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ABRASIVE WEAR ENERGY

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Abstract. This paper estimates wear energy for different abrasive wear types. The tests conducted proved that of the wear processes, two-body abrasion requires the least energy. On pure metals, the minimum relative wear energy reaches about 10. Based on the value of the relative wear energy of a pure metal or annealed steel at certain test conditions, we can evaluate the relative energy values for any other metallic material. It is valid for two-body and three-body abrasion and erosion processes provided that the hardness of an abrasive exceeds that of a metal.

Key words: indentation energy, specific wear energy, relative wear energy, metals.

1. INTRODUCTION

As a result of systematic analysis of tribological processes, an awareness has developed of these phenomena to be considered useful as energy transformation processes. Determination of energetic dependences which connect friction and wear parameters may be used as a basis for materials selection as well as for developing methods of the calculation of the wear of machine parts. Specific work or energy W obtained as a ratio of the energy E to the volume of the removed material V is proposed as a criterion of wear resistance

$$W = E/V\,. \qquad (1)$$

The energy W is estimated to be between 10 and 100 J/mm^3 for the mechanical abrasive wear [1, 2]. A detailed study of energetic dependences in various abrasive wear processes has led to some interesting information about energy consumption, as will be discussed later.

2. TWO-BODY ABRASIVE WEAR

The specific energy in two-body abrasion is expressed as [3]

$$W = Fs/V, \qquad (2)$$

where F is friction force and s is sliding distance. Experimental results have shown that the dependences of W and the relative wear resistance X on the initial hardness of tested materials are similar, i.e. they correlate [3]. Nevertheless, specific energy has an advantage over the relative wear resistance usually employed, facilitating the evaluation of different wear processes. In these tests, the W ranging from 2.3 to 66 J/mm^3 increased with the increase in material hardness. Friction coefficients in sliding metals against abrasive paper are within a narrow range of $f = 0.45$–0.6. As a result, the reciprocal compensation of strength and deformation factors influences the wear process provided the Vickers hardness HV of the materials is between 170 and 870 [4]. On this basis, the W values can be obtained for commercially pure metals and steel 45 through the wear data in [5]. Figure 1a shows the results of calculations, where the points represent the results discussed in [3]. The specific energy W is proportional to the hardness of pure metal and carbon steel in the annealed state (lines 1–3, Fig. 1a). For quenched and tempered steel, the W grows linearly with the increase of hardness (line 4, Fig. 1a). Consequently, at the same value of friction coefficients, the dependences W–HV are quite analogous to the

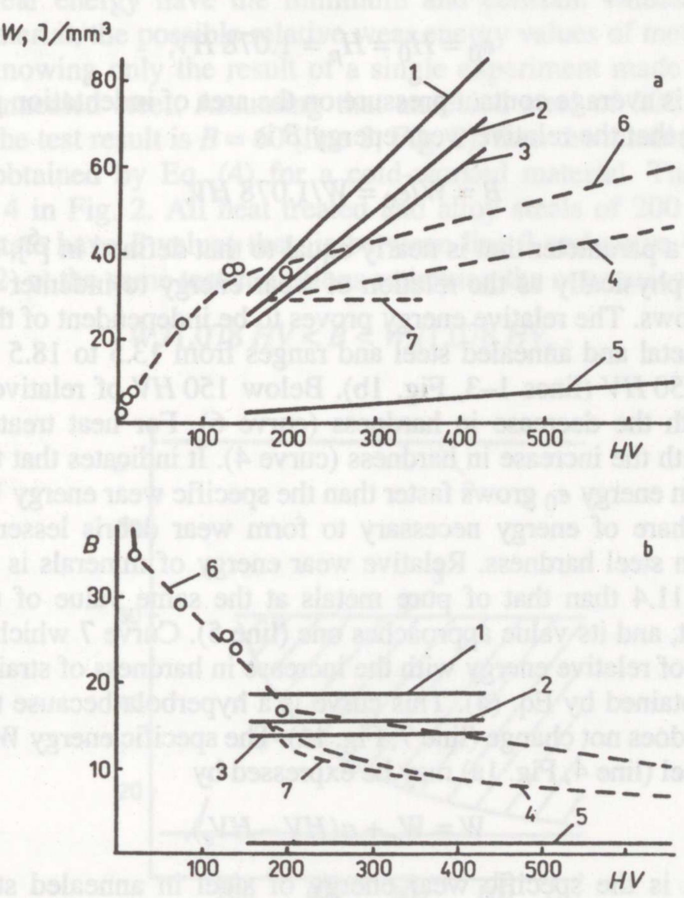

Fig. 1. Specific energy W (a) and relative wear energy B (b) of metals and minerals as a function of Vickers hardness: 1–3 – pure metals: 1 – $f = 0.6$, 2 – $f = 0.5$, 3 – $f = 0.45$; 4 – steel 45, $f = 0.5$; 5 – minerals, $f = 0.5$; 6 – metals; 7 – steel 45 in cold hardened state, $f = 0.5$.

dependences of relative wear resistance-hardness. If the hardness is smaller than 150 *HV*, the specific energy is greater than the proportional dependence of *W*–*HV* (curve 6, Fig. 1a). It is caused by an increase in friction coefficients with a decreace in hardness within the range which increases the wear energy *E* in Eq. (1). Friction coefficients in [3] show a tendency to decrease with the increase of hardness and are somewhat higher than in [4]. Apparently, this is caused by different test conditions and properties of the abrasive papers. Line 5 in Fig. 1a of the specific energy for minerals has a slope which is less by a factor of 11.4 than line 2 for pure metals at the same friction coefficient. It is because chemical bonds of metals and minerals differ [5]. Line 7 in Fig. 1a shows independence of *W* on *HV* of cold hardened steel 45.

A non-dimensional specific energy or relative wear energy *B* is defined as a ratio of specific energy to material hardness. It is a well-established fact that, for very sharp cutting tools, the specific energy is nearly equal to the hardness of a workpiece [6]. Volume hardness H_0 may be used as a measure of material resistance to static penetration of indenter. It is equal to the average specific energy e_0 necessary for material displacement from the indentation [7, 8]

$$e_0 = H_0 = H_p = 1.078\,HV, \tag{3}$$

where H_p is average contact pressure on the area of indentation projection. Assuming that the relative wear energy *B* is

$$B = W/e_0 = W/1.078\,HV, \tag{4}$$

we obtain a parameter that is nearly equal to that defined in [6], but is well-grounded physically as the relation of wear energy to indenter penetration energy shows. The relative energy proves to be independent of the hardness of pure metal and annealed steel and ranges from 13.5 to 18.5 if hardness exceeds 150 *HV* (lines 1–3, Fig. 1b). Below 150 *HV* of relative energy, *B* grows with the decrease in hardness (curve 6). For heat treated steel, *B* lessens with the increase in hardness (curve 4). It indicates that the specific indentation energy e_0 grows faster than the specific wear energy *W*. It means that the share of energy necessary to form wear debris lessens with the increase in steel hardness. Relative wear energy of minerals is lower by a factor of 11.4 than that of pure metals at the same value of the friction coefficient, and its value approaches one (line 5). Curve 7 which shows the reduction of relative energy with the increase in hardness of strain hardened steel is obtained by Eq. (4). This curve is a hyperbola because the specific energy *W* does not change (line 7, Fig. 1a). The specific energy *W* of the heat treated steel (line 4, Fig. 1a) may be expressed by

$$W = W_e + a(HV - HV_e), \tag{5}$$

where W_e is the specific wear energy of steel in annealed state, *a* is a coefficient, *HV* is Vickers hardness number, and HV_e is Vickers hardness number of steel in the annealed state. Based on Eq. (4), the equation of hyperbola for relative energy of heat treated steel was obtained.

$$B = [W_e + a(HV - HV_e)]/1.078\,HV = W_e/1.078\,HV + $$
$$+ [a(HV - HV_e)]/1.078\,HV. \qquad (6)$$

The first term in Eq. (6) expresses the relative energy of a strain-hardened metal. Consequently, B of heat treated steel is always higher than that of the same steel in the strain-hardened state.

Testing over a large range of loads, lengths of travel, sliding speeds and abrasive particle sizes of two-body abrasion shows that for pure metals, relative wear energy has a minimum value of 10 and can increase by an order of magnitude (Table). However, below hardness 30 HV energy B may be higher (Fig. 1), but this range has little practical importance. Filing needs lower energy B than abrasive paper (Table). In practice, B lies between the lines $B = 10$ and $B = 100$ for pure metals and annealed steels (lines 1 and 2, Fig. 2), and its location depends on testing conditions. In theory, metals may have the minimum value of $B = 1$ when all the material displaced is removed in the form of microchips [6]. Nevertheless, due to size effect occurring when the abrasive particle size falls below 100 μm, the values of B may exceed 100 [11]. As the relative wear resistance and specific wear energy have the minimum and constant values for cold-worked material, the possible relative wear energy values of metals can be obtained knowing only the result of a single experiment made with pure metal or annealed steel. Assuming that annealed steel of 200 HV is the case, and the test result is $B = 60$ (line 3, Fig. 2), then the minimum values of B are obtained by Eq. (4) for a cold-worked material. The result is hyperbola 4 in Fig. 2. All heat treated and alloy steels of 200 HV in the annealed state have B values that lie between line 3 and curve 4 (hatched area, Fig. 2) at the same test conditions satisfying the expression

$$W_e/1.078\,HV < B < W_e/1.078\,HV_e\,. \qquad (7)$$

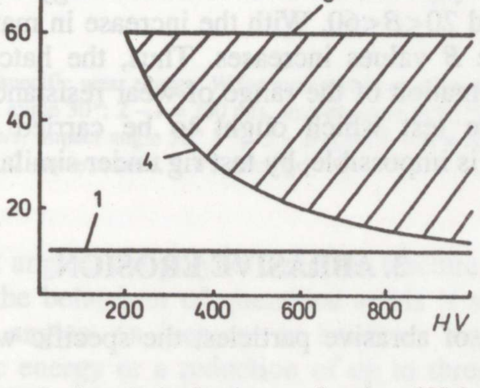

Fig. 2. Relative wear energy B of two-body abrasion as a function of Vickers hardness: 1–3 – pure metals and annealed steels, 4 – strain hardened steel.

Two-body abrasive wear parameters of metals

Material	Specific energy W, J/mm^3		Relative energy B	
	min	max	min	max
Abrasive paper [9]				
Al	3	25	10	83
Cu	9	40	11	95
AISI 1020	21	112	10	56
Mo	29	166	10	55
W	42	333	10	79
Abrasive paper [10]				
Bi	4.7	5.6	48	57
Zn	25	34	77	103
Gray cast iron	20	28	11	15
Brass	18	25	18	25
Smooth file in unworking direction [10]				
Bi	2.4	3	24	30
Zn	11	14	35	43
Gray cast iron	8	11	4	6
Brass	6	8	6	8
Smooth file in working direction [10]				
Bi	1.5	1.8	15	18
Zn	4.4	5.2	13	16
Gray cast iron	7	9	4	5
Brass	4	5	4	5
Abrasive paper [3]				
Pure metals	2.3	36	24	53
Steels	35	66	8	17

For example, at 600 *HV*, the relative wear energy of steels may change by three times and $20<B<60$. With the increase in material hardness, the range of possible *B* values increases. Thus, the hatched area in Fig. 2 facilitates the estimation of the range of wear resistance of metals on the result of a single test which ought to be carried out under service conditions or if it is impossible, by test rig under similar conditions.

3. ABRASIVE EROSION

With a stream of abrasive particles, the specific wear energy can be calculated by [12]

$$W = mv^2/2V, \qquad (8)$$

where m is mass of abrasive particles and v is velocity of abrasive particles. The dependence of specific energy on Vickers hardness of commercially pure metals obtained on the basis of experimental data [13–15] is shown in Fig. 3. In general, the specific energy increases with increasing hardness and is lower at small impact angles, reaching its maximum at normal impact. In the case of an impact velocity of 82 m/s and at 20° impact angle, W is comparable with specific energy in two-body abrasion (line 3, Fig. 3 and line 1, Fig. 1a), if the abrasive is an angular glass grit. In the stream of quartz sand, the specific energy is markedly higher than in the stream of glass grit because sand particles are round, and therefore the share of plastic deformation in wear mechanism rises. Strain hardening and repeated thermomechanical treatment have little or no influence on the wear resistance of metal in impact erosion [16, 17]. Therefore at small impact angles, it is possible to plot the similar range of possible relative energy values of metals like for two-body abrasion by testing one pure metal or annealed steel only (Fig. 2). Practically there are almost the same limits of $B = 10$ (line 5, Fig. 3) and $B = 100$ (line 6, Fig. 3). Nevertheless, the upper value of B may prove to be higher than $B = 100$.

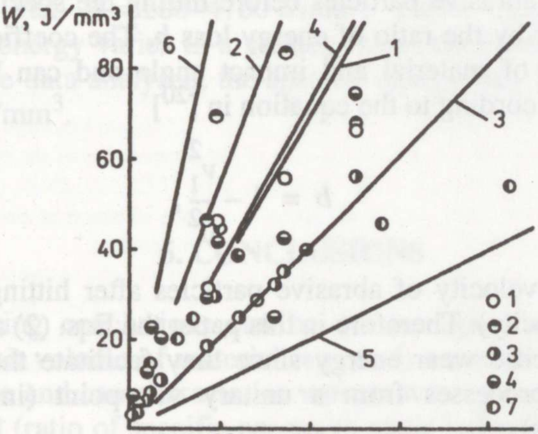

Fig. 3. The variation in specific wear energy W for pure metals as a function of their hardness HV: 1 – $v = 250$ m/s, impact angle 30°; 2 – $v = 250$ m/s, impact angle 90° [15]; 3 – $v = 82$ m/s, impact angle 20°; 4 – $v = 82$ m/s, impact angle 90° [14]; 5 – $B = 10$; 6 – $B = 100$; 7 – $v = 136$ m/s, SiC, impact angle 20° [13]. 1, 2 – quartz sand; 3, 4 – glass grit.

At high impact angles, the polydeformation fracture prevails in a wear mechanism, and the behaviour of quenched steels is somewhat different from that at low angles: an increase in hardness may lead to a slight change of specific energy or a reduction of up to three times. Some test points have significant deviations from lines 2 and 4 which show the proportional relationship between W and HV (Fig. 3). Nevertheless, the data in [18] show that relative wear resistance of pure metals grows nearly linearly with the increase in hardness. Tests were carried out with quartz sand and $v = 37$ m/s. Taking into consideration the results in [14–15, 18], we can plot the range of possible relative energy values of metals at high impact angles. Tests should be carried out with metals of intermediate hardness (Cu, Ni, and Fe) or annealed steel. It determines the upper limit of B (line 3, Fig. 2). The lower limit of B (line 4, Fig. 2) is determined by Eq. (4) as a first approximation. For quenched steel, lower limit of B may be smaller than line 4 shows, and in the case of linear relationship between W and HV according to Eq. (5), it may be obtained by Eq. (6) where the coefficient a becomes a negative quantity which can be determined by the test only. Thus, quenching for the working conditions at high impact angles is not recommended.

Comparable values of specific energy W in two-body abrasion and abrasive erosion were described in [19] for chromium steels. In [19] somewhat different expression for calculation of specific wear energy is used [20]

$$W = \frac{bmv^2}{2V}, \tag{9}$$

where b is the ratio of energy loss (ratio of energy absorbed by a specimen to the energy of abrasive particles before hitting the specimen). The Eqs. (8) and (9) differ by the ratio of energy loss b. The coefficient b depends on the hardness of material and impact angle and can be obtained by special testing according to the equation in [20]

$$b = 1 - \frac{v_1^2}{v^2}, \tag{10}$$

where v_1 is the velocity of abrasive particles after hitting the specimen (rebounding velocity). Therefore in this paper the Eqs. (2) and (8) are used to calculate specific wear energy since they facilitate the evaluation of different wear processes from a unitary viewpoint (initial energy of abrasive particles).

4. THREE-BODY ABRASIVE WEAR

Three-body abrasion involves loose particles which may turn around as they contact the wearing surface. Misra and Finnie have observed that the effects of most variables on two-body abrasion, three-body abrasion and erosion are almost the same for these three different wear processes [21]. The appearance of the eroded surface for low values of impact angle has some similarity to that for two-body abrasion where cutting or scratching is the apparent mechanism of removal. By contrast, high angle erosion and three-body abrasion appear to involve repeated indentations and extensive surface roughening by plastic deformation. This process produces extruded material which is vulnerable to removal by subsequent particles. Wear rate for three-body abrasion is less by more than an order of magnitude as compared to two-body abrasion due to smaller loading of contact and a possibility of rotating abrasive particles. In some cases, the data from one wear process can be used to predict the behaviour of metal parts in another wear process. The linear relationship between the wear resistance and hardness of heat treated steels has been observed by Valdma [22] for three-body abrasion. Hence, it may be concluded that for these three wear processes, the possible relative wear energy values for metals can be evaluated by testing pure metal or annealed steel only (Fig.2).

5. SPECIFIC WEAR ENERGY LIMITS

In sliding abrasive paper or file across a workpiece surface, specific wear energy changes from 1.5 to 333 J/mm^3 (Table). The values of the specific energy for material removal during both the initial and the steady state regimes are in the range of 40–6000 J/mm^3 [23]. At impact abrasive wear, the data in [5] show that energy W = 60–2100 J/mm^3 and the data in [24] prove that W = 280–4700 J/mm^3. These examples show that specific wear energy varies to a greater extent than assessed in [1, 2]. On the basis of the data analysed, the specific energy may be in the range of W = 1–6000 J/mm^3.

6. CONCLUSIONS

The following conclusions can be drawn. Specific wear energy W (energy per unit volume of material removed) correlates with the relative wear resistance and can characterise various wear processes. The relative wear energy B (ratio of specific energy to static indentation energy e_0) of pure metals and annealed steels depends little on hardness at some abrasive wear processes (two-body abrasion, three-body abrasion, and erosion at low impact angle). The level of relative energy depends on wear process and test conditions being the least for two-body abrasion (in that process usually B = 10–100). For two-body and three-body abrasion and erosion of metallic materials, possible values of relative wear energy can be obtained only from a single test of pure metal (Cu, Ni, Fe are desirable) or annealed steel carried out in given test conditions. The specific wear energy may vary in the range W = 1–6000 J/mm^3. It is valid for abrasive wear processes provided that hardness of an abrasive exceeds that of a metal.

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ABRASIIVSE KULUMISE ENERGIA

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On vaadeldud kulumisenergiat abrasiivse kulumise puhul. Katsed näitavad, et kulumine abrasiivpaberi toimel on kõige vähem energiat nõudev protsess, kusjuures suhtelise kulumise energia minimaalväärtus on puhaste metallide puhul ligikaudu 10. Etteantud kulumistingimustel osutub võimalikuks ühe puhta metalli või lõõmutatud terase katsetamisega kindlaks määrata metalsete materjalide suhtelise kulumise energia võimalike väärtuste vahemik. See kehtib abrasiivpaberi, abrasiivvahekihi ja abrasiiverosiooni mõjul toimuva kulumise kohta juhul, kui abrasiivi kõvadus ületab materjali kõvaduse.