INVESTIGATION OF CERTAIN PROBLEMS RELATED TO THE FAILURE OF THERMALLY LOADED REFRACTORIES

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In evaluating the carrying capacity of refractories used in fabricating thermally loaded structural members for high-temperature equipment, it is of interest to determine the possible course of the failure process when the limiting state is reached.

In this connection, investigations of thermostability [1-3] have considered both crack formation and crack propagation in test materials as a function of various factors (specimen size, thermal loading regime, material-structure characteristics, etc.). Research has specifically made it possible to determine the relationship between the rate of the failure process for hollow cylindrical specimens and the elastic energy accumulated in them during thermal loading [4, 5]. However, these studies have essentially been descriptive and estimates of the energy levels at which failure occurred were made with varying heating rates only for fireclay specimens [5] and require refinement. This is due to the fact that the calculations were based on the formulas of elasticity theory, which must be regarded as a first approximation for such materials [6].

In this connection, we conducted a special investigation in which previous results and new experimental data were analyzed. The tests were carried out on specimens fabricated at the Ukrainian Scientific-Research Institute of Refractories, in the form of hollow cylinders with an outside diameter of 50 mm, an inside diameter of 25 mm, and a height of 12.5 mm. The specimens were subjected to thermal loading with different constant temperature-rise rates (2-400 deg/min), using electrical resistance heaters applied to the inside surface. The test method was similar to that described previously [4, 7], but the measurement accuracy was somewhat higher in a number of cases. The present article gives data obtained for a larger number of specimens (no less than 8-10 for each point in determining the average values), so that they may differ slightly in absolute value from the previously published figures for the same materials in some cases. In order to provide maximum reliability of the results, the main investigations were condicted with linearly deformed materials (Al_2O_3 + 1% Ti and Al_2O_3 + 0.1% MgO), whose characteristics are given in Fig. 1 and in an earlier article [7]. When the materials reached the limiting state during testing, cracks propagated "instantaneously" in all specimens, but the failure process as a whole exhibited differences in its course. With heating rates of no more than 30-50 deg/min, failure was comparatively mild, the specimen wall being traversed by a single radial crack. When the temperature gradient was comparatively large, a second nonthrough or even through crack was formed (as a result of bending), a phenomenon resembling that observed in investigating steatite and other materials [8].

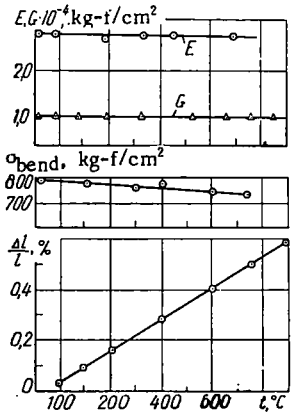

Fig. 1. Principal physico-mechanical characteristics of Al_2O_3 + 1% TiO_2 (E is the dynamic modulus of elasticity, G is the shear modulus, σ_{bend} is the bending strength, and $\Delta l/l$ is the relative thermal elongation).

When the heating rate was increased (to 150-200 deg/min), the cracks propagated more rapidly and the characteristic clicking sound accompanying their propagation became louder. In the overwhelming majority of cases, the specimens broke into two pieces, although we

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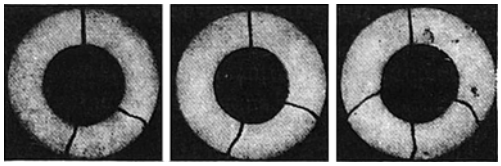

Fig. 2. Fractured specimens of Al_2O_3 + 1% MgO.

also observed patterns resembling those obtained at lower heating rates. When the rise in temperature was more rapid (up to 400 deg/min), from two to four cracks were formed; part of the specimen was sometimes thrown to a distance of 2-3 m at the instant of failure. However, only one rather smooth crack due to the action of thermal stresses could be seen in the fractured specimen (Fig. 2). A similar type of fracture has been reported in the literature [4, 7].

The behavior of porous materials, especially those with markedly heterogeneous structures, changed even more substantially when the heating rate was varied over the same range (our observations were made with materials based on zirconium dioxide, aluminum oxide, and commercial refractories). While the specimens failed almost soundlessly, the cracks propagating gradually (or discontinuously) under temperature regimes close to steady-state when the temperature gradient was increased, a rise in the heating rate caused failure accompanied by clicking and instantaneous crack propagation. However, the separation of fractured specimens of such materials and appearance of kinetic effects were observed only for technical-grade zirconium dioxide, specimens of which were fabricated by semidry pressing at the experimental plant of the Ukrainian Scientific-Research Institute of Refractories.

In order to analyze this failure pattern with the formulas of thermoelasticity theory, the data obtained in temperature-distribution measurements were used to calculate the stress and energy patterns of the specimens. Table 1 gives the results of these calculations for Al_2O_3 + 1% TiO_2, a material that undergoes only slight changes in its physicomechanical characteristics over the temperature range in question. The potential-energy values given in this table were determined from the formula

$$\Pi = \frac{\pi}{E}\int_r^R (\sigma_0^2 + \sigma_r^2 - 2\mu\sigma_\theta\sigma_r)\,\rho d\rho,$$

where σ_θ and σ_r are the circumferential and radial thermal stresses calculated for a plane stress pattern, which was realized with sufficient exactness in specimens of the size selected.

It follows from the data in this table that failure occurred with significantly different accumulated potential energies for each heating rate. As the heating rate was increased, this energy became sufficient to produce a larger loading surface and kinetic effects. The appearance of several cracks produced by bending stresses when the heating rate was increased (see Fig. 2) was due to the fact that the amount of accumulated energy increased in the compressed zone of the specimen, since only the circumferential compressive stresses increased in this case (see Table 1), causing a rise in the temperature nonuniformity in this zone. The fact that some failed with the same accumulated-energy levels when subjected to different heating rates (see Table 1) explains the observed similarity of crack formation in these specimens.

Characteristically, the energy accumulated during thermal loading and corresponding to the same temperature gradient over the specimen thickness, decreased as the heating rate increased (Table 2).

In comparing the failure-process characteristics of specimens fabricated from Al_2O_3 + 1% TiO_2 and

TABLE 1

Heating rate, deg/min	Maximum specimen temperature (average), T, °C	Temperature gradient at failure, ΔT_f, deg	Tensile stresses at outer surface, kg-f/cm²	Compressive stresses at inner surface, kg-f/cm², for average T	Energy accumulated in specimen, kg-f·cm
2	818	75 (98) / 115	530 (717) / 830	1254	0,39 (0,68) / 0,94
170	440	118 (123) / 131	620 (653) / 730	1795	0,94 (1,02) / 1,17
340	348	136 (142) / 155	595 (625) / 690	2150	1,11 (1,2) / 1,43

Note. The numerator gives the minimum values and the denominator the maximum values, while the average is shown in parentheses.

TABLE 2

Material, temperature gradient f, deg	Heating rate, deg/min		
	2	170	340
Al_2O_3+1% TiO_2, 123	1,08	1,02	0,92
Al_2O_3 (open porosity 28%), 222	0,356	0,303	0,271

TABLE 3

Specimen characteristics	Temperature gradient at failure			Range $\Delta T_{f_{max}} - \Delta T_{f_{min}}$, deg	Mean square error	Variation constant, %
	minimum	average	maximum			
Surface without visible defects	134	197,2	252	128	34,2	19,4
Polished outer surface	177	>203,5	>257	80	21,6	10,6
Defects in form of small cracks	100	139,5	193	93	25,1	18,0
Cracks on inside surface	108	139,0	170	62	17,5	13,1
Concentrator on outside surface	113	129,5	152	39	10,8	8,3

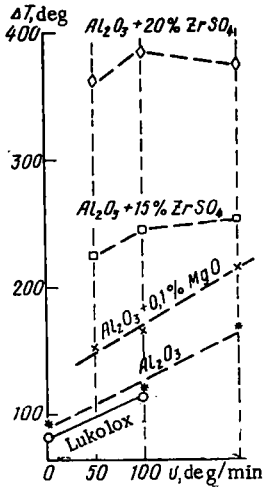

Fig. 3. Temperature gradients at failure with different heating rates for inside surface of specimens.

Al_2O_3 + 0.1% MgO, it was noted that specimens fabricated from the latter material fractured more catastrophically with increasing heating rate (the potential energy accumulated in them was almost an order of magnitude greater at the time of failure). A similar tendency toward a significant increase in fracture rate as the thermal-loading regime was intensified was previously observed for specimens of compact technical-grade corundum, semiporcelain, etc.

Certain other materials, particularly corundums with zircon added [9], exhibited a different tendency: the fracture rate underwent no increase and the temperature gradient at the time of specimen failure decreased with rising heating rate under the same conditions (Fig. 3). This can be attributed to the fact that the structure of such material is incapable of inhibiting crack propagation when some definite accumulated potential-energy level is exceeded, i. e., the crack propagation rate is important in such cases. It is consequently necessary to take into account the energy capacity at which failure occurs under real conditions when evaluating the carrying capacity of components fabricated from brittle materials, especially those intended for operation under non-steady-state thermal regimes. In connection with the fact that various thermostability criteria (R^{III}, R^{IV} [10]) do not take into account the changes in the ability of materials to inhibit crack propagation as a function of propagation rate, which is governed by failure energy capacity [11], appropriate tests must be conducted with programmed thermal loading to obtain the necessary information on this problem.

Since the scattering of the results and the corresponding variation of fracture characteristics are interrelated for given materials under identical tests conditions, we attempted to establish the influence of experimental-specimen state on these factors.

For this purpose, we selected ten specimens without any visible defects and ten specimens with cracks up to 1.5 mm deep from a batch of Al_2O_3 + 0.1% MgO specimens. In addition, ten specimens were ground in circular and flat grinders and rectangular depressions (stress concentrators) 1.5 mm wide and 2 mm deep were ground into the outside lateral surface of another ten specimens in the axial direction with a diamond wheel. We also employed ten previously fractured specimens, which exhibited cracks 3-4 mm long on their inside lateral surfaces after annealing. The test results for all these specimens are given in Table 3. The ground specimens failed most rapidly, three of them exhibiting crack formation at temperatures below 950°C, the maximum temperature for thermocouples soldered to the thermometric specimens with pure silver. All these specimens fractured into two or three pieces. The specimens with cracks and recesses failed least rapidly: only one through crack was formed. It should be noted that these three types of specimens were characterized by the smallest scattering of the results obtained in determining the temperature gradients at failure (see Table 3).

The greatest scattering of the results obtained and the largest differences in the course of the fracture process (formation of one, two, and three cracks) were observed for those specimens for which visual examination revealed no visible defects or abnormalities, i. e., specimens of the type generally employed in thermostability tests.

On the basis of the foregoing, it can be concluded that, in addition to ordinary strength tests, it is necessary to determine the characteristics of the possible failure process at accumulated potential energy levels exceeding natural levels in selecting materials for specific components. The state of the specimen surface must be taken into account in evaluating the test results.

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