FUNDAMENTAL RELATIONS OF EROSION KINETICS

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The relations between the kinetic parameters and the erosion characteristics of various materials subjected to the action of a particle stream are established for transition to the quasisteady phase.

We will consider the erosion of materials by a stream of particles as a process of surface degradation. In fact, under impact conditions the kinetic energy of the particle stream is dissipated within a certain surface layer of the target material in which numerous microcracks are formed and a damage accumulation process actively develops. As a result a damaged layer with characteristic erosion relief is created. The energy of formation of the damaged surface layer is expended on plastic deformation or brittle cracking as well as erosive degradation. At the same time, the rest of the target material remains virtually in its initial state.

The next important characteristic of erosive degradation as a damage accumulation process consists in its kinetic nature. This is primarily due to the fact that erosion by a particle stream always begins with mutually independent single impacts. As the target surface becomes saturated with craters, the erosive degradation becomes more intense. For example, in [1] it was shown experimentally that when glass particles interact with materials on the velocity range 1220-3660 m/sec the erosion becomes more intense as crater saturation of the surface develops. This is also probably responsible for the basic difference between the single and multiple erosion impact mechanisms. It also explains why in the initial phase even at a constant impact velocity the loss of mass per unit surface m_{er} is not a linear function of the incident particle mass per unit surface m_p. In Fig. 1 we have reproduced the experimental data of [2] showing the dependence of the unit mass loss m_{er} for cylindrical polycrystalline aluminum specimens on the integral mass m_p of impacting tungsten carbide particles of diameter $d_p = 1.58 \cdot 10^{-3}$ m. These results show that in the initial phase of the erosion process we get damage accumulation and, as already noted in [3], "degeneration" of the surface layer of the target material. Therefore the dimensionless erosion rate or relative erosion intensity, defined as

$$\bar{\bar{G}}_i = \frac{dm_{er(i)}}{dm_{p(i)}}, \tag{1}$$

at first monotonically increases. Subsequently, the erosion process enters the quasisteady phase in which the erosion rate is constant:

$$\bar{\bar{G}} = \frac{dm_{er}}{dm_p} = \frac{\Delta m_{er}}{\Delta m_p} = \text{const},$$

and the damage layer is displaced with the degraded surface of the body. In Fig. 2 we have reproduced the experimental data obtained by testing cylindrical specimens of D-16 material in a tungsten carbide (VK-6) particle stream. The volume particle concentration in the stream was $\rho_v = 0.12\text{-}0.22$ kg/m^3, which made it possible to avoid screening effects.

An analysis of the experimental data and the results of [3] show that the "threshold" value of the particle mass m_p^* at which the erosion rate becomes constant is related to the impact velocity V_p by the expression

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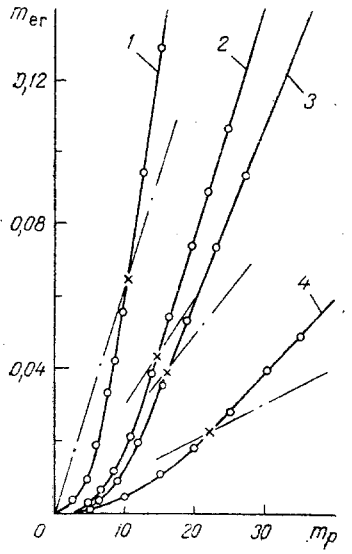

Fig. 1. Kinetic relations for the erosion of polycrystalline aluminum by tungsten carbide particles ($d_p = 1.58 \cdot 10^{-3}$ m) at various velocities: 1) V_p = 151 m/sec; 2) 126; 3) 117; 4) 101. m_{er}, m_p, kg/m^2.

$$\frac{1}{2} m_p^* V_p^2 = a, \tag{2}$$

the quantity a depending on neither the impact velocity nor the size and density of the particles. In practice, the quantity a is a constant for a given class of target material. Expression (2) has a definite physical significance, namely that the erosion process enters the steady state only after a certain "threshold" of stored energy, strictly defined for each class of material, has accumulated in the surface layer. In other words, the parameter a determines the energy capacity of the target material associated with the formation of a damaged surface layer δ_s and can serve as a reliable criterion for estimating the transition to the steady-state erosion regime. By analogy with the specific surface energy γ in fracture mechanics [4], the parameter a is the specific energy of the surface layer of the target material and, together with the effective enthalpy H_{er} [3], is an important energy characteristic of the material.

We will now consider the fundamental relations of the erosion kinetics of a material whose surface is exposed to a particle stream.

It is clear from Fig. 3 that if the incident particle mass m_p is less than m_p^*, whose value is determined from expression (2) in the form:

$$m_p^* = \frac{2a}{V_p^2}, \tag{3}$$

the erosion rate $\overline{\overline{G}}$ will not be a constant even when the particle impact velocity does not vary. The integral mass of the material removed during the approach to the steady-state regime m_{er}^* should depend on the efficiency of the particle stream η. In fact, at particle impact velocities $V_p < V_p^*$, where V_p^* is the critical velocity at which $\overline{\overline{G}} \sim V_p^2$, only part of the effective kinetic energy of the particles goes towards the erosion of the material. In this case to remove from unit surface of the body a mass m_{er}^* it is necessary to expend energy equal to

$$b = \frac{1}{\eta} m_{er}^* H_{er}, \tag{4}$$

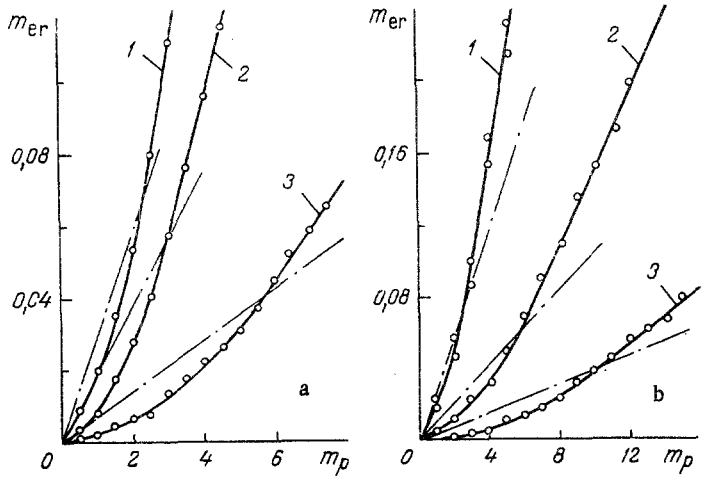

Fig. 2. Kinetic relations for the erosion of D-16 material by tungsten carbide particles with $d_p = 0.27 \cdot 10^{-3}$ m (a) at velocities of: 1) 480; 2) 420; and 3) 300 m/sec; and with $d_p = 0.55 \cdot 10^{-3}$ m (b) at velocities of: 1) 435; 2) 300; and 3) 220 m/sec.

which, like the parameter a, does not depend on the impact velocity V_p and is also a constant of the material. Then, as follows from (2) and (4), the ratio b/a is a certain universal constant of the kinetic process of erosion that does not depend either on the eroded material or on the parameters of the particle stream. However, expression (4) contains the efficiency of the particle stream η which is a function both of the impact velocity and of the size and density of the particles. In other words, η is a function of the parameters characterizing the energetics of the particle stream. It indicates what part of the specific kinetic energy of the particles goes toward the erosion of the body surface. The lower the velocity, the greater the part of the kinetic energy of the particles that can be dissipated in the form of energy of elastic vibration and deformation of the target material and ultimately converted into heat. Conversely, the higher the velocity V_p, the more the processes of destruction predominate over dissipation in the undamaged part of the target material.

An analysis of [1-3], in which the experimental information is presented in the form of kinetic relations, made it possible to establish that as the process approaches the quasi-steady state, the relation between the mass removed m_{er} and the mass of the incident particles m_p is described in general form by a second-order parabolic curve

$$m_{er(i)} = km_{p(i)}^2. \tag{5}$$

Then for the point N in Fig. 3 we can write

$$m_{er}^* = km_p^{*2},$$

whence there follows

$$k = \frac{m_{er}^*}{m_p^{*2}}. \tag{6}$$

From the simultaneous solution of (1) and (5) we obtain

$$\bar{\bar{G}}_i = \frac{dm_{er(i)}}{dm_{p(i)}} = 2km_{p(i)},$$

or, using (6),

$$\bar{\bar{G}}_i = 2m_{er}^* \frac{m_{p(i)}}{m_p^{*2}}. \tag{7}$$

If $m_{p(i)} \to m_p^*$, then $\bar{\bar{G}}_i \to \bar{\bar{G}}$. In this case (7) is written in the form:

$$\bar{\bar{G}} = 2\frac{m^*_{er}}{m^*_p}. \tag{8}$$

From (8) there follows the important conclusion

$$\frac{m^*_{er}}{m^*_p} = \frac{1}{2}\bar{\bar{G}}. \tag{9}$$

Expression (9) can be used as a check in constructing and analyzing the kinetic relations. In fact, if from the origin we draw a straight line at an angle $\alpha = \operatorname{arctg}(1/2\bar{\bar{G}})$, it should intersect the kinetic curve in the point N (see Fig. 3) with coordinates (m^*_{er}, m^*_p).

We have already noted that at a particle–surface interaction velocity equal to or greater than a certain critical value V^*_p the efficiency η takes a value equal to unity. In this case from (2) and (4) there follows

$$\frac{b}{a} = \frac{m^*_{er}}{m^*_p}\frac{2H_{er}}{V_p^2} = \text{const},$$

or, using (9) and the fact that $\bar{\bar{G}} = V_p^2/2H_{er}$, as shown in [5]:

$$b/a = \frac{1}{2}. \tag{10}$$

In the general case, for the steady-state erosion interval from (2), (4), (9), and (10) we obtain

$$\bar{\bar{G}} = \eta\frac{V_p^2}{2H_{er}}. \tag{11}$$

Substituting in (4) the value $b = 1/2a$, we find

$$m^*_{er} = \eta\frac{a}{2H_{er}}. \tag{12}$$

Clearly, in general m^*_{er} depends on the efficiency η of the particle stream and the erosion characteristics of the target material: H_{er} and a. When $V_p \geqslant V^*_p$ $\eta = 1$; then, as follows from (12); m^*_{er} takes its maximum value $m^*_{er} = a/2H_{er}$, which remains constant with further increase in V_p. This property can serve as a good criterion for estimating the transition to the postcritical regime in which $\eta = 1$ and $\bar{\bar{G}} \sim V_p^2$.

It should be noted that by formally letting V_p tend to infinity, from expression (3) we obtain $m^*_{er} \to 0$. From this it follows that the process may enter the steady-state regime without the formation of a damaged surface layer, which is obviously incorrect. The physical significance of this conclusion resides in the multiplicity of the action, i.e., in the difference between single and multiple impact. For the same interaction parameters, single-particle impact will always be less efficient from the erosion standpoint than the impact of a particle stream (in the absence of screening effects). Clearly, in the case of single-particle impact the particle strikes an undamaged surface, whereas in the case of multiple impact the individual particles strike material that has already been damaged. Consequently, $H_{er}(1) > H_{er}$. Physically, this can be attributed to the fact that as an energy characteristic of the erosion process the effective enthalpy for multiple impact H_{er} must reflect changes in the capacity of the target material for elastoplastic deformation or brittle cracking in the damaged surface layer δ_s as well as the effects associated with the interaction of the damage zones. In this connection, for distinguishing between single and multiple impact it is necessary to introduce the minimum value

$$m^*_p \geqslant (m^*_p)_{\min} \geqslant \frac{14}{3}\rho_p\frac{d_p^3}{(2\Delta d + d_p)^2},$$

which is determined by the maximum crater spacing Δd at which the damage zones still interact. For example, according to the data of [1], particle action on composites may be considered

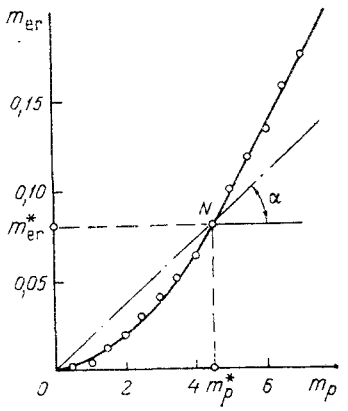

Fig. 3

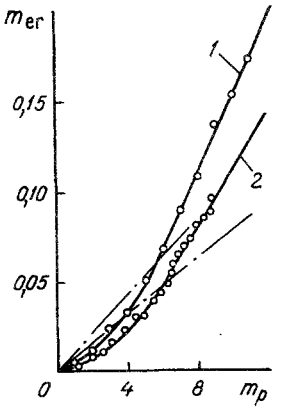

Fig. 4

Fig. 3. Erosion kinetics for D-16 material exposed to the impact of a tungsten carbide particle stream ($d_p = 0.785 \cdot 10^{-3}$ m) at a velocity $V_p = 340$ m/sec.

Fig. 4. Erosion kinetics for D-16 material exposed to the impact of tungsten carbide (1) and quartz sand (2) particle streams ($d_p = 0.55 \cdot 10^{-3}$ m) at a velocity $V_p = 300$ m/sec.

multiple-impact if the maximum spacing of the certers of impact Δd is not more than $(2.5\text{-}3)d_p$.

Below we consider how the relative erosion rate $\bar{G}$ and the principal kinetic characteristics (m^*_{er}, m^*_p, a) are affected by such parameters of the particle stream as the impact velocity, particle size, particle density, and volume particle concentration, as a factor controlling the screening effect.

From the erosion kinetics illustrated in Figs. 1 and 2 it is clear that an increase in impact velocity is accompanied by an increase not only in the relation erosion rate but also in the value of the parameter m^*_{er}. This shows that in the series of experiments in question of the erosion process lay in the precritical region, i.e., $V_p < V^*_p$. At the same time, the estimate for the values of the specific energy of the surface layer obtained in these regimes for both polycrystalline aluminum ($a = 0.12 \cdot 10^6$ J/m^2) and D-16 material ($a = 0.26 \cdot 10^6$ J/m^2) remained practically unchanged, and in all cases the ratio b/a was equal to 1/2.

An analysis of the experimental results presented in Figs. 2 and 3 show that the particle size may have a significant influence on the relative erosion rate $\bar{G}$. For example, at an impact velocity $V_p = 300$ m/sec increasing the particle size from $0.27 \cdot 10^{-3}$ m to $0.785 \cdot 10^{-3}$ m leads to an increase in the erosion rate by a factor of 1.5. However, the value of a, the specific energy of the surface layer, is not affected by changes either in the particle size or in the impact velocity.

The experimental investigation of the effect of particle density on the principal kinetic characteristics of the erosion process was carried out on cylindrical specimens of D-16 material exposed to the impact of tungsten carbide (VK-6) and quartz sand (SiO_2) particle streams ($d_p = 0.55 \cdot 10^{-3}$ m). In both series $V_p = 300$ m/sec. From the experimental data we constructed the kinetic relations reproduced in Fig. 4. Clearly, for the same sizes and impact velocities the tungsten carbide and quartz sand particles have different erosive actions. The relative rate of erosion of the D-16 material is $\bar{G} = 0.0215$ for tungsten carbide and $\bar{G} = 0.016$ for quartz sand. This is because in this series of experiments the VK-6 and quartz particle streams had different specific energetics, the erosion process falling in both cases in the precritical region. At the same time, the estimates for the specific energy of the surface layer obtained from the results of testing D-16 material in streams of particles of different density were equal. Thus, we experimentally confirmed the assumption that the specific energy of the surface layer does not depend on the particle density.

Finally, we will consider how the volume particle concentration affects the kinetic characteristics of material erosion. It is known that an increase in the volume particle concentration may lead to screening effects. In this case the erosion rate is reduced.

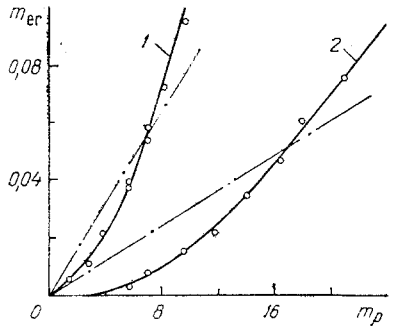

Fig. 5. Kinetic relations for the erosion of D-16 material by tungsten carbide particles (d_p = $0.27 \cdot 10^{-3}$ m) at a volume particle concentration ρ_v = 1.7 kg/m^3 and various impact velocities [1) 430 m/sec; 2) 290 m/sec].

The experiments were carried out on cylindrical specimens of D-16 material. As the particles we used tungsten carbide (d_p = $0.27 \cdot 10^{-3}$ m). The tests were performed at particle stream velocities of 290 and 430 m/sec, and the volume particle concentration was equal to ρ_v = 1.7 kg/m^3. From the results of the experiments we constructed the kinetic relations in Fig. 5. From a comparative analysis of this test series and the test series illustrated in Fig. 2a, in which the stream parameters differed only with respect to the value of the volume concentration (ρ_v = 0.12-0.22 kg/m^3), it is clear that screening has a strong influence on the kinetic characteristics, including the specific energy of the surface layer of target material. For example, at an impact velocity V_p = 300 m/sec screening led to an increase in the specific energy of the surface layer of D-16 material by a factor of more than 2, while the erosion rate was approximately halved; however, in these cases too the ratio b/a was equal to 1/2. The change in the estimated value of the specific energy of the surface layer is attributable to the fact that in the presence of screening, firstly, not all the particles in the stream interact with the surface of the specimen while, secondly, the average value of the particle–specimen interaction velocity decreases. Consequently, the presence of screening leads not only to a fall in the erosion rate but also to exaggerated values of the erosion enthalpy and the specific energy of the surface layer.

Thus, it can be stated that the specific energy of the surface layer of the target material is a constant that depends neither on the impact velocity nor on the size and density of the particles and determines the energy capacity of the target material when a damaged surface layer is formed by the action on a body of a particle stream.

NOTATION

m, mass; d, diameter; V, velocity; $\bar{\bar{G}}$, relative erosion rate; a, specific energy of the surface layer; H_{er}, effective enthalpy of erosion; $H_{er}(1)$, effective enthalpy of erosion for single impact; η, efficiency of the particle stream; ρ, density; and δ, thickness of the damaged surface layer. Subscripts: p, particle; s, target; *, critical threshold of the parameter; v, volume; er, erosion; and i, i-th value of the parameter.

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