

Influence of Surface Energy on Friction and Wear Phenomena


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Low Friction in Reciprocating Sliding

It was found quite unexpectedly that with some metals, very low friction less than 0.10 was observed. Table III lists the metals that show low friction, and some other metals for comparison.

TABLE III. Low friction.

Combination	Occurrence
Gold-gold	+
Silver-silver	+
Copper-copper	+
Platinum-platinum	+
Nickel-nickel	—
Aluminum-aluminum	—
Brass-brass	—
Steel-steel	—
Oxid. copper-oxid. copper	—
Steel-silver	—
Gold plat.-gold plat.	→+

Gold, silver, copper, and platinum exhibit low friction. However, surface-oxidized copper did not. Gold behaved the same at 200°C as at room temperature. A gold-plated steel specimen showed low friction at the beginning but as soon as the gold was rubbed off by repeated sliding, it did not. A dissimilar friction couple of silver and steel did not give the low friction.

The low friction appears when the amplitude of swing becomes more or less narrow; for gold it starts at 500 μ , for silver 170 μ , for platinum 60 μ , and for copper 50 μ . Except for gold, these metals show low friction occasionally: 0.9 of the time for silver, 0.6 for platinum, and 0.4 for copper, in the same order as with the amplitude.

Halliday and Hirst⁴ have found the lowering of friction with mild steel, aluminum, copper, and nickel at small amplitude of fretting. However, further investigation should be required to see any relation between their finding and the present one or to explain this phenomenon more perfectly.

Influence of Surface Energy on Friction and Wear Phenomena

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A number of friction and wear phenomena are explicable in terms of the surface energy of adhesion of the contacting materials. In the friction field, it is found qualitatively that high friction coefficients are found for sliding materials with high surface energy/hardness ratios and conversely. Unfortunately, it is not easy to test this relationship quantitatively because the derived expression contains parameters which cannot be independently controlled. However, in the wear field, it has been found possible to derive an expression for the size of loose wear particles which can be readily tested; namely, that the average size of loose wear particles is proportional to the surface energy/hardness ratio, the nondimensional constant of proportionality being 60 000. Experiments with 15 different materials show the validity of this expression. Another phenomenon, adhesion, which also seems to be governed by surface energy considerations, is discussed in qualitative terms.

INTRODUCTION

THE theory of the friction process in recent years has been dominated by the equation

$$f = s/p, \quad (1)$$

which denotes the fact that the friction coefficient represents the ratio of the shear strength s to the hardness p of the softer of two contacting materials. This equation has helped explain many frictional phenomena; however, it has failed to make much of a contribution to two of the main frictional problems; namely, that of describing the scale on which phenomena occur, and that of selecting frictional materials suitable for practical use. Indeed, taken at its face value, Eq. (1) suggests that almost any material will give essentially the same frictional behavior as any other, since s and p have essentially a constant ratio for all but a very few materials. However, it is known that friction coefficients do vary over a fair range, with friction coefficients of

metals, sliding in air, varying from 2.0 for indium to 0.5 for titanium; also, that the appearance of surfaces after sliding varies from very rough to quite smooth. Hence, it seems clear that we must modify Eq. (1) in some way so as to bring to bear additional properties of the sliding materials. It is my contention that this may be done by considering the work of adhesion W_{ab} of the contacting materials. The quantity W_{ab} is defined by the equation

$$W_{ab} = \gamma_a + \gamma_b - \gamma_{ab}, \quad (2)$$

where γ_a and γ_b are the surface free energies of materials a and b , and γ_{ab} the interface free energy, all per unit area.

VALUES FOR THE WORK OF ADHESION OF SOLIDS

It must be stated at the outset that reliable data for the work of adhesion of solids are not generally available.

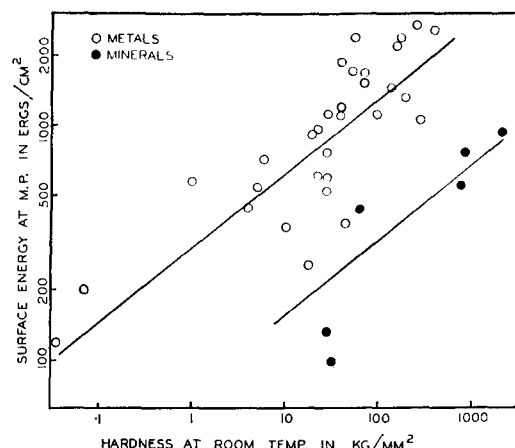


FIG. 1. Plot of surface tension as a function of hardness for the metals tabulated by Bondi¹ and Taylor,² also a few nonmetals. The surface tensions increase as a low power (between $\frac{1}{3}$ and $\frac{1}{4}$) of the hardness.

What is available, to a fairly high degree of accuracy, are values of the surface energies γ_a and γ_b of the materials in the liquid state and, in a few cases, values for the interfacial energy γ_{ab} when the lower melting material is a liquid and the other is a solid. Tabulations of the data are given, for example, in Bondi¹ and in Taylor.²

Additionally, some values are available of the surface energies of a few solids and the interfacial energies of a few pairs of solids at temperatures fairly close to their melting point. These data are tabulated by McLean,³ who shows that values of γ_{ab} are of the order of $\frac{1}{2}$ to $\frac{1}{4}$ of $(\gamma_a + \gamma_b)$. It seems that the surface energies of solids are not very temperature dependent, being at the melting point nearly the same as those of the corresponding liquids and increasing by about 0.5 erg/cm² for every 1°C reduction in temperature from that point on. If this variation is maintained down to room temperature, it suggests that the surface energies of most metals are about twice as great at room temperature as at the melting point.

These values apply only when the surfaces are investigated in a vacuum. When tests are carried out in an atmosphere such as nitrogen, the surface energies are lower by factors of the order of 2; thus, since we are ordinarily interested in the work of adhesion of solids in air at or near room temperature, we may assume that the two factors of 2 cancel out.

The surface energies of metals appear to be quite well correlated with their hardness. Thus, if we plot the surface energies of all the metals tabulated by Bondi¹ and Taylor² against their hardnesses as given by Tabor,⁴ we find that a straight line of slope $\frac{1}{4}$ fits the

TABLE I. Data of Machlin and Yankee (1954).

Sliding combination	W_{ab}	W_{aa} (softer material)	Static friction (inert atmosphere)
Ag on Cu	2330 erg/cm ²	2260	0.75
Cu on Fe	2675	2260	0.72
Ag on Fe	712	1780	0.48
Cu on SiO ₂	325	2260	0.10

data quite well (Fig. 1). This suggests that the ratio W_{ab}/p , which we shall later encounter, varies approximately as p^{-1} , being smaller for the harder metals. Figure 1 also shows some values for a few nonmetals; these seem to fall on a line parallel to that for the metals, but lower (i.e., with smaller values of surface energy for the same value of hardness).

ATTEMPTS TO EXPLAIN FRICTION PHENOMENA IN TERMS OF SURFACE ENERGIES

The earliest paper in which friction phenomena are discussed in terms of W_{ab} appears to be that of Machlin and Yankee.⁵ These authors compared the work of adhesion W_{ab} of the sliding combination with the work of cohesion W_{aa} of the weaker material, and postulated that welding during sliding would not occur if $W_{ab} < W_{aa}$. Their experimental work supported this postulate, though in a limited way, since very limited data on W_{ab} were available (see Table I).

It is of interest to note that Machlin and Yankee felt that the work of adhesion concept could also be applied in a different way, for they state: "Perhaps a more representative criterion would be the quotient of the work of adhesion and the strength of the weaker component."

Next, there is a paper by Coffin,⁶ who notes that nickel has a very low work of adhesion against aluminum oxide and that, consequently, nickel should be a good material to slide against alumina (see Table II). Experiments show that nickel does have low friction and surface damage when slid against aluminum oxide in an inert atmosphere. Coffin's method of selecting nickel as the most promising material to slide against alumina is seen to depend on quite small differences in the work of adhesion.

Coming to my own work, I showed some years ago⁷

TABLE II. Data of Coffin (1958).

Combination	Work of adhesion (in H ₂)
Si on Al ₂ O ₃	670 erg/cm ²
Ni on Al ₂ O ₃	480
Fe on Al ₂ O ₃	695

¹ A. Bondi, Chem. Revs. **52**, 417 (1953).

² J. W. Taylor, Metallurgia **50**, 161 (1954).

³ D. McLean, *Grain Boundaries in Metals* (Oxford University Press, New York, 1957), p. 78.

⁴ D. Tabor, *The Hardness of Metals* (Oxford University Press, New York, 1951).

⁵ E. S. Machlin and W. R. Yankee, J. Appl. Phys. **25**, 576 (1954).

⁶ L. F. Coffin, ASLE Trans. **1**, 108 (1958).

⁷ E. Rabinowicz, ASLE Trans. **1**, 96 (1958).

TABLE III. Data for clean metals.

Material	Work of adhesion (erg/cm ²)	Hardness (d/cm ²)	W_{aa}/p (cm)	Friction coefficient
lead on lead	900	$4 \cdot 10^8$	2.2×10^{-6} cm	1.2
low-carbon steel on low-carbon steel	2500	$2 \cdot 10^{10}$	1.2×10^{-7} cm	0.6

that Eq. (1) was not a complete expression for the friction coefficient of sliding surfaces, if the work of adhesion was considered. If we take a cone of angle θ pressed into a flat surface which deforms plastically (Fig. 2), we may write the total energy E in the form

$$E = x \cdot \Delta L - \int \pi r^2 p \cdot dx + \pi r^2 W_{ab}. \quad (3)$$

Substituting $r = x \cot \theta$ and noting that equilibrium is obtained when $dE/dx = 0$, we have

$$\Delta L = \pi r^2 p - 2\pi r W_{ab} \cot \theta. \quad (4)$$

The friction force ΔF is assumed to equal $\pi r^2 s$. Hence, if r and θ are the same for all junctions,

$$f = \frac{\sum \Delta F}{\sum \Delta L} = \frac{s}{p - 2W_{ab}(\cot \theta)/r}. \quad (5)$$

This last expression may be written in the series expansion

$$f = (s/p) [1 + 2W_{ab}(\cot \theta)/pr + 4W_{ab}^2(\cot \theta)^2/(pr)^2 + \dots]. \quad (6)$$

It will be seen that as a result of surface energy, the friction coefficient has been increased, and consideration of Eq. (5) shows that this increase becomes great without limit if

$$W_{ab}/p = r/2 \cot \theta. \quad (7)$$

This mathematical description of the friction process seems to give a good account of the high friction coefficients given by soft metals. For simplicity, we may consider the case of metals sliding on themselves, and for this case assume that γ_{aa} is zero, which is not strictly correct, but will not influence our results unduly. We may then compare W_{aa}/p ratios for a typical soft and a typical hard metal, as has been done in Table III.

Soft metals have much higher W_{aa}/p ratios. They also have higher friction coefficients (see Fig. 3). An

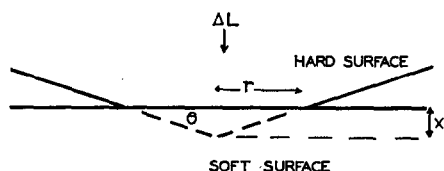


FIG. 2. Schematic representation of a conical asperity pressed into a flat surface.

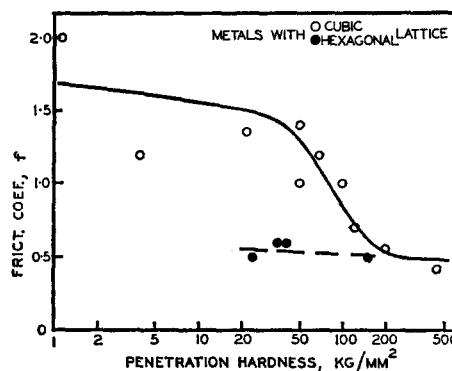


FIG. 3. Plot of friction coefficient as a function of hardness for uncontaminated metals sliding in air.

interesting effect is that metals with hexagonal structure give lower friction coefficients than metals with cubic structure, and it is possible that the extra slip planes of the cubic metals allows them to deform in such a way as to minimize the interfacial energy γ_{aa} , while the hexagonal metals have higher values of γ_{aa} and thus lower W_{aa}/p ratios. A study of friction coefficients as outlined above does not lend itself well to detailed experimental verification of the energy of adhesion concept since two of the terms in Eqs. (3) to (7), namely the junction radius and the surface roughness, are generated during sliding and not imposed externally. Hence they cannot be purposely varied, or even controlled.

EFFECT OF SURFACE ENERGY ON THE SIZE OF LOOSE WEAR PARTICLES

However, another surface phenomenon does exist which is governed by surface energy and which can be specified completely in terms of known parameters. This phenomenon is the formation of loose wear particles accompanying the sliding of smooth surfaces. In a recent paper,⁸ we have suggested that for a particle to come off loose, the elastic energy stored in the particle while it was being formed must equal or exceed the energy of adhesion which binds it to its substrate. In most cases, when a wear particle is made up by the aggregation of smaller fragments, the particle will come off loose as soon as its elastic energy becomes as large as its adhesive energy. For a hemispherical particle, we have (Fig. 4),

$$\frac{1}{2} \cdot (\sigma_r^2/E) \cdot (\pi d^3/12) = W_{ab} \cdot \pi d^2/4, \quad (8)$$

where σ_r is the residual stress in the fragment and E its Young's modulus. If, as is obtained using many models,

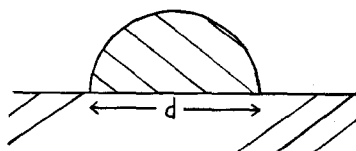
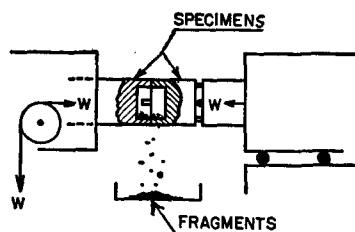


FIG. 4. Schematic representation of a hemispherical fragment on a flat surface.

⁸ E. Rabinowicz, *Wear* 2, 4 (1958).

FIG. 5. Apparatus for producing loose wear particles.



we put

$$\sigma_r^2/\sigma_{yp}^2 = \nu^2 = \frac{1}{10}, \quad (9)$$

where σ_{yp} is the yield stress of the material in compression and ν its Poisson's ratio, we find

$$d = 60EW_{ab}/\sigma_{yp}^2. \quad (10)$$

It has been found that σ_{yp} is about $\frac{1}{3}$ the hardness p , and moreover, that σ_{yp}/E is about $3 \cdot 10^{-3}$ for many materials. Hence we may write

$$d = 60\,000W_{ab}/p. \quad (11)$$

This, then, is a relation between a measurable quantity (the diameter of loose wear particles) and W_{ab} which involves no unknown quantities, and may thus be checked experimentally.

Equation (11) is unusual in that the nondimensional constant which appears in it is surprisingly large. The $1/60\,000$ with which d must be multiplied to obtain W_{ab}/p is made up of a factor of $\frac{1}{10}$ representing ν^2 ; a factor of $\frac{1}{2}$ for the energy expression, a factor of $\frac{1}{3}$ being the shape factor for a hemispherical particle; another factor of $\frac{1}{3}$ corresponding to the σ_{yp}/p ratio; and, finally, a factor of $1/333$ representing the maximum elastic strain. Owing to the successive multiplications, the small W_{ab}/p distance is amplified into a quantity, namely, the wear particle diameter, which takes on considerable size.

It should be noted that the quantity W_{ab}/p has entered both into Eq. (6) and into Eq. (11). It is my belief that this quantity is an important parameter which governs a number of frictional phenomena. It, therefore, deserves close study.

EXPERIMENTAL VERIFICATION OF THE LOOSE WEAR FORMULA

In my earlier paper on the size of loose wear particles, I gave some data on the variations of the wear particle size produced by varying the mechanical properties of zinc as a result of heating it close to its melting point. It seemed worthwhile to confirm Eq. (11) more definitely by carrying out a comprehensive series of tests, and for these we used a wear tester in which a fixed annular specimen is pressed against another annular specimen which is mounted in the chuck of a lathe (Fig. 5). Wear fragments fall out of the sliding zone through slots in the annular specimens and are collected for later examination.

The first problem which arose was that of deriving

from each collection of wear particles a typical particle diameter, which could be substituted in Eq. (11). It was found most expedient in the case of most of the collections of wear particles to sort out the particles in a set of sieves, and to define an average particle as that particle which has all the particles heavier than it equal in weight to all those particles lighter than it. The "diameter" of the particle is assumed to be the opening of a sieve which would just let the particle through. In most cases, repeat wear tests give values of the average particle diameter as defined above which differ by 10% or less from previously obtained values.

In the case of the smallest particles, the average particle size had to be determined by inspection of the fragments in a microscope, but this method is of inherently smaller accuracy.

RESULTS OF LOOSE WEAR PARTICLE EXPERIMENTS

After satisfying ourselves that the average wear particle diameters were reproducible and substantially independent of load and speed of sliding, we carried out tests on a wide variety of metals and a few nonmetals. The results are shown in Fig. 6, which plots the observed average fragment diameter against the W/p ratio. The straight line has been drawn to fit Eq. (11) and seems to fit the data quite satisfactorily. It may be noted that the average wear rate was found not to be a simple function of hardness, and some soft metal combinations gave very low wear rates. However, each wear particle was then very large.

It might be argued that it is more satisfactory to use Eq. (10) than Eq. (11), which is based on it, and constitutes a fairly severe approximation. However, Eq. (11) is so much more convenient to use, since the hardness can be readily measured while the elastic limit in compression cannot, that we have decided to use it wherever possible.

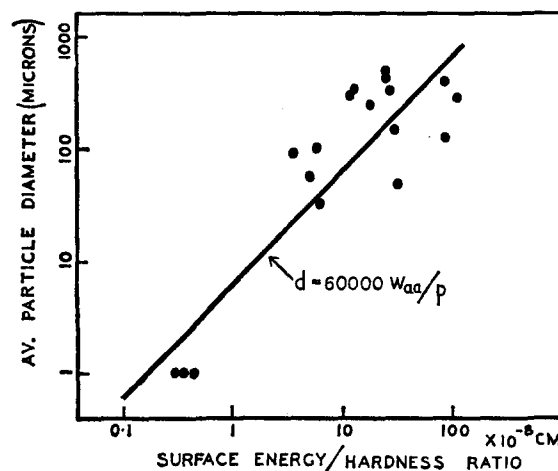


FIG. 6. Plot of average wear particle diameter against W_{aa}/p ratio for metallic and nonmetallic particles. Load 2000 g, speed 11 cm/sec.

A peculiar situation was observed with some metals, of which low-carbon steel was typical. During sliding, there were intervals, often lasting for several hours, when most of the wear debris was in the form of steel fragments of an average diameter $60\ \mu$, and then periods of several hours during which oxide particles of diameter $1\ \mu$ were formed. The same behavior was observed with aluminum. Apparently, Eq. (11) applies to the oxide and to the metal, in each case for values of W_{aa} and p characteristic of the material making up the wear debris. There is evidence to suggest that the metal/oxide ratio is determined partly by chance (random effects), partly by moisture content of the air, and partly by the load and speed.

When a lubricant is used, the fragments observed are much smaller in size than for the unlubricated metals, suggesting that W_{aa} is also smaller.

All the observations discussed above were obtained with like sliding combinations. When unlike metals are slid together, the wear particles are smaller. For example, when copper is slid on mild steel, the average wear particle size of the copper is $100\ \mu$, as against $240\ \mu$ for copper on copper. This suggests that W_{ab} is smaller in about the same ratio.

This experiment in which copper is run against a low-carbon steel allows us to make a comparison of the sizes of loose and of adherent wear particles, since the size distribution of adherent copper fragments on a low carbon steel surface has been previously published.⁹ The adherent fragments, average diameter $45\ \mu$, are smaller in diameter by a factor of about 2, and hence smaller in volume by a factor of about 8. This suggests that a number of adherent copper fragments form on top of each other, before a fragment is formed which is sufficiently large to be removed. Direct observations of such particle accumulation have been described by Kerridge and Lancaster¹⁰ and by Cocks.¹¹

DISCUSSION

In this paper, we have proposed that the work of adhesion W_{ab} is an important characteristic of surfaces in sliding contact, and that it usually enters quantitatively into friction and wear expressions as the ratio W_{ab}/p or some equivalent formulation. Illustrations of the utility of this ratio have been drawn from the fields of friction and of wear.

It is of interest to note that the concept of work of adhesion has a long and successful history in the theory of lubrication. As early as 1925, Bachman and Brieger¹²

postulated that the lubricant with the largest work of adhesion against a metal surface made the most effective lubricant. This was later interpreted to mean that a large work of adhesion implied strong lubricant-to-surface bonds, and thus good resistance to the removal of the lubricants by shear during sliding. However, our hypothesis would regard a high work of adhesion of a lubricant against a surface as being important in that it leads to a low work of adhesion when two lubricated surfaces are placed in contact.

Besides friction, wear, and lubrication, the work of adhesion concept would seem to be applicable to studies of adhesion. Indium and, to a lesser extent, lead adhere at room temperature; these are, of the metals stable in air, the ones with the highest W_{aa}/p ratios. Other metals must be heated till they soften before they adhere well,¹³ and this suggests again that a minimum W/p ratio is required. Recently, Rarey and Tabor¹⁴ have shown that the strength of adhesion of various organic materials against ice correlates positively with their work of adhesion. One of the reasons these authors give for dismissing this relationship is that the strength of adhesion and the work of adhesion do not vary in direct proportion. However, Eq. (5) in this paper shows that this kind of behavior may readily arise.

Finally, we must draw attention to one complicating factor; namely, the so-called size effect, whereby specimens of small volume appear to be stronger—often much stronger—than specimens of normal size. This effect has been ascribed to the low probability of finding enough dislocations in the small specimens. As far as surface energy effects are concerned, this means that relations such as Eq. (10) should be written in the form

$$d = 60EW_{ab}/\sigma_{yp}(d). \quad (12)$$

Depending on the way the yield strength varies with fragment size, this equation may have solutions over a wide range of fragment diameters. This effect helps to explain the range of sizes of wear particles observed during one experiment.

ACKNOWLEDGMENTS

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⁹ E. Rabinowicz, Proc. Phys. Soc. (London) **66**, 929 (1953).

¹⁰ M. Kerridge and J. K. Lancaster, Proc. Roy. Soc. (London) **A236**, 250 (1956).

¹¹ M. Cocks, J. Appl. Phys. **29**, 1609 (1958).

¹² W. Bachmann and C. Brieger, Kolloid-Z., spec. No., 142 (1925).

¹³ F. P. Bowden and G. W. Rowe, Proc. Roy. Soc. (London) **233**, 429 (1956).

¹⁴ L. E. Rarey and D. Tabor, Proc. Roy. Soc. (London) **A245**, 184 (1958).