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Lubrication and Friction in Hydrostatic Extrusion/Drawing

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The effects of extrusion speed, type of lubricant, and driving-stress ratio (extrusion-fluid pressure/drawing stress) on lubrication and friction have been studied in hydrostatic extrusion/drawing using the visioplasticity method. A computer programme has been developed to obtain from experimental data velocities, strains, strain rates, and stresses in the deformation zone. The results show that friction decreases with increasing extrusion speed and with increasing extrusion-pressure/drawing-stress ratio; also that the most favourable frictional conditions are achieved when the billets are lubricated with molybdenum disulphide grease and castor oil is used as the pressurizing fluid—followed in effectiveness by castor oil or Tellus 27 alone. The influence of extrusion speed and driving-stress ratio on friction was found to be more significant than that of the different lubricants used.

While in most metalworking processes hydrodynamic lubrication develops at high velocities, evidence exists suggesting that in hydrostatic extrusion/drawing this condition can be attained at relatively low extrusion speeds. The basic principle of the process is shown in Fig. 1. The billet is extruded by fluid pressure, assisted by tension applied to the product. One extreme condition is when the fluid pressure is zero (the process then being conventional wire or rod drawing), the other is when the drawing stress is zero (the process then becoming simple hydrostatic extrusion). Alexander and Lengyel[1] described a mechanism that could possibly assist the development of fluid or mixed lubrication in simple hydrostatic extrusion at low speeds when, in wire drawing, boundary lubrication would occur. Thus, a metalworking process now exists in which various lubrication conditions can be initiated and studied at conveniently slow speeds, merely by changing the ratio of extrusion-fluid pressure to drawing stress (driving-stress ratio), an advantage in experimentation that hardly requires special emphasis.

To differentiate between frictional effects and other process variables, plasticity theory is often applied in the study of friction in metalworking. This inevitably involves the use of simplifying assumptions, both to make the problem mathematically tractable and to overcome the lack of knowledge about the nature of the frictional process. Normally, an assumption is made, either that Coulomb friction is operative or that the frictional stress is in constant proportion to the shear yield stress of the material. Hydrodynamic lubrication has also been suggested for high-speed metalworking processes with a ready supply of lubricant.

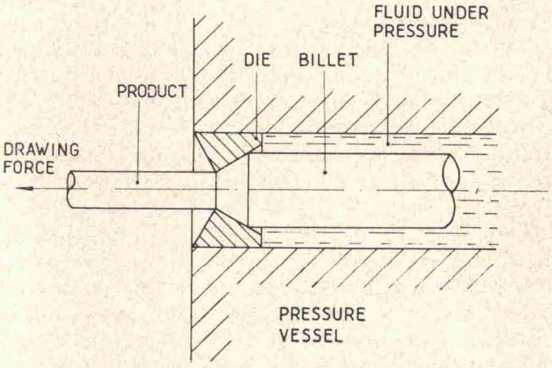

Fig. 1 Hydrostatic extrusion/drawing.

As alternatives, split or strain-gauged dies have been used both in wire drawing and in hydrostatic extrusion—methods that indicate mean values of coefficient of friction but give little or no information on the variation of friction along the die face.

A recent study of the temperature distribution in hydrostatic extrusion revealed the very significant influence of friction on temperature along the die face when the process is fast enough to be considered adiabatic.[2] It has been established that this condition is well within the range of practical speeds in metalworking. Thus, local temperature rise due to friction could well be responsible for transition from one lubrication condition to another such as that shown by the 'bamboo' effect in wire drawing or hydrostatic extrusion. Also, there is evidence to suggest that various lubrication conditions could coexist simultaneously along the die face in hydrostatic extrusion and that these could be responsible for local temperature increases and consequent changes in

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lubricant properties and frictional conditions. From these considerations it follows that methods giving information on mean values of friction along the die face can contribute little to the thorough understanding of lubrication in hydrostatic extrusion.

The semi-empirical method of visioplasticity appears capable of giving the type of detailed information required to assess the temperature and pressure of the lubricant layer and its pressure distribution over the billet/die interface, which would be needed for a detailed study of lubrication conditions in hydrostatic extrusion. This method involves experiments on billets split along their central planes and having lines scribed on these planes parallel with the billet axis. In extrusion these lines become flow lines and their co-ordinates can be used as input data to a computer programmed to obtain velocities, strains, strain rates, and stresses throughout the deformation zone, including the billet/die interface, from which conclusions relating to lubrication conditions can be drawn.

This paper describes the application of the method to the study of friction and lubrication in hydrostatic extrusion.

Experimental Apparatus and Technique

The apparatus was designed to perform experiments at constant speed and constant extrusion pressure. This technique was thought to be more likely to produce constant frictional conditions than the alternative method of setting a constant load and building up a pressure sufficient to cause extrusion.

The high-pressure vessel, described in detail earlier,[3] has recesses at each end of a horizontal bore to accommodate a die and a plug. The plug embodies four insulated terminals so that measurements of pressure and temperature can be taken inside the vessel with a Manganin coil and a Chromel/Alumel thermocouple, respectively. An air–oil accumulator was charged with nitrogen on one side of the piston; the other side was filled with oil and connected to the low-pressure intensifier, which in turn was attached to the high-pressure vessel. A closely controlled stress was applied by means of a screw jack driven by an induction motor via a variator. The speed could be varied between 8·4 and 84 cm/min. The drawing head was designed to exert a maximum of 50 kN (5 tonf) measured by a strain-gauge load cell.

The drawing-head displacement was recorded by a multi-turn potentiometer actuated by a rack-and-pinion device. The electric signals were fed into an ultraviolet galvanometer recorder and all extrusion/drawing parameters were continuously recorded vs. time.

Throughout the experiments the material, die, and billet geometry were the same, i.e. fully annealed high-conductivity copper billets, 1·27 cm in dia., RA ratio 2·56, and die semi-angle 10°.

Great care was taken in the manufacture of the copper billets to ensure that the split was in their central planes. The billets were lathe-turned to a fine finish, annealed, cleaned on their outer surfaces by polishing in the circumferential direction on 600-grade emery paper, and finally washed in carbon tetrachloride. The billets were nosed to an angle 2° less than the die angle. During annealing the two halves were firmly clamped together to ensure minimum distortion. The median surfaces were polished with 6µm diamond paste on a flat polishing table. After this treatment the flat surfaces were highly reflective. The roughening of the split surface in extrusion was less than the depth and thickness of the scribed lines and so did not interrupt their paths.

The lines were scribed and measured on a precision machine, the maximum scatter of readings taken from different directions being 0·004 mm, which represents only one-tenth of the original line thickness. In every case the centre of the lines was taken as the co-ordinate.

Tellus 27 mineral oil and castor oil have been used as high-pressure fluids, the former without additional lubricant, the latter occasionally with Molyslip (a MoS_2 lubricant), which was applied to the outside surface of the billet. A collar was used to hold the two halves of the billet together during extrusion and also to guide the billet into the bore of the high-pressure container. This collar was made to give a sliding fit over the billet and in the container bore. Longitudinal grooves were cut in the collar to equalize pressure behind and in front of it.

Computer Programme

After extrusion, the two halves of the billet were separated; the co-ordinate points of the flow lines were then measured and employed as input data for the computer programme.

The theory on which the visioplasticity method is based has been proposed elsewhere[4–6] and need not be repeated here. It involves numerical calculations carried out at intersecting grid points in the deformation zone. As the numerical differentiations and integrations inherent in the method are extremely time-consuming if carried out by hand, the method was in abeyance until the development of the digital computer.

The difficulties involved in computer application have been discussed by Shabaik *et al.*[7] They stem from the fact that when computations are carried out by hand and a smooth curve is drawn through the velocities so established before strain rates are calculated, the results of the analysis are automatically smoothed. When calculations are carried out on a computer, the errors in reading the flow lines and in the numerical fitting methods can cause the higher-order difference quotients to be both large and erratically varying.

Previous applications of the visioplasticity method have made use of rectangular or square grids for the calculations. The difficulties involved if the die half-angle is $\leqslant$ 45°, which is usually the case in hydrostatic extrusion, have been described elsewhere.[8] Furthermore, in hydrostatic extrusion, deformation can commence before the billet reaches the die and, if the present method is to be successful in predicting surface conditions, this effect cannot be ignored by assuming a sharp change of slope on the surface of the billet in contact with the die.

For these reasons it was decided that a grid having a constant step length in the axial direction but a variable step length in the radial direction should be used. This type of grid is shown in Fig. 2. Polynomial fitting and smoothing methods were employed to determine the values of the flow function at the grid points from the measured co-ordinates along the flow lines and also to find the derivatives of this

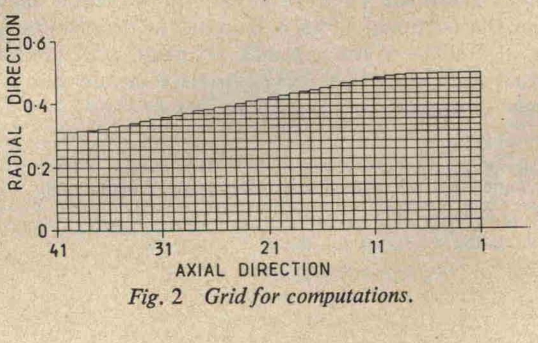

Fig. 2 Grid for computations.

function to obtain velocities, strain rates, strains, and stresses at each grid point. The method is similar to that described earlier[7] though complications are caused by the non-uniform grid.[8]

Results and Discussion

Figs. 3 (*a*) and (*b*) show the flow lines in the midsection of the billet after extrusion under oblique and direct light, respectively. The first observation that can be made is that there was no sharp change of slope at contact between billet and die. The deformation of the billet before the die was reached is not pronounced but nevertheless was present and is more obvious from the velocity and strain fields.

It was also apparent that flow in the deformation did not follow either the radial or parallel flow paths normally assumed in upper-bound solutions. There was an initial region displaying a change of slope as the deformation zone was entered. Next there was a portion in which the line was nearly straight, then the slope of the flow line decreased slightly at a point roughly one-third of the way along the die. The slope then again increased and the line was once more approximately straight up to exit from the deformation region.

Fig 3(*b*) clearly shows the boundary where the polished billet had deformed sufficiently for its surface to become roughened. If it is assumed that this roughening took place at a constant value of strain, the outer fibres of the billet must have become deformed earlier than those near the central line, contrary to the assumption made in the upper-bound solutions of hydrostatic extrusions.[9, 10]

Attempts were made to estimate the deformation region by following the lines from the billet and product until they deviated from parallelism with the axis. It was very difficult to obtain reproducible results, especially near the centre where the change of curvature was least. When these data were used in the computer programme and smoothing was carried out between the deformation boundaries, the results near these boundaries were erratic because of the inaccuracy of the estimated boundary imposing a deformation pattern on the flow that had not occurred in practice. It was found advantageous to smooth the flow function between two radial sections—one in the billet and one in the product.

Throughout the strain-rate fields the influence of these effects can be seen. However, for comparing the frictional conditions operative during extrusion it is more convenient to use the velocity and total strain fields, as it is simpler to observe changes here (Fig. 4).

In all the extrusions the variation of total strain across the section was small, as would be expected in hydrostatic extrusion through a low die angle, the part of the product that is more heavily strain-hardened being confined to the region close to the surface. The difference in total strain between the central line and the surface was 20% max.—much less than the variations for the larger die angles used in conventional extrusion.[7]

The effect of extrusion speed on friction can be most clearly seen by comparing the axial velocity fields in two extrusions carried out under the same conditions but at different speeds, e.g. Nos. 4 and 5 in Table I and Fig. 4(*a*). At the higher speed, deformation occurred before the billet surface reached the die, whereas this effect was absent at low speed. Deformation before the die was reached can be explained by build-up of pressure in the molybdenum disulphide grease as it was dragged into the wedge formed by the billet and the die.

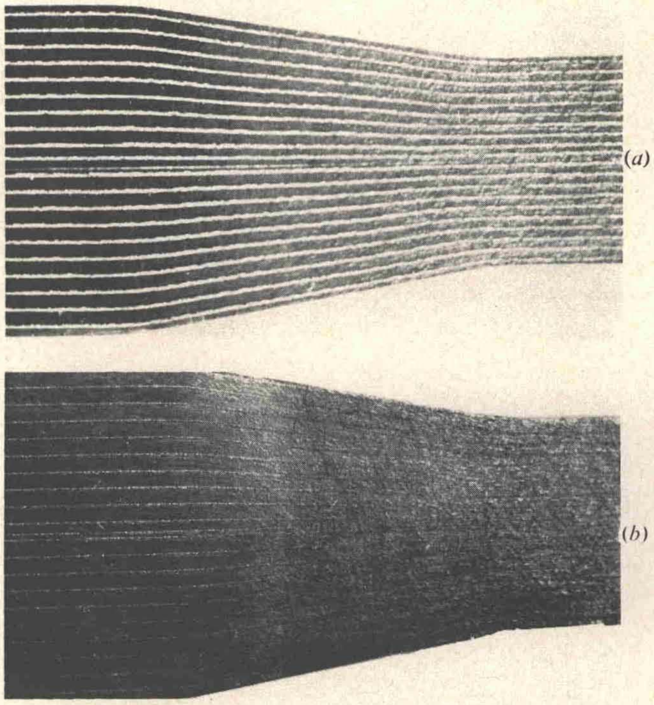

Fig. 3 *Flow lines: (a) Extrusion No. 3, under oblique light. (b) Extrusion No. 5, under direct light.*

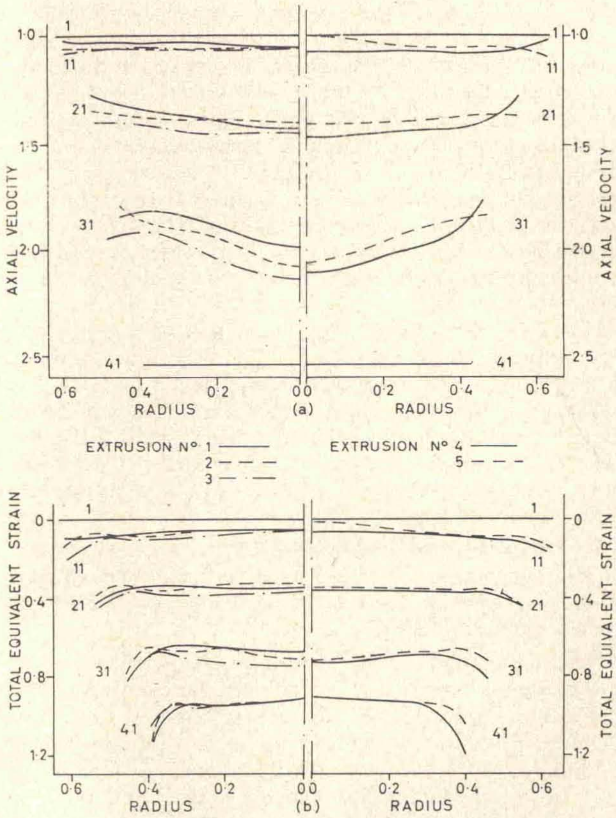

Fig. 4 *Axial velocity and total equivalent strain distribution in the deforming region: (a) Axial velocity; (b) total equivalent strain.*
Extrusion numbers refer to test numbers given in Table I. Numbers adjacent to the curves refer to axial co-ordinates in Fig. 2. Radius in cm.

TABLE I

Extrusion No.	1	2	3	4	5
Fluid pressure, N/mm^2	296·5	351	355·5	258	220
Drawing stress, N/mm^2	86·5	23·2	37·8	139·1	129·4
Temperature above ambient, degC	0°	3·5	1·0	4·0	5·3
Drawing speed, cm/min	9·31	9·27	9·05	8·89	82·5
Pressurizing fluid	Tellus 27	Castor oil	Castor oil	Castor oil	Castor oil
Lubricant	None	None	Molyslip	Molyslip	Molyslip
Ambient temperature, °C	20	19	27	27	21

This phenomenon is known as the 'viscosity-pump' effect.[11] As pressure increase is directly proportional to speed, other factors being unchanged, the speed ratio of 9 for the two extrusions explains why the effect is present only at higher speeds.

It should be noted that Reynolds' equation for this flow situation on the assumption of total contact between billet and die (namely zero lubricant flow), results in an infinite pressure build-up. There must, in fact, be some flow of lubricant or fluid through the die; and also, when the pressure build-up is sufficient the billet will yield, the changed geometry relieving further build-up of pressure.

If this explanation is correct, lower friction is to be expected over the whole die face at higher speeds as more lubricant is forced to the interface. That this is indeed the case can be seen from the axial velocity and total strain fields. The variation of velocity and strain across the section is much smaller for the high-speed extrusion, even near the exit from the die. It is also interesting to note that axial velocities are higher near the billet/die interface than deeper inside the billet in the higher-speed extrusion 5, an effect that is quite pronounced as far as section 21 (Fig. 4(*a*)). The lubricant penetrating between the billet/die interface must be responsible for the much more uniform velocity distribution at higher speeds, as far as section 31, quite close to the die exit.

Direct evidence that the lubricant flow rate is greater at higher speeds can be gained from Fig. 5. This shows the surface profiles in the longitudinal direction for two extrusions and it can be seen that burnishing is much increased at lower speed. The greater lubricant flow at higher speed is therefore effective by forming pockets and preventing contact over a large area. The profiles of the two billets were checked and found to be very similar.

To understand the dependence of friction on extrusion-stress/drawing-stress ratio, we must consider two extrusions in which the other parameters were identical, i.e. Fig. 4, Table I, extrusions 3 and 4.

Here, again, deformation before the die is reached occurs in the extrusion-orientated case. When the drawing stress is high, the extrusion pressure is correspondingly lower, and therefore to cause an initial yield in advance of the die, the build-up of pressure by the hydrodynamic effect would have to be greater by (approximately), the amount of the drawing stress.

The velocities may again be compared to show the variation of friction over the die surface. With extrusion at lower drawing stress the build-up of pressure is sufficient to cause yielding. This reduces friction, as is evidenced by Fig. 4(*a*), where the velocity is shown to be more uniform for the extrusion-orientated case (extrusion 3).

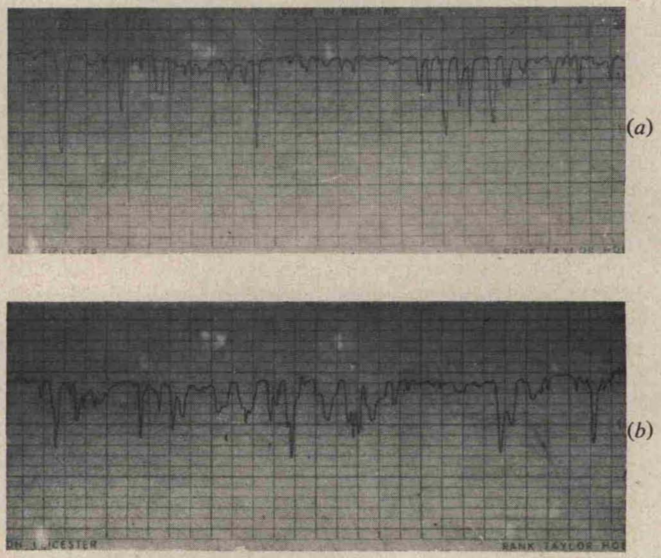

Fig. 5 Surface profile of the extruded product: (a) At 8·89 cm/min drawing speed; (b) at 82·5 cm/min drawing speed.

Considering the total strain distribution, Fig. 4 (*b*), it can be seen that there is less variation of total strain across the product for low drawing stress (extrusion 3). Also, the mean values of total strain and the total strain along the centre line are lower for the extrusion-orientated case, which indicates that the redundant strain is then smaller. The smaller redundant strain must be attributable to reduced friction as other parameters were the same for the two extrusions.

Increase in fluid pressure produces higher axial velocities near the surface, an effect similar to that found at higher speeds, though less pronounced. This indicates that within the range of pressure and speed ratios investigated extrusion speed has a more pronounced effect on lubrication than has an increase in fluid pressure.

In the present work, for otherwise identical conditions, the driving stress (sum of extrusion pressure and drawing stress) remained constant for various extrusion-pressure/drawing-stress ratios, while another investigator[12] reported decreasing driving stress in the drawing-orientated process when, according to the present results, friction increases owing to less-efficient lubrication. The probable explanation of this apparent contradiction lies in the different stress/

strain characteristics of the two materials. The build-up of pressure for fully annealed copper produces more significant billet deformation at the die entry, under otherwise similar conditions, than for the somewhat work-hardened stainless steel reported in Ref. 12. Hence, more fluid enters the billet/die interface and the decrease in the coefficient of friction compensates for the increased die pressure to provide unaltered driving stress even for larger extrusion-pressure/drawing-stress ratios, while in the case of stainless steel in the extrusion-orientated process the increase in die pressure was dominant in determining the size of frictional forces.

To establish the variation of friction with extrusion fluid and lubricant, the velocity fields can be compared (Fig. 4, extrusions 1–3). For extrusion 1 with Tellus 27, no deformation occurs in advance of the die and the central portion of the billet commences to deform first. As Tellus 27 is less viscous than the lubricants in the other two cases (castor oil and castor oil plus molybdenum disulphide grease) and as the extrusion pressure is also lower, this is to be expected. Throughout the deformation region the flow is less uniform for Tellus 27 but this effect is small. It should be noted that the difference in viscosity between Tellus 27 and castor oil is much less than is indicated by the atmospheric values, as the former has a much higher pressure coefficent of viscosity.[8]

Utilizing the strain across the product as a means of judging the effectiveness of the fluid in lubricating the deforming surface, there was less variation across the section for extrusion 3 when castor oil with molybdenum disulphide grease was used than in the other two cases, and also the mean strain was marginally lower when (as for extrusion 2) castor oil was used instead of Tellus 27. Thus, this method of grading shows that molybdenum disulphide grease gives lower friction than castor oil, which in turn leads to a lower friction value than Tellus 27. The difference between the three conditions is very small, indicating that visioplastic analysis is sufficiently sensitive to distinguish between frictional conditions even if the changes are small and unlikely to be detected by other methods. Such small changes certainly could not be revealed by measuring differences in the driving stress.

In this paper comparisons relating to the various frictional conditions are drawn from the axial velocity and the total equivalent strain fields, as the most revealing of all computations: two velocity fields (axial and radial), five strain-rate fields (axial, hoop, radial, shear, total), one total effective strain field, and six stress fields (radial, hoop and axial direct stresses, shear stress, mean effective stress, and hydrostatic stress).

Calculation of the stress fields by the visioplasticity method, which would be expected to provide quantitative data on friction, were inaccurate and erratic. This is mainly due to inaccuracies in calculating the shear strain rate which is used to calculate the distribution of axial stress along lines of constant radius. As the shear strain rate is equal to the change of axial velocity in the radial direction plus the change of radial velocity in the axial direction (both small quantities), small errors in the velocity field will be magnified, after numerical differentiations, in the stress field. Further work could be aimed at refining the smoothing procedure to give more reliable values of the shear strain rate. Inaccuracies in the stress field mean that no useful values of local coefficient of friction can be found, nor can the hydrodynamic theory be used to calculate a film thickness in relevant cases. However, visioplasticity analysis confirms the results of experiments and finite element analysis[13] in that it shows two maxima in the distribution of normal stresses along the die face—one near the entry and another close to the exit plane, indicating that further development of the method would be worth while and should provide quantitative data on friction.

In conclusion, the results show that in the hydrostatic extrusion/drawing of fully annealed copper, friction increases with increasing drawing stress and with decreasing extrusion speed. A better knowledge of the stress field would be necessary to predict billet deformation before entry into the die because, according to the present findings, this initial deformation has a significant influence on lubrication conditions.

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