# STABILIZATION OF THE EROSION PROCESS AFFECTING THE MATERIAL OF A BARRIER UNDER REPETITIVE IMPACT BY PARTICLES

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The initial period of erosion is analyzed in the case where a stream of solid or liquid particles impinges on various materials.

The action of a stream of particles on various materials is not simply the sum of individual impact processes involving each particle alone. A fundamental aspect of the difference is the change in the erosion rate $m_{er}$ even when the velocity $V_p$ of the stream remains constant. Experimental data taken from another study [1] indicate (Fig. 1) that the loss of mass $m_{er}$ by a nickel or lead plate depends on the integral mass $m_p$ of precipitated particles at either of the two different velocities $V_p$ = 82 and 29 m/sec.

These results demonstrate that there are definite values $m_p^*$ and $m_{er}^*$ beyond which the dependence of $m_{er}$ on $m_p$ becomes almost linear, i.e., the erosion process of the barrier material stabilizes. Considering that at a constant velocity $V_p$ of the particles their specific flow rate $G_p$ at the barrier surface also remains constant, one can interpret the integral mass $m_p$ of precipitated particles as being equal to $G_p$ multiplied by time $\tau$

$$m_p = G_p\tau. \tag{1}$$

Accordingly, one can introduce the concept of stabilization time $\tau_V$ for the erosion process and define it as

$$\tau_V = m_p^*/G_p. \tag{2}$$

In the technical literature, parameter $\tau_V$ is variously called "stabilization period," "wear-in time," etc. Here the term "stabilization time" will be used so as to emphasize the similarity, both external and internal, between erosion and thermal breakdown.

It is well known [2] that, at a constant rate $q_0$ of heat transfer at the surface of a body in a rapid stream of hot gas, the body begins to wear not immediately but after a definite period of time (stabilization time) $\tau_V$, the length of which may be related to the heating depth $\delta_T$ and to the linear velocity $V_\infty$ of the wearing surface, viz. (Fig. 2)

$$\tau_V \propto (\delta_T/V_\infty) , \tag{3}$$

both $\delta_T$ and $V_\infty$ being calculated for the quasisteady segment after stabilization.

It has been shown earlier [2] that, at different values of the thermophysical parameters and velocity $V_\infty$, the thickness $S(\tau)$ of the layer of material broken away during the stabilization time $\tau = \tau_V$ is almost proportional to the quasisteady heating depth

$$S(\tau = \tau_V) \approx 3\delta_T, \tag{4}$$

with $\delta_T$ corresponding to the thickness of the surface layer within which the temperature drops to e ≈ 2.7 times the temperature of the heated outside surface. This thickness is equal to the thermal diffusivity $a$ of the material divided by the velocity of the wearing surface: $\delta_T = a/V_\infty$. The process of wear rate stabilization is in this case associated with a restructurization of the temperature profile in the body, from an initially steep nonsteady distribution to a finally flatter exponential one. Completion of the process is marked by removal of the entire layer of material within which the temperature distribution had been other than quasisteady.

The mechanism of erosion in the case of a barrier in a stream of particles is, evidently, different from the mechanism of thermal breakdown, but in the process of repetitive impacts here also occurs a change in

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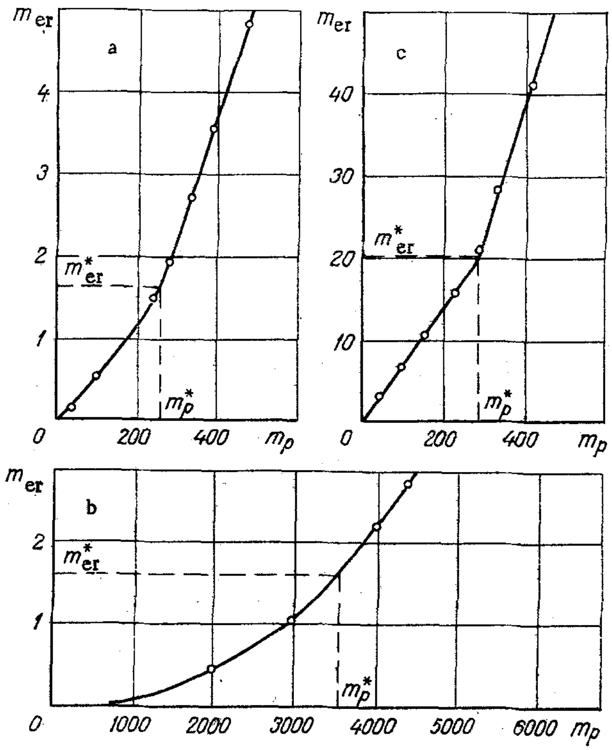


Fig. 1. Dependence of the loss of mass $m_{er}$ (mg) by a nickel plate (a, b) or a lead plate (c) on the integral mass $m_p$ (kg/m²) of precipitated quartz sand particles at impact velocities $V_p$ = 82 m/sec (a, c) and $V_p$ = 29 m/sec (b).

some properties of the material such as a decrease in the breakdown energy of internal bonds. With the action of a single particle taken separately being local in nature, degeneration of the entire surface layer of material requires a definite number of single impact events. Therein lies the internal similarity between the stabilization processes in the cases of thermal breakdown and erosion: end of the stabilization period must be marked by a complete removal of a layer of degenerated material of some characteristic thickness $\delta_{er}$.

If it were somehow possible to determine thickness $\delta_{er}$ for a given material subject to wear in a stream of particles, then the stabilization time, by analogy to relation (3), and thus also the necessary mass of precipitated particles according to relation (2) could be easily found by calculation from the erosion rate.

The wear rate $G_{er}$ of mass during erosion can be evaluated from the total loss of mass $m_{er}$, considering that after a sufficiently long testing time $\tau \gg \tau_V$

$$m_{er} = \int_0^\tau G_{er} d\tau \approx G_{er}\tau, \tag{5}$$

this relation together with relation (1) yielding the relative intensity of erosion

$$\bar{\bar{G}} = (dm_{er}/dm_p) \approx G_{er}/G_p. \tag{6}$$

The stable value of relative erosion intensity $\bar{\bar{G}}$ is related to the impact velocity $V_p$ according to the expression [3]

$$\bar{\bar{G}} = \frac{V_p^2}{2H_{er}}\left[1 - \exp\frac{V_{cr} - V_p}{0.5V_{cr}}\right], \tag{7}$$

where $H_{er}$ is the effective enthalpy of erosion and $V_{cr}$ is the critical impact velocity $V_p$ at which erosion begins (at which $\bar{G} = \varepsilon$, more precisely, $\varepsilon$ denoting some chosen small value such as 0.005).

The effective enthalpy $H_{er}$ does not depend on the impact velocity $V_p$ but, just as the heat of fusion or the heat of evaporation, characterizes the breakdown energy for internal bonds in the material. As has been

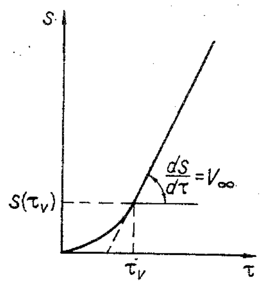


Fig. 2. Thickness of the worn away layer as a function of time for a material under a rapid stream of hot gas.

demonstrated in the earlier study [3], the effective enthalpy $H_{er}$ is much lower in the case of repetitive impact than in the case of a single impact.

Upon an analysis of the experimental data in Fig. 1, one ought to emphasize two anomalies in the trends which the critical values $m^*_{er}$ of the worn mass and $m^*_p$ of the integral mass of precipitated particles follow.

1. For a given kind of barrier material the value $m^*_{er}$ is almost independent of the impact velocity $V_p$ or the erosion rate $\bar{\bar{G}}$, but it can vary widely from one material to another (Fig. 1).

2. For a given kind of barrier material the value $m^*_p$ depends strongly on the impact velocity $V_p$, but it varies very little from one material to another.

Both experimentally established trends are explainable, if it is assumed that the thickness $\delta_{er}$ of the degenerated layer depends not on the wear rate (as in the case of thermal breakdown) but on another parameter which characterizes the stability of a material, namely the effective enthalpy of erosion $H_{er}$. The wear rate and the effective enthalpy are related to each other according to expression (7), which for $V_p \geq 2V_{cr}$ can be simplified to

$$H_{er} = V_p^2/(2\bar{\bar{G}}) = G_p V_p^2/(2G_{er}).$$

The higher $H_{er}$ or, which is equivalent, the energy of bonds between individual particles in the material is, the smaller will obviously be the thickness $\delta_{er}$ of the layer of degenerated material. In accordance with the theory of dimensional analysis, one can let

$$\delta_{er} \propto (\rho_p d_p^2 g)/(\rho_0 H_{er}), \tag{8}$$

where $\rho_p$ and $\rho_0$ are the densities of the particle material and of the barrier material, respectively; $d_p$, particle diameter; and $g$, acceleration due to gravity needed in relation (8) for balancing the dimensions.

One can now establish a relation for the loss of barrier mass over the interval within which the erosion rate stabilizes to a constant value

$$m^*_{er} = \delta_{er}\rho_0 \propto (\rho_p d_p g)/H_{er}, \tag{9}$$

this relation being in a satisfactory agreement with the experimental data in [1] (Fig. 1). Indeed, the erosion resistance of nickel is over 12 times higher than that of lead (with the densities of both materials figured in) so that, over the respective stabilization intervals for each, the loss of lead mass ought to be by more than one order of magnitude larger than the loss of nickel mass.

By virtue of the analogy between the stabilization processes in the case of thermal breakdown and erosion, one can now determine the stabilization time $\tau_V$ or the integral mass $m^*_p$ of particles precipitated on the barrier during this time:

$$\tau_V \sim (\delta_{er}\rho_0)\, G_{er} \propto (\rho_p d_p^2 g)/(G_{er} H_{er}), \tag{10}$$

$$m^*_p = \tau_V G_p \propto (\rho_p d_p^2 g)/(\bar{G} H_{er}). \tag{11}$$

The denominator in expression (11) depends mainly on the impact velocity $V_p$, according to relation (7), so that this expression can be more explicitly rewritten as

$$m_p^* \sim (\rho_p d_p^2 g)/\left\{\frac{V_p^2}{2}\left[1-\exp\left(\frac{V_{cr}-V_p}{0.5V_{cr}}\right)\right]\right\}. \qquad (12)$$

Written in this form, this relation confirms the earlier-mentioned fact that the integral mass $m_p^*$ of precipitated particles depends strongly on the impact velocity $V_p$ and the difference between materials, on the other hand, remains small (being manifested only in some differences between respective critical impact velocities $V_{cr}$ at which erosion begins).

It would be worthwhile to verify this conclusion experimentally at much higher impact velocities. In [4] a study is reported of erosion of a model moving at velocities from 1850 to 3700 m/sec through a quiescent cloud extending over hundreds of meters and containing droplets in mass concentrations up to several grams per cubic meter. It was demonstrated that the model had worn down not at a constant rate but, just as in the case of low streamlining velocities, with a stabilization interval. The experimental data were evaluated in terms of parameter k, the ratio of total midspan area of all particles which had precipitated on the model to the midspan area of the model alone. This ratio was called the overlap or eclipse parameter referring to a model in a cloud of particles.

It is easy to prove that $m_p = (2k\rho_p d_p)/3$ so that under stable conditions the product

$$k^* d_p V_p^2 = 1.5 m_p^* V_p^2/\rho_p \infty (d_p^2 g)/\left[1-\exp\left(\frac{V_{cr}-V_p}{0.5V_{cr}}\right)\right]$$

must be constant independent of the velocity of the model (at least when $V_p \geq 2V_{cr}$). This is in full agreement with the data in [4].

One can ascertain, therefore, that in the case of repetitive impacts of particles against a barrier at a constant velocity $V_p$ there is a period of stabilization, during which the wear rate increases gradually to its quasisteady level. During this period of time a layer of the barrier material is worn away whose thickness depends only on the dimensions of the particles, on the ratio particles density to barrier density, and also on the effective enthalpy of erosion $H_{er}$. The integral mass of particles precipitated during their stabilization period depends essentially on the density, the diameter, and the velocity of particles.

The most important factor to be considered in subsequent experimental verification should be the diameter of particles, inasmuch as in [1] and in [4] their diameter was close to a millimeter.

## NOTATION

| | |
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| $V$ | is the velocity; |
| $m$ | is the mass; |
| $\underline{G}$ | is the specific mass flow rate; |
| $\underline{\underline{G}}$ | is the relative erosion intensity; |
| $\tau$ | is the time; |
| $\delta$ | is the heating depth or the thickness of the degenerated layer; |
| $q_0$ | is the intensity of heat transfer; |
| $a$ | is the thermal diffusivity; |
| $\varepsilon$ | is the chosen small positive value; |
| $H_{er}$ | is the effective enthalpy of erosion; |
| $d$ | is the diameter; |
| $g$ | is the acceleration due to gravity; |
| $\rho$ | is the density; |
| $S$ | is the thickness of worn away material. |

### Subscripts

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|---|---|
| p | particles; |
| er | is the eroding barrier; |
| T | is the heated layer; |
| V and * | are the beginning of stabilized wear; |
| $\infty$ | is the quasisteady thermochemical breakdown; |
| cr | is the beginning of intensive erosion. |

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# A MODEL FOR CALCULATING THE EROSION OF A COMPOSITE MATERIAL


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We generalize experimental data and present a model for calculating the erosion of some composite materials subject to impact by solid particles.


By the "erosion" of a material (an "obstacle") we mean a process in which the mass of the material is carried away under the action of a stream of particles impinging upon it. The erosion of a body immersed in a high-speed flow of a gas-particle mixture (so-called two-phase flow) is affected thermochemically at the expense of heat and mass transfer in the gaseous boundary layer. In order to separate these two processes we concentrate our attention, in the present paper, on two-phase flows over bodies with flow speeds less than 2000 m/sec or with temperature due to drag not exceeding typical values of body surface temperatures arising from "pure" thermochemical decomposition (2000°K for quartzitic glass composites).

Despite this limitation, we need to analyze, where possible, a wider range of interaction rates in order to observe how the dynamics of the material decomposition mechanism changes, beginning with the region of influence of elastic forces and ending with the effects of high-speed impact. A large number of experimental and computational papers (see, e.g., [1]) have been devoted to the study of high-speed impact of single particles. As the lower limit of the range of high-speed impact, the authors of these papers assume a speed $V_p$ for which a pressure is generated at the point of contact of the particle and obstacle which is significantly higher than the flow limit under compression for both materials. In the case of colliding metals this situation already applies for $V_p \geq 1000$ m/sec.

Unfortunately, the majority of the papers published are devoted to the study of the high-speed collision of homogeneous materials, mainly, the impact of a metallic particle onto a metallic target. Many authors note, however, that in the case of high-speed impact the target material parameters of primary significance are the hardness and the density [2]. The most interesting result to be noted here is the practically linear dependence of the mass $G_{er}$ of the target material eroded away on the kinetic energy of the particle $(G_p V_p^2/2)$. In Fig. 1 we show the experimental data from [1] for the case of the impact of steel particles onto a lead target.

In contrast to the impact of a single particle, in the case of multiple impacts each previous particle not only carries away some mass of target material but also changes the properties of the layer of target material remaining; moreover, during the impact interaction waves of compression and rarefaction propagate in this layer. In particular, even in the case of impact by micron-sized particles on a homogeneous material (quartz), numerous microcracks and spalls appear [3]. This complicates the use of arbitrary parameters relating to the initial material, such as hardness, elasticity modulus, etc., when treating experimental data for the case of multiple impact.

Parameters used in the case of single impact (crater volume, depth of penetration, etc.), which are of frequent occurrence in the literature, cannot be used for treating experimental data relating to multiple impact. A more accurate and more preferred parameter in this case is the damage intensity parameter $\bar{G}$, defined as the ratio of the outflow $G_{er}$ of eroded material to the specific particle flux $G_p$ reaching the target surface.


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