DETERMINATION OF BRITTLENESS OF REFRACTORIES TESTED FOR HEAT RESISTANCE

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Problems of thermal stability are normally considered somewhat differently from other problems concerning strength of materials. In this connection special characteristics of heat resistance (σ_T) are introduced [1], specific aspects of scatter of experimental results are investigated [2], and the thermal states of specimens are thoroughly studied on the assumption of the simplest relations between stress and strain for any material [3]. This approach is also followed in working out criteria used for analytical evaluation of heat resistance [5] and for developing a theoretical basis for heat resistance [6].

However, despite certain success in this field, until now no theory of heat resistance has been developed to explain behavior of most materials, much less all, under conditions of thermal stress. Certain criteria of heat resistance correspond only to particular cases. Therefore, very many have been proposed (in the opinion of the authors of [7], only the principal 21 criteria). The applicability of any particular criterion to new material cannot generally be predicted successfully, and frequently the criterial determinations do not agree with experimental results [8]. Test data on heat resistance, obtained for different materials by identical experimental methods, do not give equal values in accuracy and reliability. This fact creates uncertainty in laboratory determinations of heat resistance, and the most important wares are generally tested under conditions approximating actual operating conditions.

In this connection, to develop, during tests, more general methods then those now existing for evaluating heat resistance, a number of factors have been analyzed that are not generally emphasized by investigators.

Thus, in comparing observational results with test results on beams in bending and hollow cylinders under conditions of thermal loading of their external surface, it may be noted that the failure of specimens of like materials seems to be similar if the rates of deformation are comparable. In materials such as dense corundum, glass ceramics, carbides, and others, specimens are almost instantaneously cut through by cracks. Increase in porosity of corundum, change in structure of material with biaxial zirconium because of degree of stabilization, for example, formation of special microfractures in fireclay, and similar factors cause corresponding changes in the failure process, which, for individual unroasted refractories, may even suggest "spreading out" of parts of the specimens and formation, in the final analysis, of cracks with very complex relief.

Microcracks as well as macrocracks develop, similar under different types of loading (such as when the structures of the material and the stress distribution in the specimens are similar). As an illustration of this, we have shown in Fig. 1 the fracture scheme of a specimen of concrete [9] in compression and have shown a photomicrograph of a section of a hollow cylindrical specimen with a crack. This latter specimen was made of aluminosilicate with grains of corundum, tested in thermal stresses on a gas-dynamic stand [10]. The fracture processes are similarly described for both cases, but the cracks responsible for fracture prove to be more dangerous for materials stretched by the stress σ_t acting perpendicular to the load in the compressed specimen, and in a tangential direction during thermal loading. (In Fig. 1, P is compressive force and q is outgoing heat flow from the heated specimen.)

When we compare materials differing in chemical composition and type of crystal lattice, but similar to some extent in macrostructure, we then observe certain common features in their behavior during identical loading, particularly thermal loading. Thus, in hollow cylindrical specimens made of coarse-grained

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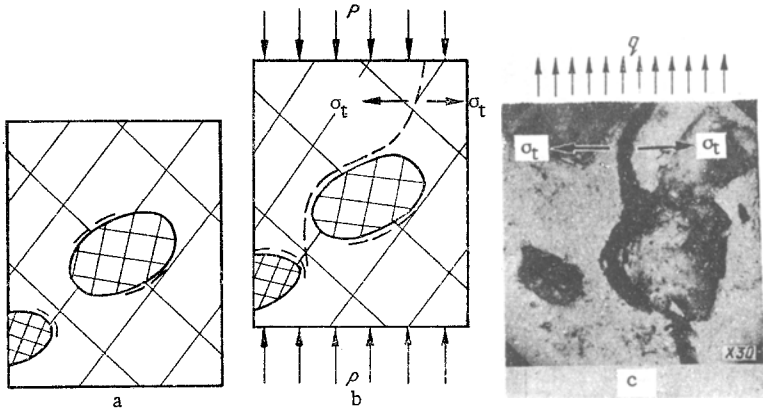

Fig. 1. Fracture of a prismatic specimen of concrete during axial compression before loading (a) and after loading (b), and also of a cylindrical specimen in thermal loading (c). 3/4 reduction.

graphite [11], coarse-grained biaxial zirconium, and magnesial concrete, the nature of branching cracks in the axial direction is the same.

There are other well-known facts also, on the basis of which, as a first approximation, we may assume definite equivalence for material under any type of load when the distribution of loads in the specimens is similar. In this connection, when determining heat resistance, it is suggested that materials be classified not according to composition, fields of use, technology of manufacture, or other similar characteristics, but according to behavior under effective forces. * For this, it is probably advisable to use the common characteristics, particularly energy characteristics, which may be considered in like manner for thermal loading as well as mechanical loading of specimens.

In considering the balance of energy expended in deforming the specimen and further in fracturing the specimen by means of energy accumulated up to the time destructive cracks appear, in the general case we determine that each material is characterized not only by the total amount of energy expended but also by the relations of their parts. Specifically this refers to energy used in elastic deformation and accumulated in the specimen (potential energy), but also lost because of residual strains in the material. For elastic material, all energy expended during deformation accumulates in the specimen in the form of potential energy.

According to Fig. 2, the energy of deformation

$$U = \eta \sigma_{lim} \varepsilon_{lim},$$

where η is the space factor of the curve; σ_{lim} represents limiting stresses at failure; ε_{lim} represents limiting strains at failure, and the potential energy is

$$\Pi = \eta' \sigma_{lim} \varepsilon_{pe},$$

where η' is the space factor of the part of the curve for the area corresponding to potential energy accumulated in the specimen to the instant of fracture (for the linearly elastic case $\eta' = 1/2$), and ε_{pe} is the elastic component strain at fracture.

We consider the ratio of the indicated energies to be a parameter characterizing the behavior (deformation and fracture) of a material:

$$\chi = \frac{\Pi}{U} = \frac{\eta'}{\eta} \cdot \frac{\sigma_{lim} \varepsilon_{pe}}{\sigma_{lim} \varepsilon_{lim}} = \varphi \frac{\varepsilon_{pe}}{\varepsilon_{pe}},$$

where φ is the relative space factor of the curve.

For simplifying the computations, let us assume that $\varphi = 1$; then the approximate measure of brittleness of materials will be the parameter

*In the mathematical description of the fracture process in brittle materials under thermal stress, it is effective to use the analogy between development of cracks in steady tensile deformation and the thermal shock of loaded specimens [12].

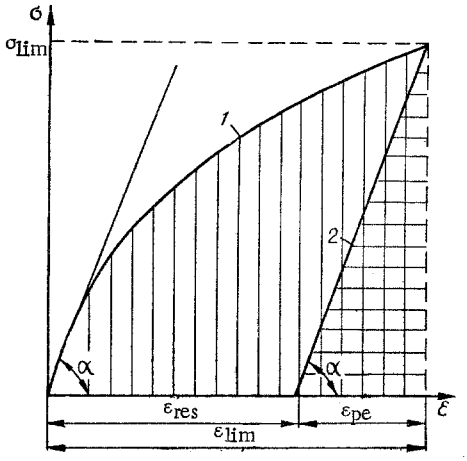

Fig. 2

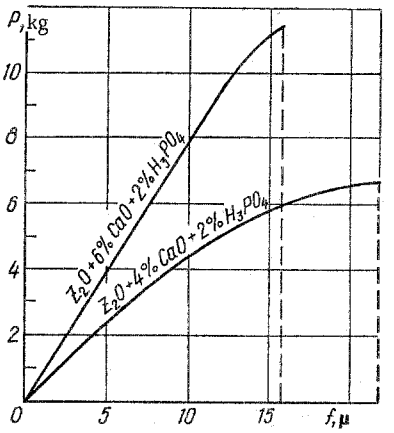

Fig. 3

Fig. 2. Deformation curve of specimen during loading (1) and unloading (2) (linearly elastic case).

Fig. 3. Deformation curve of nonroasted specimens of biaxial zirconium during bending with a Hartley oscillator.

$$\chi' = \frac{\varepsilon_{pe}}{\varepsilon_{lim}},$$

which, * as shown earlier, may be used for approximate evaluation of the nature of the fracture process of thermally loaded specimens of materials. Since the parameter χ, being a criterion of brittleness, characterizes the state of the material, it depends on temperature.

On the basis of the parameter χ, it is possible to classify materials after plotting series corresponding to aspects of their behavior under the investigated force loading. At the beginning of this classification series (at values of $\chi = 1$) will be found materials whose fracture process takes place catastrophically. Specimens with lower values of χ will be more brittle and will fracture less catastrophically. This is also observed in practice. Even with no calculations we may note that the greater the curvature of the strain curve of the material because of the appearance of residual strains (Fig. 3), the less brittle the fracture of the material during thermal loading.

Thus, as with materials, it is possible to classify criteria of heat resistance. The simplest analysis of known criteria of heat resistance [4, 6, and others], examined in [14] as characterizing the appearance of cracks in a specimen, attest to the fact that the basis of such criteria is the ratio of limiting strain of material to the coefficient of linear expansion (the remaining values in the equation characterize the particular case for which the given criterion has been derived).

For most known criteria of heat resistance, the value of limiting strain is determined from the ratio of breaking strength to modulus of elasticity; i.e., it is considered to be the case of linearly elastic dependence of strain on stress corresponding to the value $\chi = 1$. At other values of χ such criteria should not be applied, since it is impossible to account for the actual behavior of the material by means of them. This has been repeatedly confirmed by analysis of results from determining heat resistance of different industrial and other structurally inhomogeneous refractories.

We should consider also a group of energy criteria, which characterize the capacity of materials to resist crack growth [14]. The use of these for materials for which $\chi = 1$ has no meaning, since this case is one of catastrophic fracture, and any arrest of cracks here is insubstantial. Therefore, in comparative evaluations of such types of criteria, we must consider the criteria to be effective for materials having the parameter $\chi < 1$. This is confirmed in practice.

Experimental methods of determining heat resistance are most suitably selected on the basis of the proposed classification of materials.

For materials for which $\chi \approx 1$ one should use methods providing for determination of temperature drops or other characteristics (such as strength, limiting strains, etc.) in single-stage thermal loading.

*The value of the parameter χ' is equal to the reciprocal of the brittleness parameter proposed in [13].

In this case we use the simplest method of recording instants of fracture of the specimens, based on the recording of acoustic effects accompanying fracture, records of rupture of a conductive layer, and so forth. Since with such materials the structure is not damaged during deformation of the specimen, we should not expect to obtain any especially useful information for them from thermocyclic tests on a limited base (units of tens of thermocycles; tests that are generally conducted during technological evaluations of heat resistance). This is confirmed experimentally.

For materials with the parameter χ much less than unity, fracture takes place gradually. The instant at which cracks form and the distribution of cracks in the specimen may be recorded by measuring deformation or by recording the change in any structure-sensitive characteristics of the material during thermal loading. In such cases we find interest in data concerning resistance of material to crack propagation during both single-stage and repeated thermal loading, when, because of the development of microfracturing or plastic flow, continuous damage of the structure takes place.

Similar conclusions may be drawn also concerning methods of calculation when treating experimental results or when evaluating heat resistance of any structural elements.

CONCLUSIONS

1. When determining heat resistance, it is advisable to classify materials not by their chemical composition, technology of manufacture, regions of application, or other such features, but by their behavior (deformation and fracture) during force loading.

2. For evaluating the behavior of materials during force loading we have proposed the ratio of potential energy accumulated in the specimen at the instant of fracture to the total energy expended on deformation of the specimen prior to its fracture.

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