thin film of PTFE is formed on the extrudate surface in room temperature extrusion. The film is torn at places exposing the aluminum surface. The surface micrograph in Fig. 9 shows PTFE particles coalesced together giving rise to a continuous lubricant film. It also shows that the particles which were round before extrusion have been deformed and flattened. It is probably this flattening and the proximity of the particles that account for a good coverage of the metal surface. No significant film formation, flattening or orientation of particles was noticed for PVC in room temperature extrusion. PVC was, therefore, not able to cover the extrudate surface as well as PTFE did and thus resulted in higher extrusion and friction forces. In the case of extrusion at a higher temperature, the PTFE film formed was about the same in appearance and thickness variation as in room temperature extrusion. Figure 10 shows the PTFE film formed on the extrudate surface during extrusion at high temperature. Examination at higher magnification reveals that the regions adjacent to the locations where the film is broken (denoted by circle A) have more than one layer of the polymer film on the extrudate surface which occurs due to folding of the broken film. In spite of this, the coverage of the metal surface with polymer film is thorough enough to prevent the possibility of any metal-to-metal contact. There was also a continuous PVC film formed in extrusion at high temperature (Fig. 11) in contrast to very little film formation in room temperature extrusion. The coverage of the extrudate surface with PVC film here appears to be thorough. The examination of the film at higher magnification (Fig. 12) revealed considerable flattening of the PVC particles. This led to the inference that the process of film formation occurs more easily at high temperatures. The mechanism of film formation seems to be flattening followed by packing of loose particles. The PVC film thickness, as estimated from the measurement of the gap between the arrows in Fig. 13, was found to be in the range of 45 to 75 μm. In a similar way, the PTFE film thickness was estimated to lie between 10 and 60 μm for both the cold and hot extrusions.

Conclusions

PTFE and PVC powders in tetrahydronaphthalene suspension provide effective lubrication in the extrusion of aluminum both under ambient and high temperature conditions. PTFE is practically as good a lubricant as MoS_2 in oil suspension. PVC has somewhat poorer lubricating properties and so results in a higher extrusion force and rougher extrudate surface finish. The lubricating properties of PCTFE, low density polyethylene and high density polyethylene are unacceptable. The effectiveness of lubrication depends upon the capability of the polymer in suspension to adhere to the metal surface and cover it uniformly. The polymer particles are flattened during the extrusion process giving rise to a thin polymer film which prevents adhesion between the sliding metal surfaces. The thickness of this film is in the range of 10-75 μm. The finer the polymer powder particle size, the smaller is the force needed for extrusion.

Acknowledgments

The authors gratefully acknowledge the support provided for this work by the Engineering Research Institute at Iowa State University, Ames, Iowa.

References

1 Cannon, P., and Norton, F. J., "Reaction between Molybdenum Disulphide and Water," *Nature*, Vol. 203, 1964, pp. 750-751.

2 Zaslavsky, Yu. S., Berlin, A. A., Zaslavsky, R. N., Cherkashin, M. I., Beloserova, K. E., and Rusakova, V. A., "Antiwear Extreme Pressure and Anti-Friction Action of Friction-Polymer-Forming Additives," *Wear*, Vol. 20, 1972, pp. 287-297.

3 Zaslavsky, Yu. S., Zaslavsky, R. N., Cherkashin, M. I., Brodsky, E. S., Lukashenko, I. M., Lebedevskaya, V. G., Nikishenko, S. B., and Belozerova, K. E., "Some Aspects of Polymer Formation Chemistry," *Wear*, Vol. 30, 1974, pp. 267-273.

4 Furey, M. J., "The Formation of Polymeric Films Directly on Rubbing Surfaces to Reduce Wear," *Wear*, Vol. 26, 1973, pp. 369-392.

5 Peace, J. B., "Solid Lubricants," Chapter 2 in *Lubrication and Lubricants*, ed., E. R. Braithwaite, Elsevier Publishing Co., New York, 1967.

6 Ovreset, A., and Duncan, J. L., "Polyethylene Film as a Lubricant for Metal Working at High Contact Pressures," *J. Inst. Met.*, Vol. 93, Part 11, 1965, pp. 403-405.

7 Blake, D., Bailey, H. P., Bonnar, J., and Rakison, A., "Polymer Lubricants for the Cold Extrusion of Mild Steel," *Metallurgia and Metal Forming*, Vol. 39, No. 1, Jan. 1972, pp. 30-31.

8 Towle, L. C., "Shear Strength and Polymer Friction," *Advances in Polymer Friction and Wear*, Polymer Science and Technology, Vol. 5A, ed., L. H. Lee, Plenum Press, New York, 1974, pp. 179-189.

9 Bowers, R. C., "Coefficient of Friction of High Polymers as a Function of Pressure," *J. Appl. Phys.*, Vol. 42, No. 12, Nov. 1971, pp. 4961-4970.

10 Saleem, M. A., and Bahadur, S., "Polymer Friction under Conditions of Deformation Processing," *Advances in Polymer Friction and Wear*, Polymer Science and Technology, Vol. 5A, ed., L. H. Lee, Plenum Press, New York, 1974, pp. 165-177.

11 Cook, C. R., "Lubricants for High Temperature Extrusion," *ASLE Proceedings* — Int'l Conf. on Solid Lubrication, Denver, 1971, pp. 13-26.

12 Avitzur, B., *Metal Forming: Processing and Analysis*, McGraw-Hill, New York, 1968, pp. 262-264.

13 Jain, V. K., and Bahadur, S., "Surface Topography Changes in Polymer-Metal Sliding — I," ASME Journal of Lubrication Technology, Vol. 102, No. 4, Oct. 1980, pp. 520-525.

DISCUSSION

R. P. Steijn[1]

Messrs. Suresh and Bahadur have presented a most interesting paper. Their well documented finding that PTFE in tetrahydronaphthalene (THN) is about as good as MoS_2 in oil, is quite revealing and may prove to be potentially significant for use in metal-forming operations. Perhaps this is why the authors do say next to nothing about the concentration of the polymers in the THN, whether it is thick with PTFE, or PVC, or very thinly dispersed but surely this discusser wonders how critical the polymer concentration was in their experiments. Also, strictly for reasons of comparison, did the authors ever try MoS_2 in THN and, if not, have you any idea how this would compare to PTFE in THN?

It is quite surprising that HDPE which, because of its smooth molecular profile, is known to form thin lubricating transfer films and has, therefore, unlike LDPE and PCTFE, a low coefficient of friction, was not found beneficial in these extrusion experiments. I like to think that a properly designed suspension of HDPE in THN would give similar results in room temperature extrusion as PTFE.

[1] Sr. Research Associate, E. I du Pont de Nemours & Co., Engineering Technology Laboratory, Wilmington, Del. 19898.

Authors' Closure

The authors thank Dr. Steijn for his valuable discussion. We studied the effect of polymer concentration in THN to a limited extent and found that the extrusion force was independent of concentration as long as the mixture was in the form of a paste. When the mixture was too dilute, for example, THN-to-polymer volume ratio being greater than 5, the lubrication was very poor. In this work, however, equal parts by volume of the polymer and THN mixture were used.

We did not try MoS_2 in THN as a lubricant. Instead we compared the lubrication ability of PTFE in oil with MoS_2 in oil and found that both were at par giving an average maximum extrusion force of 217 kN. Considering that this is the same as the force observed in extrusion with PTFE suspended in THN (which by itself is not a good lubricant whereas the oil is), the effectiveness of PTFE as a lubricant is evident.

The coefficient of friction during extrusion with HDPE in THN as a lubricant was higher than with PTFE in THN possibly because the extrusion experiments were performed at very slow speeds. This behavior is identical to that observed in very slow speed sliding. However, at high sliding speeds the two materials have the same coefficient of friction. We may thus expect to observe the same behavior if high speed extrusion conditions are used.