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Structure-energy criterion of the wear resistance of metals and alloys with allowance for the stiffness of the stressed-strained state of the surface

A structure-energy model of material wear is proposed. The results of studying a new criterion of wear resistance in the form of the limiting deformation power density are presented. Experimental data on the wear resistance of a wide variety of materials are generalized using the proposed criterion for the conditions of hydroabrasive (HA), impactabrasive (IA), and cavitation erosion. The dependence of the wear resistance criterion and its invariants on the stiffness coefficient of the stressed-strained state of the surface of a material is demonstrated.

In the case of dynamic (microimpact) external loading (for the relative deformation rates 10^2-10^4 l/s) the energy transfer in the wearing volumes of the material occurs due to the propagation of the waves of elastic and plastic deformations and is related to the motion of the discontinuity surface of the functions. For a heterophase material the energy flow across the discontinuity surface has the form:

$$\left[p^{(k)}\theta^{(k)}v^{(k)}\left(\frac{1}{2}v_1^{(k)}v_1^{(k)}+U^{(k)}\right)\right] = -\left[\theta^{(k)}v_1^{(k)}p^{(k)}\right] \quad (1)$$

where $p^{(k)}$ is the density of the particles of the kth component of the material, kth is the projection of the velocity $v_1^{(k)}$ of the kth component of the material onto the x_1-axis, $v^{(k)}$ is the relative velocity of the particles of the heterogeneous material in the discontinuity plane, which is normal to the discontinuity surface, $\theta^{(k)}$ is the concentration of the kth component, $U^{(k)}$ the internal energy of the panicles, $p^{(k)}$ is the projection of the surface forces acting on the corresponding particles on the normal to the discontinuity plane element; subscripts *k* indicate summation over *k* (*k* = 1,2,3, ..., N), i.e. over the number of components, and the brackets denote the jumps in the values of the functions across the discontinuity surface.

In the case of the critical density of the energy flux of a plane longitudinal deformation wave confined within the material volume V, the volume fails under the:

$$V_N = \text{const}_1 \frac{\theta^{(k)} p^{(k)} \left(v_1^{(k)}\right) V v^{(k)}}{\theta^{(k)} \left(E_{sp}^{(k)} - E_0^{(k)}\right) v^{(k)}} N f(N) \tag{2}$$

which follows from equation (1).

Here const_1 is a constant that takes into account the fraction of external energy spent for increasing the internal energy of the material, $E_{sp}^{(k)}$ is the critical density of the stored energy which is sufficiently large to destroy the volume V, E_0 is the energy intensity of the material spent prior to the start of wear, *N* is the number of external actions on the volume V and f(N) is a kinetic function related to the distribution of external pressure pulses. If thermal effects arc ignored, then:

$$\text{const}_1 = \frac{\Delta E_{sp}}{E_{BH}} = \frac{G_s^{(1)}}{\frac{1}{2}(\theta G_S e^2)^{(2)} + \frac{1}{2}(\theta \tau_S e)^{(2)} + (\theta \tau_S)^{(1)} \Delta e + \frac{1}{2}(\theta G_S)^{(1)} \Delta e^2} \tag{3}$$

where E_{sp} is added energy, $\Delta e = e^{(1)} - e^{(2)}$ is the difference between the deformations of the base and more elastic emanations of the second phase, $G_S^{(1)}$ is the shear modulus of the base, $\tau_S^{(1)}$ is the shear stress of the base, and $G_S^{(2)}$ and $\tau_S^{(1)}$are the analogous quantities for the other phase.

The denominator of relation (3) indicates that the elastic stresses in the stiff particles of emanations grow with increase in the elastoplastic deformations of the base. If the stresses in the base differ from those in the emanation particles on the phase boundaries, then either relative slipping sets in or cleavage occurs in the second-phase particles and there appear microscopic cracks.

For an impact external loading the velocities and $v^{(k)}$ and $v_{kp}^{(k)}$should be viewed as the vectors of the velocity with which the waves of elastic and plastic deformations travel. The solution of the equation of motion of an element of the material:

$$\frac{\partial \sigma}{\partial e} \frac{\partial e}{\partial x} = f'(e) \frac{\partial^2 u}{\partial x_1^2} = p \frac{\partial^2 u}{\partial t^2}$$

(where the stress-strain relation has the form σ = f(e), *u* is the displacement of an element along the x_i-axis, $f'(e) = \partial\sigma/\partial e$ is the local slope of the dependence $\partial(e)$, and $e = \partial u/\partial x$) yields for an infinite rod:

$$v_1 = e_{el} c_0 \text{ and } c_0 = (E/p)^{1/2} \tag{4}$$

where v_1 is the elastic deformation rate, c_0 is the elastic wave speed, and E is the modulus of elasticity.

The plastic deformation wave front travels with a velocity $c_{pl} = [f'(e)/p]^{1/2}$, $e = e_1$, for an impulse load velocity:

$$v_1 = \int_0^{e_1} c_{\mathrm{pl}} \mathrm{d}e = \int^{e_1} (f'(e)/p)^{1/2} \mathrm{d}e \qquad (5)$$

At the instance of failure of the material when f'(e)-> $\sigma \to \sigma_b$, e_1->e_{kp}, and $c_{pl} = 0$, the impact velocity becomes critical: $v_1 = v_{kp}$. The critical impact velocity is reached when the waves cannot any longer transfer the larger part of their energy, thus restraining the deformation, and increasing the stiffness. The theoretical value of v_{kp}, may be found from (5) by means of graphical integration of the dependence $c_{pl} = f(e)$ on the stress-strain diagram.

The critical deformation rate of a heterogeneous material is determined by the expression:

$$v = \int_0^{e_{\mathrm{kp}}} \left(\frac{1}{p_{y}} \sum_{k=1}^{n} \theta^{(k)} \frac{2E^*_{\mathrm{pl}}}{\Delta e^2_{\mathrm{pl}}} \right)^{1/2} \mathrm{d}e \qquad (6)$$

where:

$$p_{y} = \sum_{k=1}^{N} \theta_{y}^{(k)} p_{y}^{(k)}$$

is the mass density of the material at the clastic limit level, E^*_{pl} is the energy of deformation hardening, and Δe_{pl} is the deformation of the material in a plastic wave.

Expression (6) characterizes the component of the critical impact velocity related to the plastic deformation of at least one component of the heterogeneous material. Generally, the critical velocity must comprise the elastic, equation (4), and plastic, equation (6), components of deformation, i.e.:

$$v_{\mathrm{kp}} = v_{\mathrm{el}} + v_{\mathrm{pl}} = \frac{\left(\theta_p^{(k)} p_p^{(k)} - \theta_0^{(k)} p_0^{(k)}\right) c_0}{\theta_p^{(k)} p_p^{(k)}} + \int_0^{e_{\mathrm{kp}}} \left(\frac{1}{p_y} \sum_{k=1}^{N} \theta^{(k)} \frac{2E^*_{\mathrm{pl}}}{\Delta e^2_{\mathrm{pl}}} \right)^{1/2} \mathrm{d}e \qquad (7)$$

where subscript *0* refers to the undisturbed state of the material, and subscript *p* characterizes the deformation of the hardening phase emanations which are more elastic than the base.

By analogy with (7), the energy of elastoplastic deformation of a heterogeneous material includes the energy of elastic compression and shear deformations:

$$E_{\mathrm{el}}^{(k)} = \frac{1}{2} \sum_{k=1}^{N} \theta^{(k)} K \Delta e^2 + \frac{1}{3} \sum_{k=2}^{N} \theta^{(k)} \sigma_{\alpha}^{(k)} \Delta e \qquad (8)$$

where K is the modulus of volume compression, $\sigma_{\alpha}^{(\pi)}$ are associated stresses in the planes normal to the direction of the front of a (plane) shock wave, and Ae is the elastoplastic deformation) and the energy of hardening:

$$\left(E_{\mathrm{pl}}^{*}\right)^{(k)} = e_{\mathrm{pl}}^{(1)} - \frac{2}{3}\theta^{(1)}\sigma_{T}^{(1)}\Delta e_{\mathrm{pl}} + A \tag{9}$$

where $\sigma_T^{(1)}$ and $e_{pl}^{(1)}$ are, respectively, the yield limit and the specific energy of the material's matrix hardening for a plastic deformation Δe_{pl}, and A is the specific energy of interaction between them base and the second-phase emanations.

By (1) and (7)-(9), the critical deformation power density, represented in (2) by the product $E_{sp}^{(k)}\, v_{kp}^{(k)} \sim W_{kp}^{*}$,

$$W_{\mathrm{kp}}^{*} = \left(W_{\mathrm{kp}}^{*}\right)_{\mathrm{el}} + \left(W_{\mathrm{kp}}^{*}\right)_{\mathrm{pl}} = p^{(k)}\theta^{(k)}v_{\mathrm{el}}^{3} + p^{(k)}\theta^{(k)}v_{\mathrm{pl}}^{3} = \theta^{(k)}E_{\mathrm{el}}^{(k)}v_{\mathrm{el}}^{(k)} + \theta^{(k)}\left(E_{\mathrm{pl}}^{*}\right)^{(k)}v_{\mathrm{pl}}^{(k)} \tag{10}$$

Expressions (6)-(10) indicate that the critical parameters v_{kp}, E^{*}_{sp}, and W^{*}_{kp} are related to a complex of physico-mechanical characteristics and structural parameters of the deforming (wearing) materials. The experience (Pogodaev and Ezhov, 1991; Pogodaev and Shevchenko, 1984; Sushchenko, 1989; Lzirsen-Badse and Mathew, 1969 and elsewhere) shows that, depending on the structure of the materials and the loading conditions (the scale, the specific features of the material's deformation within the contact zone, etc.), the critical parameters may be represented by a number of invariants either composed of the work of plastic deformation under the rigid conditions of IA wear of plastic austenitic materials or representing the energy of failure which takes into account the microcrack geometry and the failure viscosity K_{IG} for the wear of very hard fusing materials under analogous conditions.

Integrating (7) and substituting the result in (10), we arrive at the equation:

$$W_{\mathrm{kp}}^{*} = \theta^{(k)}E_{\mathrm{el}}^{(k)}\left(\frac{2E_{\mathrm{el}}^{(k)}}{p_y}\right)^{1/2} + \theta^{(k)}\left(E_{\mathrm{pl}}^{*}\right)^{(k)}\left[\frac{2\left(E_{\mathrm{pl}}^{*}\right)^{(k)}}{p_y}\right]^{1/2} \tag{11}$$

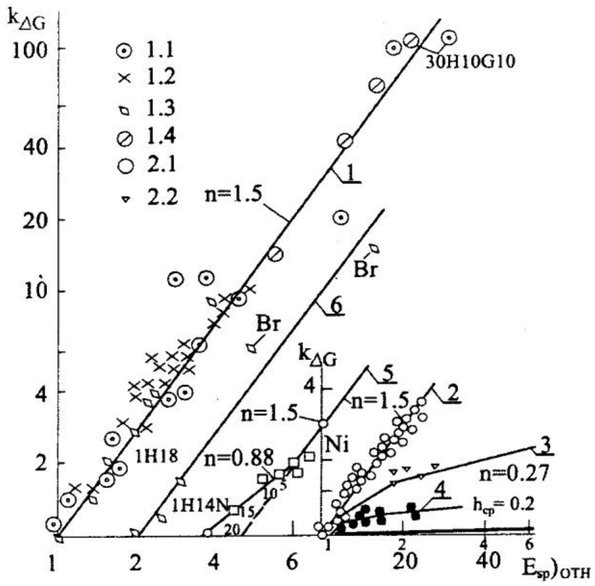
according to which the two-termed energy criterion proves to depend on the specific energies of elastic and plastic deformations raised to power 3/2. The experimental data indicate that the transition from impact to *quasistatic* deformation results in expressions (10) and (11) degenerating into energy relations with $n \leq 3/2$.

The operability of criterion W_{kp}^{*} is estimated by comparing the theoretical dependences with experimental data obtained for various kinds of wear of severed groups of metallic materials.

It is obvious that for an individual material, the more so, materials belonging to different classes, the values and relative contribution of the components $(W_{kp})_{el}$ and $(W_{kp}^{*})_{pl}$ to the wear-resistance criterion W_{kp}^{*} may prove to be rather different depending on the deformation rate, scale effects, the stiffness of the stressed-strained state of the surface, the unhardening effect of the working medium, and several other factors. All this creates unavoidable difficulties in comparing the wear resistance with the properties of the materials over a rather wide range of the variation in the structure of the materials and the conditions of external loading. The proposed structure-energy approach allows systemizing the results of our studies as well as the experimental data (Bogachev and Mints, 1959; Hobbs, 1967; Mousson, 1967; Korotushenko and Bogachev, 1973; Vinogradov et al., 1982; Sorokin, 1972; Tenenbaum, 1966; Stechishin, 1983; Kaczynski and Tchoulkine, 2002) (Figure 1).

The comparative tests of materials in cavitation wear were conducted on a magnetostrictive installation UZDN-2T in fresh and artificial sea water for the concentrator amplitude of 33 μm, frequency of 22 kHz, and the distance between the stationary specimen and the concentrator of 0.5 mm. The coefficient of the relative wear resistance of the specimens, $k_{\Delta G}$, was determined by measuring the loss of mass. The HA wear of the materials was measured in an open channel, where the specimens were rotated with a linear velocity of 3.1-11.2m/s. The working mixture consisted of fresh water and quartz sand (with the grains 0.3-0.6 mm across) in the proportion 50/50 and 30/70 by volume, respectively. LA wear was studied on specimens; in the form of cylinders 10 mm in diameter. During the tests the bases of the cylinders collided repeatedly with a massive anvil covered with abrasive cloth 14A32NM, which remained stationary at the instant of impact. In carrying out the comparative tests of the materials the energy of an impact was equal to 0.53 J.

In the process of HA and IA wear the stiffness coefficient of the stressed-strained state of the surface of the materials, II, was determined using the Tsvetkov's technique (Pogodaev et al., 1997) according to which II = $(\sigma_x + \sigma_y + \sigma_z)/\sigma_i$ = 1.651n(3,450/HV), where σ_x, σ_y, and σ_z are the principal stresses acting along the axes X, Y, and Z, respectively; σ_i is the stress intensity, and HV is the Vickers hardness measured in megapascals.



Notes: 1 - steels of classes P, M, A, and F, Ni-Al bronzes subjected to cavitation erosion; 2 - structural alloy steels, bronzes, and brasses subjected to hydroabrasive wear (and steel U7 subjected to impact-abrasive wear); 3 - structural alloy steels subjected to impact-abrasive wear; 4 - steel SAE 1040 sliding over abrasive cloth [4]; 5 and 6 - steels and nonferrous metals in (3-20)% solutions of NaCl; 1.1 - magnetostrictive vibrator, the reference specimen made of steel Ni28 [5]; 1.2 - magnetostrictive vibrator, the reference specimen made of bronze Si30 [6]; 1.3 - Venturi tube, the reference specimen made of steel 45Mn2 [7]; 1.4 - UES, the reference specimen made of SCh28 [8]; 2.1 - hydroabrasive wear, the reference specimen made of steel 25L; 2.2 - impact-abrasive wear, the reference specimen made of steel U7 [9-11]; 5 - magnetostrictive vibrator, (3-20)% solutions of NaCl, the reference specimen made of steel 25L [12]; and 6 - magnetostrictive vibrator, (3-20)% solutions of NaCl, the reference specimen made of steel 25L

In plotting the dependences $k_{\Delta\sigma}$ $(E_{sp})_{отн}$ Figure 1 the relative energy capacity of metals and alloys was determined as

$$(E_{\text{sp}})_{\text{OTH}} = \left[\frac{\left(E_{\text{sp}}\sqrt{E_{\text{pl}}}\right)_i}{\left(E_{\text{sp}}\sqrt{E_{\text{pl}}}\right)_r}\right]^{2/3} = \left[\frac{(E_{\text{sp}}v_{\text{kp}})_i}{(E_{\text{sp}}v_{\text{kp}})_r}\right]^{2/3} = \left(\frac{W^*_{\text{kp}_i}}{W^*_{\text{kp}_r}}\right)^{2/3} \quad (12)$$

where subscripts *i* and *r* denote the characteristics of the material under study and the reference material, respectively.

In estimating the cavitation-erosion resistance of austenitic nickel steels suffering phase transformations in the process of wear, relation (12) took into account not only the deformation hardening but the period of internal energy accumulation too.

The approximation of experimental data by exponential dependences (curves 1, 2, 5, and 6 in Figure 1) yields a single dependence

$$k_{\Delta G} = \mathrm{const}_2 (E_{\mathrm{sp}})^{3/2}_{\mathrm{OTH}} \quad (13)$$

where the experimental constant depends on the working medium and the class of tested materials. The practical result (13) well agrees with the theoretical model represented by Equations (10) and (11).

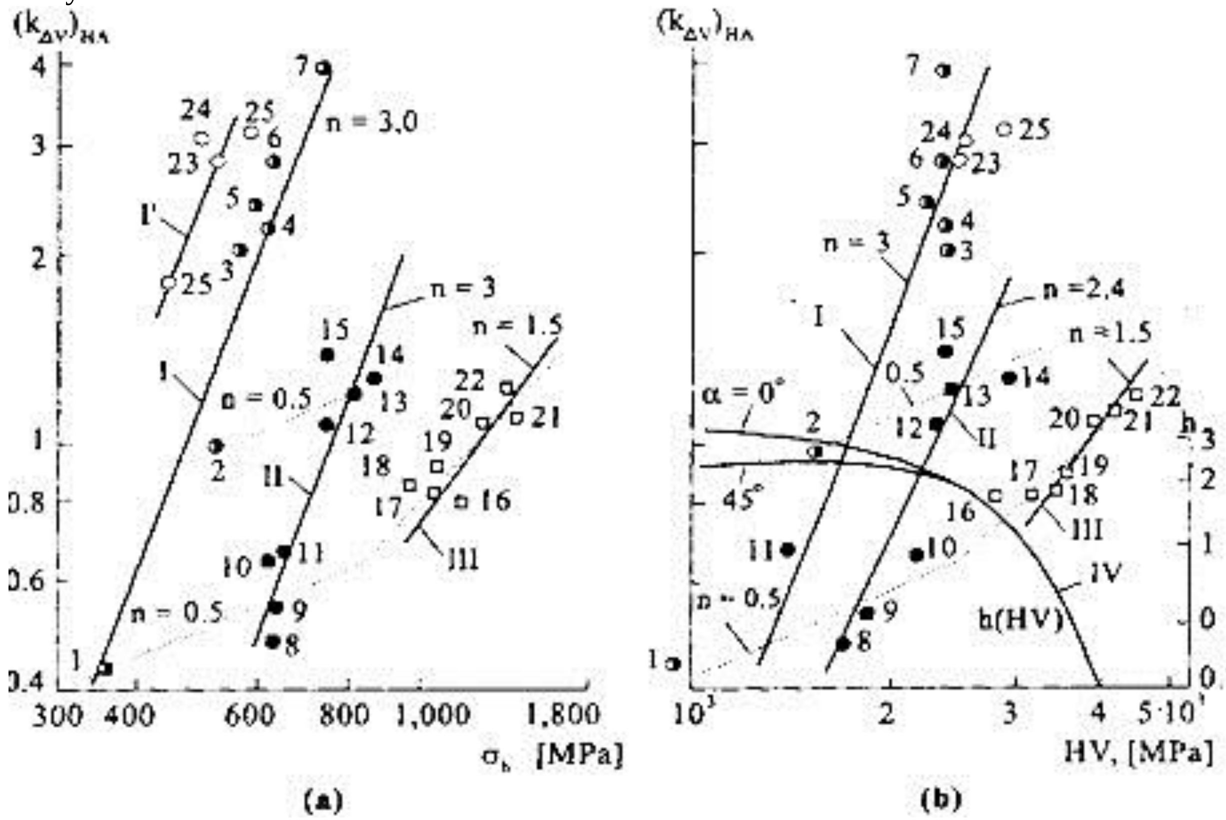
A reduction in the exponent of $(E_{sp})_{OTH}$ in (13) from 1.5 to 0.88 in the case of cavitation wear of nickel in a (3-20 percent) water solution of NaCl (curve 5 in Figure 1) is related to the unhardening effect of the corrosion-active medium on the surface of the metal. A still greater reduction in the exponent (to 0.7-0.2) under the conditions of IA wear for an impact energy of 0.53 J (curve 3 in Figure 1) and in sliding over an abrasive surface by analogy with a Kh4-B machine (curve 4 in Figure 1) is related to an excessive plasticity margin of the studied structural steels (Table I). The highest resistance to IA wear was demonstrated by steel 155Mn5Cr2SiL subjected to hardening and low-temperature tempering, the relative reduction of whose cross-sectional area was 6 percent and corresponded to the transition from viscous to brittle destruction on the macroscale. Since, under the conditions of medium-intensity HA wear of steel specimens towed through an open channel with a velocity of 3.1 m/s, normalized steel 130Mn7Cr2Avl- with a still lower relative reduction of the cross-sectional area (of approx. 1.5 percent) proved to be the most wear resistant, it was concluded that the scale of the loading and the regularities governing the revelations of the brittleness of the material's surface layer cm the macro-, submicro-, and mesoscopic levels are of special importance. In this connection, the establishment of quantitative relations between the criteria of the strength and brittleness of materials and coatings on the macro- and mesoscopic scales seems to be extremely significant. However, at present, there are no conclusive answers to the above questions, especially so as far as the effects of the stiffness of the stressed-strained state of the surface layers of materials and the external loading rates for various kinds of wear are considered.

Table I and Figure 2 present the data obtained by testing various steels and nonferrous alloys in HA wear. Using microstructural criteria, the experimental points on the plotted dependences of wear resistance on the ultimate strength and hardness may be crowded near several curves. Cubic dependences of wear resistance on the ultimate strength and hardness

Table I The data obtained by testing various steels
and nonferrous alloys in HA and IA wear

	Material	$(k_{\Delta r})_{HA}$	$(k_{\Delta r})_{IA}$	$(\Pi)_{HA}$	$(\Pi)_{IA}$
Number in Figures 2-4					
1	Armco-iron (tempering)	0.44	-	3.5	-
2	Steel 25L (cast)	1.0	1.0	3.1	1.39
3	130Mn7Cr2AVL (n + h)	2.11	1.76	-	-
4	115Mn6Cr2SiNiDVBT (n + h + lt)	2.24	-	-	-
5	130Mn7Cr2AVL (n + h)	2.45	1.53	-	-
6	130Mn7Cr2AVL (n + h)	2.92	1.81	-	-
7	130Mn7O2AVL	4.0	1.66	-	-
8	Bronze Neva-70 (cast)	0.48	0.69	2.9	1.16
9	Bronze Kumanal (cast)	0.54	0.55	2.8	1.07
10	Titanium-base alloy (cast)	0.65	0.9	2.4	0.75
11	Bronze A9Fe4Ni4L (cast)	0.68	0.54	3.05	1.48
12	110Mn13 (austenited at 1,050°C, water)	1.1	1.93	2.3	0.66
13	08Cr15Ni4DMoL (cast)	1.27	0.99	2.1	0.82
14	08Cr15Ni4DMoL (cast)	1.31	1.16	1.3	0.25
15	12Cr18Ni10Ti (cast)	1.41	2.2	1.11	0.60
16	40CrMnSiMoNiDVL (n + ht + h + ht)	0.82	1.21	0.8	0.1
17	40CM MoNiDL	0.85	1.23	-0.5	-0.15
18	20CM MoNiDL (n + ht + h + ht)	0.85	-	1.35	-
19	19CrB/MoDVL (h + ht)	0.93	-	-0.2	-
20	38CrMnSiMoNiDL (n + ht + h + ht)	1.12	2.07	-0.8	-0.05
21	19CrNi/MoDVL (h + ht)	1.15	-	-1.5	-
22	19CrNi3MoDVL (h)	1.23	-	-2.0	-
23	130Mn6Cr2SiNiDL (n + h + ht)	2.92	-	-	-
24	150Mn5Q2SiNiDVBTsL (n + h + ht)	3.17	-	-	-
25	25155Mn5Cr2SiL(n + h + ht)	3.2	2.64	-	0.3
Numbers in Figures 1-4					
26	27130 Mn7Cr2AVL (n)	1.81	1.18	-	-
Numbers in Figure 3					
27	Steel 25D (n + ht)	0.95	0.79	-	-
28	1Cr18Ni9Ti (austenited at 1,050°C, air)	1.45	3.75	-	-
29	1Cr14NiD (hardened in air + ht)	1.59	2.8	-	-
30	0Cr17Ni3Mn4D2Ti (austenited at 1,050° air)	1.92	3.6	-	-
31	0Cr16Ni4Mn9ADV (cast)	1.8	6.4	-	-
Notes: Thermal treatment: n – normalization, h – hardening, lt - low-temperature tempering, ht - high-temperature tempering, and a - austenization					

Figure 2 Wear resistance of metals exposed to HA wear versus the mechanical properties, (a) $k_{\Delta r_{HA}}$ versus the ultimate strength, (b) $k_{\Delta r_{HA}}$ versus the Vickers hardness. II(HV) is the dependence of the coefficient of the stiffness of the stressed-strained state of the surface of metals on the hardness for the HA flow attacking the wearing surfaces at angles of 45° and nearly zero



Notes: (a) $k_{\Delta r_{HA}}$ versus the ultimate strength, (b) $k_{\Delta r_{HA}}$ versus the Vickers hardness. II(HV) is the dependence of the coefficient of the stiffness of the stressed-strained state of the surface of metals on the hardness for the hydroabrasive flow attacking the wearing surfaces at angles of 45° and nearly zero

strength and hardness are valid for materials with $\sigma_b \tau \leq$ 800 MPA $\leq$ 3,000 MPA (curves I'-II), while harder alloy steels (curves III) arc better described by the dependences

$k_{\Delta V}$ = const$_3 \sigma_b^n$ and $k_{\Delta V}$ = const$_4$ HV^n (14)

where n = 3.0...1.5 for various groups of the materials.

Rewriting (14) in the form:

HV = (const$_2$/const$_3$)$^{1/n}$, σ_b = const$_4$ σ_b, (15)

we deduce that const$_4$ is different for different groups of steels (Table II).

In passing from steels with a preeminently austenitic structure to unproved steels, i.e. from cluster I'-I to cluster III, $const_4$ decreases, according to (15), by approximately a factor of 1.5, and the coefficient of the relative wear resistance decreases by approximately threefold in accordance with the expression

$$k_{\Delta G} \cong const_5 (HV/\sigma_b)^3 \qquad (16)$$

where $const_5$ = 1/26.3 for the upper sequence of steels whose austenitic structure passes gradually to bainite, and $const_5$ = l /55 for the lower sequence of materials (Figure 2): 25-2-(8-l1) which alongside with austenitic and perlitic steels includes cooper-base alloys.

Expressions (14) and (16) agree with the theoretical formulas (10) and (11). Moreover, the latter allow explaining the cause for the difference in the wear resistance of the studied groups of materials: it is due to a change in the relation between the elastic and plastic components of the deformation power density, i.e. in a change in the relation between the terms on the right-hand sides of Equations (10) and (311). In fact, the wear resistance of the materials decreases with decrease in $const_4$ in (15) or the ratio HV/σ_b, in (16). According to (10), this results in a decrease in the component $(W^*_{kp})_{pl}$ and the criterion W^*_{kp} as a whole, despite a certain growth of the component (W^*_{kp}) el due to an increase in the ultimate strength of the materials.

The said reduction in the exponents of σ_b and HV for the steels of cluster III in formulas (14) may be explained by the fact that the microscopic value of v_{kp}, either remains constant or decreases for improved steels with $\sigma_b \geq 800$ MPa. Hence, in accordance with (10) and (14), the criteria W^*_{kp} and $k_{\Delta G}$ are quadratic functions of σ_b (HV) for v_{kp} = const, and for $v_{kp} \sim [\sigma \text{ (HV)}]^{1/2}$

$$k_{\Delta V} \sim \sigma_b^{1,5} \sim HV^{1,5} \qquad (17)$$

Table II Sizes of consts for different groups of steels

Line in Figure 2	I’	I	II (steels and copper-base alloys)	III
Const$_4$ in (15)	4.8	3.7	3.2	3.0
Pre-eminent structure	Austenite + carbides		Austenite + martensite + ferrite	Bainite, martensite + bainite

which coincides with the experimental dependences for the steels comprising cluster III (Figure 2).

It is also beyond doubt that both the wear resistance of materials and the character of the dependences $k_{\Delta V}$ (σ_b, HV) are affected by the stiffness of the stressed-strained state of the wearing surfaces. The concentration of the materials near the dashed lines in Figure 2 is determined by the correlation between their wear resistance and the coefficient of the stressed-strained state stiffness $k_{\Delta V}(\Pi)$. We see that the lower dashed curves, which may be viewed as dependences v_{kp} (HV), for $\sigma_b \approx 820$ MPa and HV $\gg$ 2,200 - 2,400 MPa break due to a change in the stiffness of the stressed-strained state of the surface, i.e. due to a transition from tension to shear and compression by analogy with the dependence Π(HV) (Figure 2(b), IV). In so doing, the relations:

$$k_{\Delta V} \sim W^{*}_{\mathrm{kp}} \sim E_{\mathrm{sp}} v_{\mathrm{kp}} \sim v^{3}_{\mathrm{kp}} \sim \left(\sqrt{\frac{\mathrm{HV}}{p_y}}\right)^{3} \sim \mathrm{HV}^{1.5} \sim \sigma_b^{1.5} \qquad (18)$$

prove to be valid for improved steels on the basis of (10) and (12). As a result, relations (18) coincide with the earlier derived relations (17).

The point of inflection on the dashed curve for the indicated values of the parameters characterizes changes in both the stiffness of the stressed-strained state and the scales of deformation of the surface layers of the materials.

Since, the transition to a milder stressed-strained state is accompanied by an increase in the plasticity of metals, relation (18) and, especially so, the exponent n = 1.5 correspond to a concrete situation in the group of improved steels due to a favorable variation in the coefficient II, namely, an increase in the wear resistance of steels due to an increase in the energy ratio:

$$k^{*}_{\Delta G} \cong \frac{W^{*}_{\mathrm{kp}} - \left(W^{*}_{\mathrm{kp}}\right)_{\mathrm{el}}}{\left(W^{*}_{\mathrm{kp}}\right)_{\mathrm{el}}} = \frac{E_{\mathrm{pl}} c_0 k_{\phi} (2\Delta\sigma e_p/E)^{1/2}}{E_{\mathrm{el}} c_0 \sigma_b / E}$$

where c_0 is the speed of sound in metals, $k_{ф}$ is a coefficient that takes the shape of the curve σ(e) into account in the plastic region, $\Delta\sigma$ is the deformation hardening of metals in the process of wear, e_p is the failure deformation, and E is the modulus of elasticity that takes into account the anticipatory growth of the steels plasticity accompanied by an increase in their strength.

The established rather abrupt transition from a stiff stressed-strained state of the wearing layers of metals to a milder one corresponds to the points of inflection on the plotted dependences of wear resistance on the mechanical characteristics (hardness, strength, plasticity, the work of deformation) of the surface. The said points of inflection may be seen on the dependences $k_{\Delta G}(E_{sp})_{\text{отн}}$ shown by curves 3 and 4 in Figure 1.

In greater detail, the effect of the stiffness of the stressed-strained state on the wear resistance of materials subjected to HA and IA wear is shown in Figure 3(a). The character of the dependences $k_{\Delta V}$ (П) is analogous to that of curves 3 and 4 in Figure 1 and the widely known dependence e(HV) obtained by testing materials in abrasive wear on the Kh4-B installation. Rather mild pure metals and nonferrous alloys with П = 3.5...2 are seen to cluster around the steeply ascending exponential dependence I: $k_{\Delta V}$=2.7exp (-0.545П). Unlike them, the dependences $k_{\Delta V}$(П) of harder steels characterized by a milder stressed-strained state of the surface (П = 1.5...2), branch off (curves I and II) from the main line: $k_{\Delta V}$ = 1.2 exp(-0.125П) and $k_{\Delta V}$ = 0.95 exp (-0.125П) for IA and HA wear, respectively. The vertical position of the branches on Figure 3 depends on the external action energy level.

A comparison of the coefficients of relative wear resistance of materials exposed to HA, IA, and cavitation wear (($k_{\Delta V}$)$_{\text{HA}}$. ($k_{\Delta V}$)$_{\text{IA}}$ and ($k_{\Delta V}$)$_{\text{C}}$, respectively) also demonstrates a strong effect of the stiffness of the stressed-strairied state of thin wearing layers on the wear (Figure 3(b)). In this case there also exist the main line corresponding to plastic materials (pure metals, bronzes, brasses, and steels with structures A and A-F) and two branches (II and III) for materials in a milder stressed-strained state as compared with HA wear. The main line is described by the functional dependence:

$$(k_{\Delta V})_{\Gamma A} = 1.13(k_{\Delta V})_{\text{IA}}^{1.5} \quad (19)$$

and the branches II and III by:

$$(k_{\Delta V})_{\Gamma A} = 0.7(k_{\Delta V})_{\text{IA}}^{0.9} \quad (20)$$

and

$$(k_{\Delta V})_{\Gamma A} = 0.7(k_{\Delta V})_{C}^{1/3} \quad (21)$$

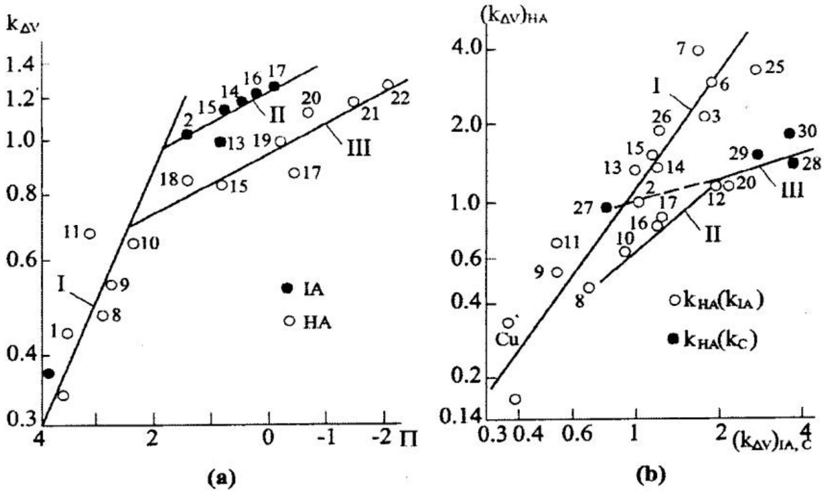
respectively.

The exponents appearing in equations (19)-(21) characterize the stiffness of the stressed-strained state of wearing surfaces. The mean coefficient of the stiffness of the stressed-strained state, II, is maximum for IA wear, smaller for HA wear, and still smaller for cavitation wear. In the latter case compressive stresses dominate in the thin surface layers of metals, thus creating the most favorable conditions for the use of very hard materials and coatings. Experiments showed that the acicular martensite structure is the most resistant to cavitation erosion. It may be assumed that the inflections on the dependences 3 and 4 in Figure 1 and the curves in Figure 3 are associated with a sudden change of the kinematic mechanisms of multiscale structural variations in deformed volumes of the materials and the corresponding transitions between activation-energy levels of elementary atom-molecular clusters.

Relations (19)-(21) allow estimating the resistance of materials to various kinds of wear, i.e. determining the resistance to cavitation erosion or IA wear for a known resistance to HA wear, and vice versa. However, using the relations in practical calculations, one has to take the scale level of the energy of external influence into account.

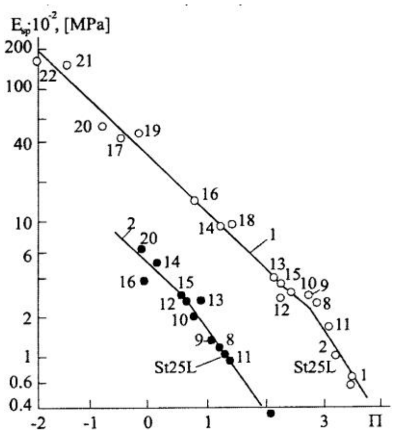
Thus, an increase in the stiffness of the stressed-strained state results in a reduction in the energy capacity and wear resistance of metals and alloys. A comparison of the position of the curves in Figures 3 and 4 shows that for П = const an excessive plasticity margin of alloys does not enhance their wear resistance, in particular, in the case of HA wear at the mesostructural level.

Figure 3



Notes: The effect of the stiffness of the stressed-strained state on the wear resistance of materials subjected to hydro- and impact-abrasive wear (a) and a comparison of the coefficients of relative wear resistance of materials exposed to hydroabrasive, impact-abrasive, and cavitation wear

Figure 4



Effect of the stiffness of the stressed-strained state of the surface layers of metals on the energy capacity in the presence of HA and IA wear (curves 1 and 2, respectively)

Note: The point numbers correspond to the ordinal numbers of materials in Table 1

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