The work presented here has only scratched the surface of the analytical modelling of solid lubrication in metal forming. Better models for the transport of solid films are needed, as well as more experimental data on the influence of coating thickness and surface topography. A method to predict the onset of sticking would be of great value.

Acknowledgments

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DISCUSSION

S. C. Jain[4]

The authors appear to be pioneers in studying an important area of lubrication mechanism that has been somewhat neglected by the research workers in the past. For this effort, I would like to congratulate the authors for this and several other papers on the same subject.

Some of my comments relate to the experimental details and the procedures used by the authors, such as:

1. How was the surface roughness of the dies maintained at about 0.1 μm (4 μin.) AA during the experiment?
2. Aluminum has a tendency to stick or weld onto the die surfaces locally wherever there is a breakdown of the lubricant film. How were the dies cleaned and restored to the .1 μm (4 μin.) AA surface roughness?
3. While changing lubricants, what steps were taken to remove traces of previous lubricant films from the die surfaces?
4. The thickness of the lubricant film depends on the consistency of the lubricant, spraying techniques (shape and size of the nozzle, pressure, angle and distance of spray nozzle, speed and time of spray), human skill and other factors, such as air velocity, etc. What was the accuracy of the weighing technique in determining the film thickness? Also, did the authors investigate other methods, such as mechanical and/or eddy principles, etc. for thickness measurement?
5. In a typical metalworking operation, depending upon the type of lubricant and the transportation mode, three phases of interface lubrications exist. These are—complete slipping, slipping and sticking, and sticking. Using solid cylindrical specimens, the lubricant breakdown and transportation mode were studied in hot forging.[5,6] By measuring the mean diameter of the sticking zone, the effect of a larger die surface area, specimen and die surface finish, and larger deformation can be studied. Do the authors, in future, plan to continue their theoretical and experimental work by using specimens of different shapes?

[4] Research and Development, Wyman-Gordon Co., North Grafton, Mass.

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A. T. Male[7]

This is yet another interesting report on a continuing line of research being pursued under the leadership and direction of Dr. Wilson. The development of suitable analytical models for lubrication effects in metals processing operations will be yet another step in the direction of turning an art into a science and, as such, will be a useful tool for increasing industrial productivity.

The apparent anomaly observed by the authors between the behavior of lead and polyethylene sheet lubricants is particularly intriguing. This anomaly may possibly be explainable in terms of the compressibility (reciprocal of bulk modulus) of the two materials. There is approximately one order of magnitude difference between the bulk modulii; 1.1×10^6 psi for lead and an average of 0.13×10^6 psi for polyethylene. Under the test conditions used here, the lubricant sheet would be expected to obtain some mechanical strengthening from its contact with the die surface. Increasing the polyethylene thickness, together with its relatively high elastic compressibility, may allow for more rapid penetration of the film at the workpiece edge.

An alternative explanation may lie in the possibility of the various thicknesses of polyethylene sheet possessing differing physical and mechanical properties. Perhaps the authors would care to comment on this possibility.

J. A. Schey[8]

As so many of Dr. Wilson's papers, this one again brings novel approaches and quantitative treatment to an important field.

The test method is new and invites comparison with older ones. It

[7] Westinghouse Electric Corp.

[8] University of Waterloo, Waterloo, Ontario, Canada.

could be described as one half of Hill's "cigar test"[9] and one wonders if prevention of possible skidding of the workpiece is worth the complication of a stepped die. Ring compression would provide the same information with the added convenience of determining the rheological properties of the solid lubricant.[10]

The results indicate that lubricant transport follows the mathematical model only with lead, and with polyethylene on smooth specimens, but not at all with PTFE or graphite. The limited applicability of a single model is perhaps not surprising if the great variations in lubricant properties are considered, and one can only sympathize with the sentiments expressed in the last paragraph of the conclusions.

[9] Hill, R., *Phil. Mag.*, *Vol. 41*, 1950, pp. 733–744.

[10] Schey, J. A., in Proceedings NAMRC IV, T. Altan, ed., Society of Manufacturing Engineers, Dearborn, Mich., 1976, pp. 108–114.

Authors' Closure

In response to Dr. Jain's remarks, the die was periodically surveyed for changes in surface roughness or the presence of transferred aluminum. If these conditions were found the die was re-lapped on abrasive paper to restore its surface. The die was also re-lapped and washed with suitable solvents between runs with different lubricants.

Great difficulty was found in controlling the thickness of sprayed graphite and PTFE coatings. It was also tedious to measure the coating thickness by weighing and such measurements only give a mean thickness over the whole piece. These problems led to the adoption of lead and polyethylene as lubricants since these could be applied in the form of uniform readily measured sheets.

In the present work the objective was to study the transport of the lubricant. Thus the authors tried to achieve conditions of complete slipping. This was not always possible and the sticking plus sliding regime was also observed. This regime was very unsatisfactory for the purposes of the present work.

The authors are presently involved in the development of more fundamental models of the lubricant transport process using the upper bound method of plasticity. Our immediate plans call for further analytical work backed up with further experiments using the geometry described in the present paper. However, one of the authors plans to extend the work to other geometries.

Dr. Male's suggestion that the compressibilities of the lubricants might be important is most interesting. Our modelling activities have not dealt with this possibility. Perhaps it should be the basis for some future work. It is, as Dr. Male suggests, quite likely that the different thicknesses of polyethylene have different properties. This may be a result of the deformation of the sheets during forming since the effects described were present even when the thickness variation was produced by using different numbers of layers of the same sheet material.

As Dr. Schey states the test method is very similar to half a Hill "cigar test." In earlier work with liquid lubricants [2] it was found that the reproducibility of tests without a step was very poor and the stepped die eliminated this problem. The ring test could be used to generate similar information. However, the lubrication process in this system can affect the mode of deformation which makes the interpretation of the results difficult. It is also likely that large variations in friction occur across the workpiece surface. Under such circumstances the use of the existing "calibration" theory for the ring test to determine frictional conditions is open to criticism.

The relatively limited applicability of the simple model proposed in the paper is probably due to its high empirical content. It is to be hoped that as we understand the processes involved better our modelling methods will be applicable to a larger range of situations.

In conclusion, the authors would like to thank Drs. Jain, Male, and Schey for their thoughtful comments on our paper.