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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