

The agreement between the pin-on-disk data and the specialized theory for variable film thickness and constant load, i.e., equation (9), indicates that the model is again of sufficient accuracy to represent that situation.

As the two specialized forms of equation (8), that is, equations (9) and (10), have been experimentally verified, one may conclude that the more general equations (7) and (8) which relate friction to film thickness and normal load have also been substantiated.

The experimental data examined in support of the theory represents a very large range of values of film thickness. Bowden and Young's [16] graphite films on diamond were apparently quite thin. In contrast Johnson and Sliney's [8] bonded PbO films were as thick as 0.0065 in. The theory then is seen to apply to a significant range of values of film thickness.

Summary of Conclusions

1 The film thickness effect for the thin film regime depends on the mode of deformation at the contact; therefore no single expression can uniquely describe it for all materials situations.

2 For bonded solid lubricant films, such as MoS₂, PbO, etc.;

(a) For variable load and constant film thickness

$$f \propto \sqrt{1/P}$$

(b) For constant load and variable film thickness

$$f \propto \sqrt{h}$$

(c) In general

$$f \propto \sqrt{h/P}$$

3 The derived theory applies both to cases of nominal point contact and nominal line contact.

Acknowledgments

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DISCUSSION

E. Rabinowicz³

Dr. Finkin is to be commended for having shown so convincingly that an empirical relationship exists between the friction coefficients of surfaces covered by solid film lubricants and the square root of the thickness/load ratio at the contact.

Has Dr. Finkin done more? He has produced a complete mathematical relationship assuming a rigid sphere contacting a rigid flat covered by an elastic film. This part of his paper is much less convincing, and what we know about elastohydrodynamic and plastrohydrodynamic lubrication by liquid lubricants suggests that his model is an artificial one. It would seem that a complete model would include the properties of the substrate as well as those of the film. Some kind of strength ratio of film to substrate would be a logical choice, and to illustrate how this could be applied, I give some experimental data correlated to one such ratio; namely, the film/substrate hardness quotient.

In the figure, friction coefficient values are shown for metal on metal films. These were obtained under the uniform conditions of 4 kg load, 3×10^{-4} cm film thickness, and a hard rider of 0.6 cm dia. Three of the data points are taken from Bowden and Tabor⁴ while four are taken from our own work. A friction coefficient of about 0.8 may be assumed as a terminal point for a film on its own substrate. The friction coefficient is seen to increase monotonically with the hardness ratio. Although comparable data for nonmetallic films do not seem to be available, it would be logical to suppose that a similar relationship would prevail.

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⁴ Bowden, F. P., and Tabor, D., *The Friction and Lubrication of Solids*, Oxford University Press, 1950, Chapters V and VI.

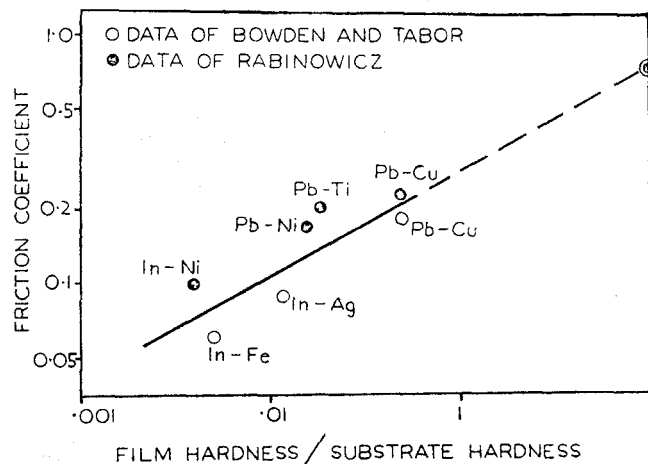


Fig. 10 Friction coefficient, obtained when a hemispherically ended rider of a hard metal slides over a surface covered by a thin film of soft metal, is plotted against the ratio of film hardness to substrate hardness. The friction increases with the hardness ratio.

V. Hopkins⁵

Finkin's theory dealing with solid film lubricants and physical property data to use with this theory are badly needed for the advancement of solid film lubricants. This discussor is glad to see that Dr. Finkin is working toward the development of such a theory. My comments about this paper are concerned primarily with the application of the theory.

Since the theory deals with the elastic behavior of solid lubricant films, it cannot be applied to films, such as some of the sodium silicate bonded films, which permanently deform under load. These types of films are porous and appear to be very fluffy when viewed through a microscope. Loading such films with even light loads causes them to yield. Films which become molten at the interface during sliding are not covered by the theory either. Many investigators of ceramic bonded films, which exhibit low friction at elevated temperatures, believe that localized melting at the interface may account for these low frictions. In the work of Johnson and Sliney mentioned in the paper, friction data were collected at 1250 deg F. Since the test temperature was only 400 deg F below the fusion temperature of these films and rubbing took place at 430 fpm under a 1 kg load, localized melting at the interface is a distinct possibility. If melting did occur, it would appear that the reasonably good fit of theory to the data was just a coincidence.

The mean shear strength of the junction is taken as a constant in the theory. Does this mean that the theory only applies to the average values of the stabilized friction in friction and wear tests?

The friction data presented in Figs. 4-9 of the paper were probably taken after some wear occurred. The contact geometry, particularly for the pin-on-disk apparatus, changes significantly with wear. Does the theory permit the change in contact geometry resulting from wear?

Were curve-fitting techniques used to locate the theoretical curves in Figs. 4-9?

Is it possible to use the relationships, $F\alpha\sqrt{h}$ and $F\alpha\sqrt{1/P}$ to calculate physical properties of films after empirically deter-

mining a proportionality constant from the theoretical curve fitted to experimental data?

Author's Closure

Professor Rabinowicz is quite correct in pointing out that one needs a criterion, based on the mechanical properties of both the film and the substrate, in order to know if the theory is applicable to the case one wishes to consider and, indeed, such a criterion is given in the paper; for the theory to be applied, the Young's modulus of the film must be very much less than that of the substrate. Consequently, the theory doesn't apply to metallic films, and this too is stated in the paper.

Mr. Hopkins' discussion is most valuable as it raises points of considerable importance, which might have otherwise been overlooked.

The mechanical properties of solid lubricant films (and not just the properties of their individual constituents) were shown to be of considerable importance, yet this information is presently almost nonexistent. In the future, one should be able to use the derived relationships, together with experimental friction data, and the results of a film shear strength test, to determine these vitally needed mechanical properties.

A sprayed and bonded solid lubricant film is quite porous as applied, but rapidly compacts under load. Once this compaction occurs, the values of the mechanical properties should stabilize, and the predictions of the theory using the equilibrium values of the mechanical properties should be quite accurate. If one had, or could predict, the instantaneous values of the mechanical properties, prior to the achievement of equilibrium, then hopefully the theory could predict friction values for this transitional stage as well.

The theory can be used to predict friction throughout the entire wear life of a film. As the film wears, the value of h will change, and the predicted friction will correspondingly change.

The shapes of the curves in Fig. 4-9 result from theory and not from curve fitting techniques. But, the actual placement of these theoretical curves in the fields of data points was done for best fit, because of the absence of knowledge concerning the mechanical properties of the films used in these experiments.

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