ON THE RUPTURE MECHANISM OF REFRACTORY MATERIALS CAUSED BY INTERNAL HEAT EVOLUTION

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Investigations on the fracture of zirconium carbide by using a thermal shock simulated by a pulse of electrical power at a $(1-10)^3$ kW/sec supply rate are conducted. An analysis is given of the rupture products on the basis of the formation of liquid phase seeds and of local melting of the material.

Refractory materials are used extensively in modern machine construction. Knowledge of their characteristics will permit intensification of the working processes and a rise in the efficiency of apparatus and their aggregates.

Experiments on zirconium carbide (ZrC) specimens in an argon medium were conducted to study the rupture mechanism of refractory materials. The pressure in the working section was about 1.5 atm. The specimens were subjected to a thermal impact, simulated by a pulse of electrical energy. The specific energy E/G_i (E is the electrical energy delivered to the specimen during pulse operation, and G_i is the initial weight of the specimen material) was about $(0.2-1.2)\cdot 10^3$ kJ/kg. The rate of power growth dN/dt varied within the range $(0.8-11)\cdot 10^3$ kW/sec, and the initial specimen temperature between ~300 and 2300°K. It is characteristic that specimens preheated to ~1800-2200°K do not rupture for minimum values of the parameters E/G_i, dN/dt mentioned above. A visual study of the specimens under a microscope permitted the detection of congealing drops of melted carbide on the surface, as well as of caverns which are probably a source of spattering of the drops. The surface temperature of the specimen material was hence 200-300° below the melting point of the specimen material. However, the specimens in the cold state and subjected to an electrical pulse rupture before the melting point for the same values of the parameters.

An analysis of the rupture products permitted disclosure of particles of two kinds: of irregular or spherical shape, which are mainly drops of melted carbide.

The results of the rupture products were characterized by $N_{i_2}/N_{\Sigma_2} = f(d_i)$ for the sets of particles and also by $N_{i_{1,2}}/N_{\Sigma_{1,2}} = f(d_i)$ for each of the above-mentioned types of these particles. The specimen dispersion spectra are presented in Fig. 1a,b,c. The mean diameter $\bar{d}$ was determined from the particle diameter distribution for both the sets of particles and for each type of particle individually. The mean diameter was calculated from the formula

$$\bar{d} = \frac{\sum_i d_i N_i}{N_\Sigma}.$$

The mean diameter of particles of spherical shape is approximately 1.5-fold less than the mean diameter of the particles of irregular shape. It is characteristic that the time interval between the time of pulse delivery and the time of material rupture de-

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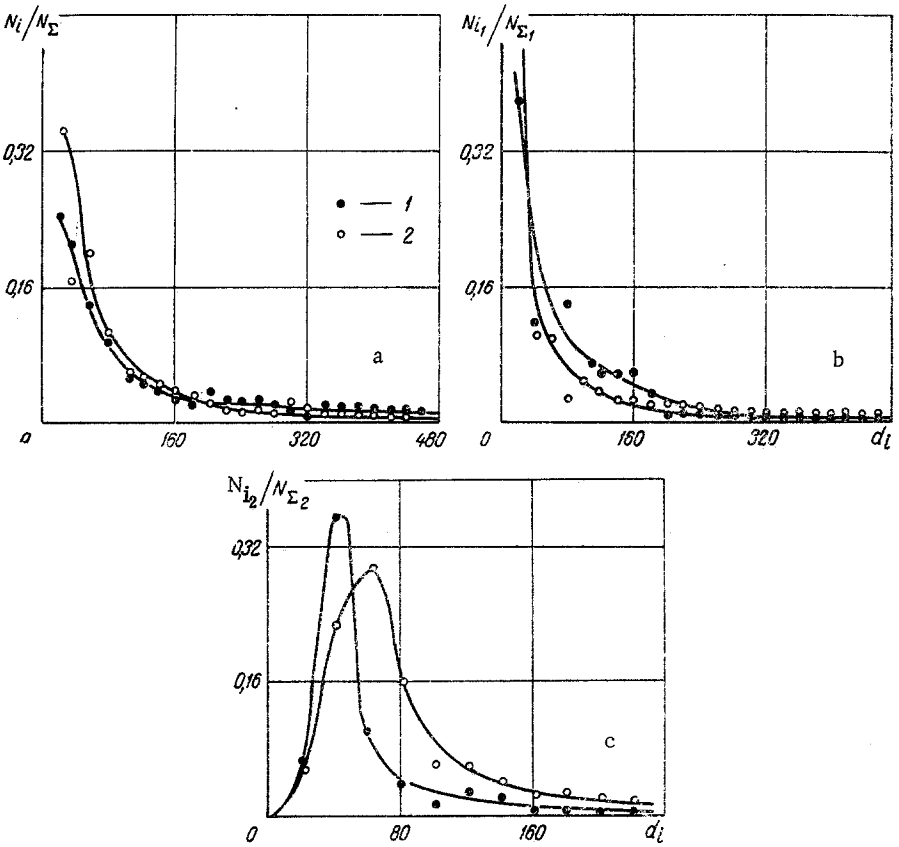

Fig. 1. Dependence of the spectra of sets of particles (a), particles of irregular shape (b), particles of circular form (c), on the specific energy: 1) E/G_i = 197 kJ/kg, $dN/dt = 0.833 \cdot 10^3$ kW/sec; 2) E/G_i = 800 kJ/kg; $dN/dt = 4 \cdot 10^3$ kW/sec. d, μ.

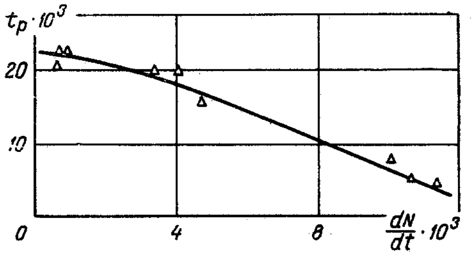

Fig. 2. Dependence of the time to specimen rupture on the rate of supplying power. Points refer to experiment. t, sec; dN/dt, kW/sec.

pends on the rate of the power supplied. The change in the time to specimen rupture due to the rate of supplying the power is shown in Fig. 2.

The presence of particles of two kinds in the rupture products permitted the assumption of the existence of two probable rupture mechanisms, which act simultaneously: rupture because of thermostresses, and rupture because of liquid-phase formation. Either mechanism dominates, depending on the conditions (the initial temperature of the specimen material, the rate of supplying power, the specific energy, etc.). The mechanism due to the presence of thermal stresses apparently predominates for a low initial temperature of the specimen surface and relatively low rates of supplying power during rupture.

The magnitudes of the thermal stresses σ_z originating in the specimens reached about 50 kg/mm^2. This exceeds the tension yield point of ZrC substantially for $[\sigma]_{\text{kns}}^{1500^\circ\text{K}} \sim 10$ kg/mm^2 and is closer to the compression yield point for $[\sigma]_{\text{comp}}^{1500^\circ\text{K}} \sim 170$ kg/mm^2 [2]. As the initial temperature rises (T > 2000°K), the role of the thermal stresses diminishes because of the increase in material plasticity and the velocity of the relaxation processes.

However, when the material is heated rapidly, local heat evolution is possible, resulting in local heating of the material above the melting point, i.e., in the local organization of a liquid phase, although the mean temperature over the volume of material does not exceed the melting point. Local elevated heat evolution is possible because of the anisotropy of the properties. Moreover, the material ordinarily consists of a large quantity of arbitrarily ordered grains of irregular shape. All possible impurities, whose melting point is below the melting point of the base material, are concentrated along the grain boundaries. Hence, the generation of liquid-phase centers on the inhomogeneities is possible. The higher the temperature of local domain heating, the higher the probability of origination of new phase centers. As the size of the new-phase center increases, the stresses in the nearest-lying domains increase. As the yield point of the material is reached, a crack originates. If it is assumed that many such new-phase centers appear over the volume of the material and which produce a stress field during their growth, then the origination and growth of cracks are possible, resulting in material rupture upon being combined.

Let us estimate the increase in temperature at the inhomogeneities, inclusions, and impurities as compared with the mean temperature over the volume of the material, and let us also estimate the temperature difference $\overline{\Delta T}$ between the main material and the inhomogeneity.

To estimate $\overline{\Delta T}$, let us take the following simplified scheme. Let us consider that: a) the material consists of grains with the characteristic dimension R_1 (R_1 is the mean grain size) and of inhomogeneities of one kind with the characteristic dimension $R_2 > R_1$; b) the inhomogeneity is spherical in shape.

Let us compute the temperature of the base material and the inhomogeneity in the presence of internal heat evolution. Henceforth, all the thermophysical characteristics of the base material will be denoted by the subscript 1 and of the inhomogeneity by the subscript 2. The temperature distribution in the material and in the inhomogeneity is determined from the solution of a system of nonstationary heat conductivity equations

$$\begin{aligned} \frac{\partial T_1}{\partial t} &= a_1^2 \nabla^2 T_1 + \alpha_1 q_1(t), \\ \frac{\partial T_2}{\partial t} &= a_2^2 \nabla^2 T_2 + \alpha_2 q_2(t) \end{aligned} \tag{1}$$

under the initial and boundary conditions

$$\begin{gathered} t = 0, \; T_1 = T_2 = T_0; \\ \lambda_1 \frac{dT_1}{dr} = \lambda_2 \frac{dT_2}{dr} \quad (r = R_2); \\ \left.\frac{dT_2}{dr}\right|_{r=0} = 0, \quad \left.\frac{dT_1}{dr}\right|_{r=0} = 0, \end{gathered} \tag{2}$$

where $\alpha_{1;2}$ are the constant coefficients which will be defined below.

Let us take the average of the system (1) with respect to the volume:

$$\begin{aligned} \frac{\overline{dT_1}}{dt} &= \alpha_1 q_1(t) - \frac{a_1^2 S_2}{V_1} \cdot \left.\frac{\overline{dT_1}}{dr}\right|_{r=R_2} + \frac{a_1^2 S_1}{V_1} \cdot \left.\frac{\overline{dT_1}}{dr}\right|_{r=R_1}, \\ \frac{\overline{dT_2}}{dt} &= \alpha_2 q_2(t) - \frac{a_2^2 S_2}{V_2} \cdot \left.\frac{\overline{dT_2}}{dr}\right|_{r=R_2}. \end{aligned} \tag{3}$$

Let us assume that heat evolution occurs nonuniformly in the specimen and the main part of the heat is liberated in the inhomogeneities $q_1(t) \ll q_2(t)$. Let us consider the specific electrical resistivity of the inhomogeneity to be greater than the specific electrical resistivity of the base material, hence, the heat evolution therein is greater (without taking account of the redistribution of the current flowing in the specimen). In turn, the specific resistivity of the inhomogeneity is greater since the inhomogeneity consists of various impurity metalloid compounds. Let us introduce the mean heat evolution

$$\overline{q}(t) = \frac{N_0(t)}{V}.$$

Let n_1 be the mean grain concentration, and n_2 the mean concentration of inhomogeneities in the specimen. On the average, there is one inhomogeneity on each grain (if the grain junction is understood as an inhomogeneity). Then

$$\begin{gathered} n_1 \simeq n_2, \\ n_1 q_1(t) + n_2 q_2(t) = \frac{N_0(t)}{V}. \end{gathered} \tag{4}$$

Let us introduce a parameter p showing the relative fraction of inhomogeneities, inclusions, and impurities, compared with the base material. We obtain from the relationship (4)

$$q_2(t) \simeq \frac{\frac{4}{3}\pi R_2^3 N_0(t)}{Vp} = b_2 N_0(t)$$

under the condition that

$$\frac{q_1(t)}{q_2(t)} \simeq \frac{\rho_1^* R_2}{\rho_2^* R_1} \ll 1,$$

where ρ_1^*, ρ_2^* are the specific resistivity of the grain and the inhomogeneity, respectively,

$$\alpha_1 = \frac{1}{m_1 C_1}; \quad \alpha_2 = \frac{1}{m_2 C_2};$$

where m_1, m_2 are the mass of the grain and the inhomogeneity.

To estimate the derivatives $\overline{dT}/dr$, let us replace them by the finite differences

$$\left.\frac{d\overline{T}_1}{dr}\right|_{r=R_1} \simeq \frac{\overline{T}_1 - \overline{T}_2}{R_1}; \quad \left.\frac{d\overline{T}_2}{dr}\right|_{r=R_2} \simeq \frac{\overline{T}_2 - \overline{T}_1}{R_2}.$$

We shall henceforth consider the mean temperature over the volume in both the grain and in the inhomogeneity. Taking into account that

$$\frac{a_1^2 S_2}{V_1} \cdot \frac{d\overline{T}_1}{dr} \sim \frac{\lambda_1 R_2^2}{R_1^4 \rho_1 C_1} \ll \frac{\lambda_2}{R_1 \rho_2 C_2},$$

the system (3) reduces to

$$\begin{gathered} \frac{d\overline{T}_1}{dt} = \frac{b_1 N_0(t)}{m_1 C_1}, \\ \frac{d\overline{T}_2}{dt} = \frac{b_2 N_0(t)}{m_2 C_2} + \beta[\overline{T}_1 - \overline{T}_2], \end{gathered} \tag{5}$$

where

$$\beta = \frac{3\lambda_2}{R_2^2 \rho_2 C_2} \text{ and } b_1 \ll b_2.$$

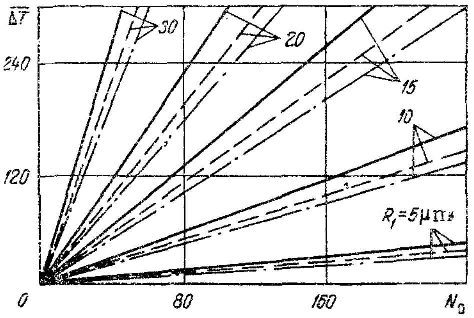

Fig. 3. Rise in inhomogeneity temperature as compared with the mean temperature over the material volume. Solid line — porosity, p = 0.03; dashed lines — porosity, p = 0.05; dot-dash lines — porosity, p = 0.07. ΔT, deg; N_0, kW.

Subtracting the first equation from the second, we obtain

$$\frac{d\overline{\Delta T}}{dt} = b_2' N_0(t) - \beta \overline{\Delta T}, \tag{6}$$

where

$$\overline{\Delta T} = \overline{T}_2 - \overline{T}_1;\ b_2' = \frac{b_2}{m_2 C_2} = \frac{1}{V p \rho_2 C_2}.$$

Equation (6) characterizes the heat balance of the system. The first member $b_2' N_0(t)$ characterizes the heat evolution, and the second $\beta\overline{\Delta T}$ the heat elimination through the inhomogeneity surface. The general solution of (6) is [1]

$$\overline{\Delta T}(t) = A \exp[-\beta t] + \exp[-\beta t] \int_0^t b_2' N_0(t) \exp[\beta t]\, dt.$$

The constant A is determined from the initial conditions. Since ΔT(0) = 0, it follows that A = 0. Then

$$\overline{\Delta T}(t) = \exp[-\beta t] \int_0^t b_2' N_0(t) \exp[\beta t]\, dt. \tag{7}$$

In the experiments $N_0(t)$ varied linearly; therefore, $N_0(t) = \alpha t$.

Integrating (7), we obtain

$$\overline{\Delta T}(t) = \exp[-\beta t] \left[\left(\frac{b_2' \alpha t}{\beta} + \frac{b_2 \alpha}{\beta^2} \right) \exp[\beta t] - \frac{b_2' \alpha}{\beta^2} \right] = \left(\frac{b_2' \alpha t}{\beta} + \frac{b_2' \alpha}{\beta^2} \right) - \exp[-\beta t]\, \frac{b_2'(t)}{\beta^2}.$$

Taking into account that $\beta t \ll 1$

$$\overline{\Delta T}(t) \simeq \frac{b_2 N_0(t)}{\beta m_2 C_2}. \tag{8}$$

After substituting the values of β and b_2 into (8), we obtain

$$\overline{\Delta T}(t) \simeq \frac{N_0(t) R_2^2}{V p \lambda_2}. \tag{9}$$

Using the relationship $n_1 \simeq n_2$, we find

$$R_2 = R_1 \left(\frac{p}{1-p} \right)^{1/3}.$$

Results of the computations are presented in Fig. 3, from which it is seen that the quantity $\overline{\Delta T}$ can exceed 500° for some values of the parameters. Therefore, if the mean temperature of the base material is $\overline{T}_1 \simeq 3000$°K, then the temperature of the inhomogeneity exceeds 3500°K and local melting of the material can occur. It should be mentioned that the computation has been performed with a lowering of $\overline{\Delta T}$. The lowering is determined by the exaggerated value of λ_2 (under the condition $\rho_1{}^* R_2 \ll \rho_2{}^* R_1$) and the melting point of the inhomogeneity which is ordinarily lower than in the base material.

It is seen from an analysis of the computation results that the rise in temperature of the inhomogeneity over the grain temperature $\overline{\Delta T}$ grows as the mean grain size of the base material increases. However, $\overline{\Delta T}$ will diminish as the porosity increases. It is characteristic that the influence of the change in porosity on $\overline{\Delta T}$ is less than the influence of the grain size, and increases as the latter grows.

Therefore, the presence of congealing drops of zirconium carbide together with particles of irregular shape and their distribution over the diameter in the rupture products confirms the assumption about the origination of liquid phase foci, the growth and influence on the rupture of refractory materials.

NOTATION

N_i is the quantity of particles of both kinds of diameter i; $N_{i_{1,2}}$ is the quantity of particles of irregular and circular shapes of diameter i, respectively; N_Σ is the total quantity of particles of both kinds; $N_{\Sigma_{1,2}}$ are the total quantity of particles of irregular and circular shape, respectively; d_i is the i-th particle diameter; $a^2_{1,2}$ is the coefficient of temperature conductivity; $q_{1,2}(t)$ is the heat evolution; $N_0(t)$ is the total power evolved in the specimen; V is the specimen volume; $n_{1,2}$ is the mean concentration of the grains and inhomogeneities, respectively; p is the porosity; ρ^* is the specific resistivity; m is the mass; $\alpha = 1/mC$ is a coefficient; C is the specific heat of the material; ρ is the material density; λ is the coefficient of heat conduction; $\overline{\Delta T}$ is the excess in inhomogeneity temperature as compared with mean specimen temperature over the volume; S is the area of inhomogeneity surface.

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