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9 Burwell, J. T., "Survey of Possible Wear Mechanisms," *Wear*, Vol. 1, 1957, pp. 119–141.

10 Rabinowicz, E., Dunn, L. A., and Russell, P. G., "The Abrasive Wear Resistance of Some Bearing Steels," *Lubrication Engineering*, 1961, pp. 587–593.

DISCUSSION

E. Rabinowicz[2]

In this interesting paper, Dr. Finkin has described the various criteria for abrasive wear contained in the literature, involving basically the elastic modulus and the yield stress. He has then compared the wear resistance of two alloy systems with the predictions of these criteria, and finds no simple direct correlation.

Many years ago, this seemed to me to be a promising approach (c.f., author's reference [10]). But for some time now, I have felt that a consideration of the geometry of abrasion suggests a different procedure, since basically the wear resistance is proportional to hardness, and departures from pure proportionality arise from various second order effects, which make the size of the abraded groove different from the size of the abrasive.[3] For ductile metallic systems the two parameters which would appear to be most important are the propensity to work hardening, and the coefficient of friction.

Thus, a criterion for abrasive wear of ductile metals involving hardness, work hardening, and friction might be worth pursuing.

K. C. Ludema[4]

In 1964 Bowden and Tabor[5] wrote, "In general it is safe to say that wear increases with time of running and that with hard surfaces the wear is less than with softer surfaces." If there were any other variables that could be correlated with wear resistance as a general rule at that time, the above cautious statement would have been accompanied by far more information. The references quoted by Dr. Finkin are of the same era as the book by Bowden and Tabor and therefore cannot be considered to be new information that would alter the statement above. One could argue that perhaps the perspective of Dr. Finkin versus that of Drs. Bowden and Tabor is a matter of scale. Finkin appears to say in one place that Khrushchov and Babichev did wear tests with twenty commercially pure metals and found the relative wear resistance to be related to the modulus of elasticity by $E^{1.3}$. Finkin writes that other material follows the same law although the source is not indicated. Then Finkin takes other data of Khruschchov and Babichev for copper-nickel alloys and finds that relative wear resistance is proportional to $E^{0.9}$ and for lead-tin alloys wear resistance is proportional to e^{E}. In essence he has only said that, taking the scattered data points through which Khruschchov and Babichev draw a line defining a wear resistance proportional to E^{X} Finkin finds that by selecting certain points one can arrive at different slopes. This means to Finkin that Young's modulus is a parameter that correlates strongly with wear resistance. Whereas Finkin is careful to say in some places that his conclusion applies to *specific* materials yet the title of the paper leads one to believe that he refers to a universal criterion. On page 5 he himself criticizes a universal criterion since it does not apply to heat treated steels, for example.

On the other hand, Finkin nicely demolished old and persistent claims of a correlation of relative wear resistance with hardness, yield strain, elastic strain energy capacity, and the elastic-to-plastic contact transition.

Another difficulty I have with the paper is that it does not distinguish between abrasive wear resistance and abrasion resistance. There is a vast difference in the type of abrasive wear caused by the oxides that form on metal surfaces as studied by Welch, Lancaster, etc., the abrasion resistance which comes about from abrasive particles in a lubricant, and the resistance to material loss from sliding on abrasive wheels, papers, etc. Dr. Finkin references his previous papers on this latter subject but offers no assistance to the reader of this paper.

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[2] Massachusetts Institute of Technology, Cambridge, Mass.

[3] Rabinowicz, E., *Friction and Wear of Materials*, Wiley, New York, 1965, p. 176.

[4] The University of Michigan, Ann Arbor, Mich.

[5] Bowden and Tabor, *The Friction and Lubrication of Solids*, Vol. II, Oxford Press, 1964, p. 350.

Author's Closure

Ludema's Comments:

The wear of metals takes many different forms. Fig. 7 presents

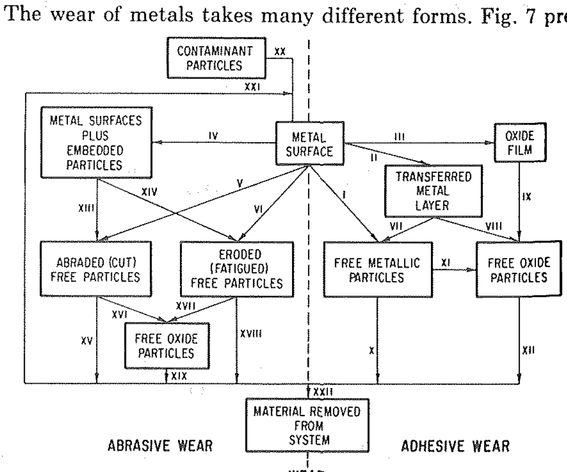

Fig. 7

(Paper continued on p. 246)

(Paper continued from p. 214)

a scheme for distinguishing the relationships among the more important types. Generally, these types can be divided, as shown in the figure, into two general classifications; adhesive wear and abrasive wear. Adhesive wear has received the bulk of attention in the literature, and has been the subject of recent theoretical development.[6]

Over the years abrasive wear has received an unreasonably small proportion of the total effort devoted to wear research. The present publication is devoted solely to abrasion by hard particles and in no way pretends to treat the entire subject of wear.

Prof. Ludema's difficulties with this paper probably arise purely from its definition of abrasive wear, which is resolved by Fig. 7.

Rabinowicz's Comments:

It's gratifying to learn that some years ago Prof. Rabinowicz considered carrying out a critical examination of the variously proposed abrasion resistance criteria. It's too bad he didn't do so.

He suspects that a criterion involving hardness, work hardening and friction might be worth pursuing. I will be interested in examining such a criterion should he derive it. However, at this point, it's hard to see how a criterion containing just these governing materials parameters would explain either the abrasion behavior of precipitation hardened alloys (e.g., aluminum alloys, beryllium copper), or the striking empirical dependence of the abrasion resistance of nonferrous materials on Young's modulus.

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[6] Finkin, E. F., "Speculations On The Theory Of Adhesive Wear," *Wear*, Vol. 21, 1972, pp. 103–114.