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THE INFLUENCE OF SOLID STATE COHESION OF METALS AND NON-METALS ON THE MAGNITUDE OF THEIR ABRASIVE WEAR RESISTANCE

ASHOK K. VIJH
Hydro-Quebec Institute of Research, Varennes, P. Q. (Canada)
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Summary

The abrasive wear resistance of metals and inorganic non-metals has been shown to be determined by the magnitude of their bonding. It appears that the solid state cohesion (*i.e.* the strength of bonding) of materials provides a more general correlation with their abrasive resistance than previously suggested properties such as hardness and the modulus of elasticity.

Introduction

Wear of materials can proceed by several processes such as the abrasive, adhesive, fatigue and corrosion–mechanical mechanisms. Abrasive wear is caused by the friction between a material under stress and a harder body or grain such as a mineral or an ore. Khruschov has recently published a comprehensive review [1] of the mechanisms of abrasive wear in which he seeks to correlate the magnitudes of the abrasive wear of materials with some of their fundamental properties. He succeeds in relating the abrasive wear of materials with some of their mechanical properties, *e.g.* hardness and modulus of elasticity. A further step in the exploration of the fundamental aspects of abrasive wear is to examine its possible correlation with some physico-chemical properties (*e.g.* electronic structure, solid state cohesion and the quantitative magnitudes of bonding etc.) of the materials. The object of the present paper is to investigate some of these matters.

Abrasive wear of metals

Although vague qualitative references to the possible correlation between the relative abrasive resistance ϵ of metals and the strength of bonding in them have been made in the literature [1], the idea has not been quantified. The metal–metal bond energy b(M–M) in a metal may be calculated from the equation [2]

TABLE 1

Relative wear resistance ϵ, metal–metal bond energy b(M–M) and the melting points of metals

Metal	M. p. (°C)	Relative wear resistance ϵ	b(M–M) (kcal)
Pb	327	0.9	7.8
Mg	650	2.7	6.0
Sn	232	2.8	12.1
Cd	321	3.0	8.9
Al	660	4.0	12.5
Zn	420	6.3	10.4
Au	1063	7.0	14.6
Cu	1084	9.3	13.5
Ag	960	7.5	11.4
Pd	1550	10.6	15.0
Zr	1852	12.0	24.4
Pt	1769	12.5	22.7
Ni	1452	18.0	16.9
Co	1490	20.0	16.9
Fe	1535	20.5	16.6
Mn	1244	27.0	11.7
Cr	1875	30.0	23.6
Rh	2250	35.0	22.1
Mo	2610	39.0	39.6
Be	1283	45.0	13.0
W	3410	60.0	50.5

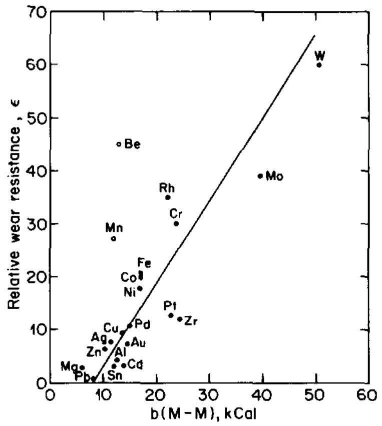
The abrasive resistance values ϵ are from ref. 1.
The b(M–M) values have been calculated using eqn. (1) with the ΔH_S and CN values from refs. 3 and 5, respectively.

$$b(\text{M–M}) = \frac{2(\Delta H_S)}{\text{CN}} \tag{1}$$

Here, ΔH_S is the heat of sublimation of the metal and CN is its bulk coordination number. The ϵ values of various metals as reported by Khruschov [1] are presented in Table 1, together with their b(M–M) values calculated from eqn. (1) and their melting points [3]. A plot of ϵ *versus* b(M–M) for various metals (Fig. 1) gives a reasonably good straight line correlation, although the points for Mn and Be do not fall near the line for reasons which are not clear at the present time. The rest of the metals, however, show a rather good correlation between ϵ and b(M–M) and the slope of the line is given by

$$\frac{\Delta \epsilon}{\Delta b(\text{M–M})} = 1.5 \tag{2}$$

For every kilocalorie increase in the M–M bond energy, the relative abrasive resistance increases by approximately 1.5 units. It is important to note that this graph (Fig. 1) contains metals covering a complete spectrum of properties, *e.g.* it includes non-transition sp metals (Pb, Cd, Al, Zn, Sn, Mg



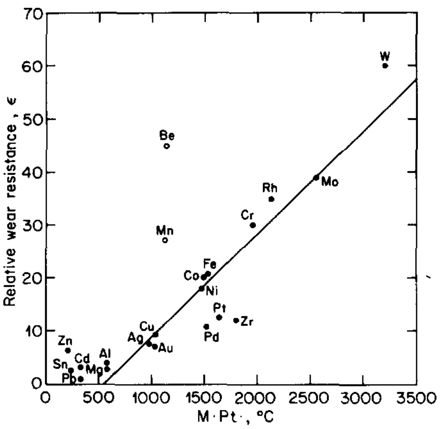


Fig. 1. A plot of relative wear resistance ϵ *vs.* the metal–metal bond energy b(M–M), for metals; for the data and their source references see Table 1.

Fig. 2. A plot of the ϵ values of metals *vs.* their melting points; for the data and their source references see Table 1.

etc.), transition metals with unfilled d-bands (Fe, Ni, Co, Pt, Rh, Pd etc.) and the metals (Ag, Cu, Au) which constitute a borderline between the sp and the transition metals. The range also includes extremely hard as well as extremely soft metals.

Although b(M–M) values represent the quantitative measure of the solid state cohesion in metals, another general index of the magnitude of this cohesion is the melting point. A plot of ϵ against the melting points of the metals (Fig. 2) again shows that higher ϵ values are associated with higher solid state cohesion in metals and vice versa.

In the light of Figs. 1 and 2 it is of interest to explore whether the proposed considerations are also valid for non-metals, more specifically the inorganic minerals reviewed by Khruschov [1].

Abrasive resistance of inorganic materials

Minerals are inorganic materials with a wide range of composition and complexity. In inorganic materials the bonding, ideally, can be either ionic or covalent. The magnitude of ionic bonding may be represented by the lattice energy whereas the bonding in covalent materials may be denoted by the bond energy [2]. Real materials, however, are seldom either purely ionic or purely covalent. An index of solid state cohesion valid for real inorganic materials, which almost always exhibit mixed ionic–covalent bonding, is the melting point [2]. A plot of the ϵ values of inorganic materials against their melting points (Table 2) shows that higher relative abrasive resistances are associated with higher melting points (Fig. 3).

From these correlations (Figs. 1 - 3), one may conclude that the abrasive resistances of metallic and non-metallic materials are determined by a fundamental physico-chemical quantity, namely, the magnitude of bonding in them.

TABLE 2

Relative wear resistance values and melting points of some materials

Compound	M. p. (°C)	Relative wear resistance ϵ
(Fluorite) CaF_2	1360	2.1
(Corundum) Al_2O_3	2045	27.5
(Quartz) SiO_2	1610	15.5
(Calcite) $CaCO_3$	825 (d)	1.6
(Gypsum) $CaSO_4$	>200	0.4
NaCl	801	1.05
WC	2870	155
(Apatite) $Ca_3(PO_4)_2 \cdot CaF_2$	975	3.2
Si	1410	16.7
Ge	937	10.4

(1) The ϵ values are from ref. 1.
(2) The m.p.s are from ref. 6.
(3) The m.p. of gypsum is greater than 200 °C and calcite decomposes at 825 °C.
(4) The m.p.s of minerals refer to the pure compound of which the mineral is constituted; for apatite the m.p. of $Ca_3(PO_4)_2$ has been used.
(5) The m.p.s of some other minerals discussed by Khruschov are not available.

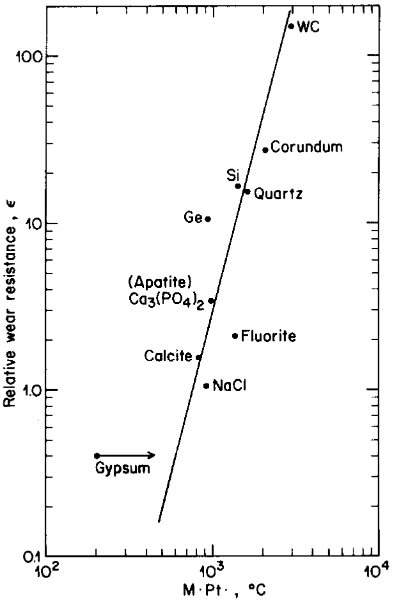


Fig. 3. A plot of the ϵ values for some non-metals *vs.* their melting points; for the data and their source references see Table 2.

Discussion

The main point in the previous literature, reviewed by Khruschov [1], is that the abrasive resistance ϵ increases with increasing hardness (or some related property such as the modulus of elasticity) of the material. A critical examination [4] of this viewpoint shows several shortcomings. For example, the addition of impurities and alloying elements in the pure metals does not enhance wear resistance in proportion to the increase in hardness. This suggests that hardness *per se* is not the principal factor determining the magnitude of ϵ in metals but that the correlation between ϵ and hardness perhaps arises because of the dependence of the latter on some other fundamental property. It is suggested that this fundamental property is the b(M–M) of metals. It should be added that the presence of slight impurities in metals will not change the magnitude of the b(M–M) values in any appreciable way, whereas the hardness will be enhanced significantly by the addition of impurities. Hence the suggested correlation between b(M–M) and ϵ values will explain the experimental fact that addition of impurities does not substantially augment the measured ϵ values in metals.

Again, it has been pointed out [4] that hardness does not describe the wear resistance of very ductile, extendable or brittle materials. The criterion of solid state cohesion suggested here is applicable to the complete range of hardness values of metals and non-metals (Figs. 1 - 3). It would appear, therefore, that the fundamental property determining the ϵ values of metallic and non-metallic materials is the solid state cohesion and not the hardness.

Acknowledgement

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