the molecular structure; that is, simpler structure gives lower shear strength. This tendency of shear strength which was observed at high pressure of real contact is very similar to that of viscosity at high pressure. It has been reported that the largest pressure effect on viscosity is for those substances with the most complicated molecules. As for the order of cetane, palmitic acid and cetyl alcohol, it is in exact agreement with the order of viscosity of those paraffinic compounds of shorter chain length which are liquid at room temperature.

There should be some difference, however, between the viscosity of liquid and the shear strength of adsorbed film, because the adsorption force may have an effect on the shear strength. Further studies are necessary on this problem.

The order of α is shown in Table 7 with the values of dipole moment of the corresponding substance. As discussed in the foregoing, α could be considerably influenced by the inaccuracy of measured μ, and hence the value of 0.05 or 0.3 in this table might not be reliable. This obviously makes, however, little difference in discussing the general tendency of the lubricants. As the table indicates, poor polarity seems to cause large α. The steric hindrance, which prevents the polar groups in the molecule from approaching closely to the surface, may be also considered. The polar end of fatty acid or alcohol can easily reach the surface. The intermolecular attraction is another well-known factor to be taken into account.

From the results obtained so far, it is clear that both α and μ are very important factors in estimating the lubricity of a lubricant. Cetane has a very small μ but the large α makes it a poor lubricant. With silicones, the shear strength is the same for 1000-cs and 50-cs fluids, but α is considerably smaller for 1000 cs than for 50 cs, suggesting the effect of the size of the molecule or viscosity. In this case some influence of sliding velocity may be expected.

Another interesting finding on α is the effect of solvent. As seen in Table 3, α of liquid lubricant in bulk-liquid lubrication differs very little from that in thin-film lubrication. On the other hand, the bulk and thin-film values of α for a solid lubricant in solution are appreciably different. This may be explained by the difference between the energy of adsorption from solution and from vacuum or air as has been suggested by Rabinowicz.

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DISCUSSION

R. S. Fein

The authors ambitiously have carried out a sophisticated interpretation of friction data. This interpretation is based on the simple Bowden and Tabor boundary lubrication model and accurate and precise friction measurements.

The requirement of precision in the friction measurements follows from an analysis of the errors involved in the solutions of the simultaneous friction equations. Allow Δμ, Δμ, and Δμ, to represent the differences between two simultaneous equations in frictions μ, μ, and μ, respectively. It is found that the standard errors in the estimations of μ and μ are

\[ \sigma_\mu = \frac{\Delta \mu}{\mu} \left( \frac{\sigma_{\Delta \mu}}{\sigma_\mu} + \frac{\Delta \mu}{\Delta \mu} \right)^{1/2} \]

\[ \sigma_{\mu'} = \left( \frac{1}{1 - \alpha} \right) \left[ \left( \frac{\mu - \alpha \mu}{1 - \alpha} \right)^2 + \sigma_\mu^2 + \alpha^2 \sigma_{\mu'}^2 \right]^{1/2} \]

If it may be assumed from the authors’ discussion of repeatability that the standard error of the lubricated friction-coefficient measurements, σμ, is about 0.01 and of the dry friction-coefficient measurements, σμ, is about 0.1, then one finds that σμ varies from about 0.5 to 2 percent and σμ = 0.01 for the good lubrication cases. These estimated values of σμ and σμ are the same magnitude as differences in α and μ which the authors treat as significant. Therefore, more information on the precision of the authors’ results would be of interest. Also of interest from the standpoint of the accuracy of the results would be a discussion of the method the authors used to average the commonly found friction fluctuations, including, if observed, those corresponding to the period of disk rotation.

Another point of interest concerns the theoretical significance of the authors’ data treatment method. The Bowden and Tabor equation \[ P = \alpha \mu' + \frac{1 - \alpha}{1 - \mu} \] was derived on the assumption that all load-supporting asperities were identical in size of the load-supporting area. Undoubtedly there is a distribution of asperity sizes and the fraction of metallic contact on the asperities. Consideration of such a distribution with a load-supporting area of α and fraction of surface contact, α, for the ith asperity indicates that the α calculated in the usual manner from friction data is \[ \sum a_i \alpha_i / A, \] in which A is the total load-supporting area, \[ A = \frac{W}{P} = \sum a_i. \] Thus, when the authors treat their data as if α and μ were lubricant constants, they are implicitly assuming that: (a) The distribution of α, after a short run-in does not depend on surface preparation or lubricant; and (b) the distribution of α, which depends on the ability of a lubricant to absorb and react at the surface to prevent solid-solid contact, does not depend on surface preparation.

Lastly, two possible rationalizations of the authors’ “edge effect” should be pointed out. These are: (a) The bulk lubricant restricts access of oxygen to the surfaces, thus reducing surface oxidation and lubricant reactions; and (b) the bulk lubricant disperses or dissolves the products of lubricant reaction at the friction surfaces, thus restricting their contribution to boundary lubrication. Both of these possible rationalizations are supported by recent work.

E. Rabinowicz

The authors are to be congratulated for an interesting paper which adds a new method to those previously in use for evaluating α, the proportion of the lubricant which is penetrated during sliding. The data which the authors obtain are inherently reliable, internally consistent, and agree well with earlier data (Rabinowicz, 1954). It is perhaps worth pointing out that the earlier data, too, have rather better internal consistency than I, as a somewhat disillusioned worker in this field, have come to expect.

In view of the satisfactory state of affairs I have just outlined, it is perhaps ungraceful of me to point out that the good agreement in values of α—as calculated from friction values for a fresh surface, an aged surface, and an oxidized surface—is somewhat surprising. Thus, the fact that a fresh copper surface gives a friction coefficient 2\(1/2\) times as great as does an aged surface suggests, not that the shear strength of the fresh copper is 2\(1/2\) times as great, but rather that the real area of contact is 2\(1/2\) times as great. Now the data appear to show that this larger value of the metal-to-metal component of the real area of contact is maintained in the presence of the lubricant. However, the great cleanliness of the copper surfaces, which is responsible for

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the factor of $2^{1/2}$ increase in contact area, probably disappears as soon as we add the lubricant.

In a recent paper (Rabinowicz, 1964), I have outlined an alternative way of looking at a lubricant, in which its function is not primarily to diminish the metal-to-metal contact, but rather to diminish the surface energy of adhesion. In this formulation, the fact that "good" values for $\alpha$ are obtained by the use of equations based on equation (2) of the paper becomes but a coincidence. Perhaps I am straining credibility in suggesting that the results of this paper constitute yet a further coincidence. More probably there is some underlying general relationship which has not yet been discovered.

Authors' Closure

In regard to Dr. Fein's remarks on precision, we agree that differences of the order he calculates cannot be regarded as very meaningful. Many of the results listed in Table 5 are nonetheless significant; for example, $\mu_1$ for cetane is 0.052, while that for Na-soap is 0.087. Furthermore, in Table 7, the ordering on $\alpha$ can hardly be dismissed as coincidental. It should be mentioned again that we gave not the standard deviation, but the range, which is preferable in treating a small number of measurements.

Dr. Fein's opinion that neither $\alpha$ nor $\mu_1$ is a constant of the lubricant is quite right. Each is a function of temperature, load, speed, and so on.

We agree with Dr. Fein's suggestion that diffusion of oxygen through oil and/or the solvent action of oil on adsorbed matter may be important. These factors, however, tend to affect $\alpha$ rather than the shear strength, on which our discussion was based. For $\alpha$, we did consider these points, and the one of interest may be diffusion of oxygen. As shown in Table 5, $\alpha$ for cetane is smaller for a thin film than for bulk. Oxygen could diffuse easily to the surface in the case of the thin film.

In reply to Professor Rabinowicz's comments on the shear strength of fresh and aged surfaces, we would point out that the latter has an appreciably thicker oxide film, so that a difference in shear strength is to be expected. Indeed, the coefficients of dry friction are different under the same load. The finding that $\alpha$ is the same for both surfaces thus does not appear unreasonable.

The possibility of interpreting friction in terms of surface-energy effects is intriguing. The tendency of a lubricant to absorb on a solid surface is measured thermodynamically by the reduction in the free energy of the lubricant-solid system when adsorption occurs. One would expect, therefore, that a system exhibiting a large decrease in free energy would tend to have a small $\alpha$, and vice versa.