conditions. These models can allow for the large variations in friction which occur from one regime to another.

NOMENCLATURE

A = −66.1 exp (0.019445), semi-empirical function
B = 1.05 + (4.32/s), semi-empirical function
C_r , roughness correction factor
C_t , thermal correction factor
C_1, C_2 , arbitrary constants
G = $\gamma\sigma$, non-dimensional pressure coefficient of viscosity
H = h_0/h_a, non-dimensional entrained film thickness
L = $\mu_0\alpha\bar{U}^2/k$, viscous thermal parameter
L^* = $\dfrac{\mu_0\alpha V^2}{k}\left(\dfrac{x_1\sigma}{3\mu_0 V}\right)^{\frac{2}{3}}$, viscous thermal parameter
R = r/h_0, non-dimensional roughness
S , ratio of workpiece strength to lubricant strength
T , temperature
T_0 , surface temperature
$\bar{U}$, mean surface speed
U_1 , inlet workpiece speed
V , die approach speed
a , roll radius, fractional contact area
b , fraction of pressure carried by contact
h , local lubricant film thickness
h_a , applied lubricant coating thickness
h_0 , entrained or entrapped lubricant film thickness
k , lubricant thermal conductivity
m = τ_f/τ_w, friction factor
p , local pressure
q , extrusion pressure
r , RMS surface roughness, radius from axis of symmetry
t , time
x , distance along lubricant film

x_1 , contact length, workpiece radius, workpiece half-width
α , lubricant temperature coefficient of viscosity
β , angle between roughness lay and rolling direction
γ , lubricant pressure coefficient of viscosity
θ , die semi-angle, angle of nip
μ , lubricant viscosity, coefficient of friction
μ_0 , lubricant viscosity at zero pressure and surface temperature
μ_b , coefficient of function in boundary regime
μ_t , coefficient of function in thick film regime
σ , workpiece flow strength
τ_f , friction stress
τ_w , workpiece shear strength
ϕ , redundant work factor

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