STRENGTH AND FRACTURE OF ELASTIC AND BRITTLE BODIES AT THERMAL LOADING

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ABSTRACT

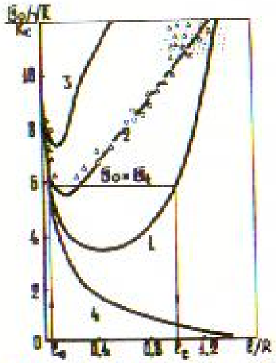
In this report we discuss the results of the developed theoretical and experimental methods of estimating the thermal stress state of finite bodies having single and multiple cracks. We detect the above-mentioned factors effect on the fracture kinetics and bearing ability of thermally loaded bodies. Using the nonstationary thermal shock methods, e.g. axisymmetric heating or cooling the side surface of cylindrical bodies in liquid media, plasma or electron-beam heating of a cylinder top, it is shown the fracture character changes from appearance of some cracks resulting in a partial loss of bearing ability to a complete body fracture. According to the extent of the compression and tension areas in a body and the stress relation in these areas the relative thermal stress resistance of elastic and brittle materials may vary from tensile strength values to compressive strength ones. It is shown on the basis of the linear mechanics concepts that in the general case for estimating the bearing strength of a thermally loaded body it is necessary to take into consideration the history of loading and fracture kinetics in view of the stress redistribution in the whole volume of a finite body at the intermediate stages of cracks development and interaction.

KEYWORDS

Thermal shock Resistance, Stressed State, Fracture Kinetics.

Brittle ceramic materials used in power engineering industry (R.N. Katz, 1990) are, as a rule, subject to thermal effects of different kinds under operating conditions. Such effects can cause these materials fracture.
The feature of the stressed state conditioned by the nonuniform temperature distribution in a body without any external forces is its complexity and nonuniformity (presence of both tension and compression areas is obligatory). The

latter has a considerable effect on the character of brittle fracture of a thermally loaded body causing its partial or complete fracture (W. B. Crandall and G. Ging, 1955; A. G. Lanin et al., 1973). The used thermal stress resistance criteria (W. D. Kingery, 1955; G. S. Pisarenko et al., 1966) can't represent the influence of the thermal stressed state complexity and nonuniformity in full measure. On the basis of either the first strength theory or the statistical one these criteria identify the fracture beginning with its completion when the thermal stresses reach the ultimate strength in any point of the body or in the maximum loaded part of it.
The early criteria based on the energy approach (D. P. H. Hasselman, 1963; F. G. Clarke et al., 1966) give an integral estimation of the body fracture strength and don't allow to define the body state at the intermediate failure stages. The subsequent energy concept development taking into account change of the energy accumulated in the uniformly loaded body when a lot of cracks appear resulted in an important proof of the possibility of the intermediate failure nonstability stage after which the equilibrium crack development stage follows (D. P. Hasselman, 1969). Describing the general pattern of fracture of a thermally loaded body correctly, these theoretical relationships don't take into account the influence of the stressed state nonuniformity, the limited body dimensions and the cracks interaction, which can change the pattern of the stressed state of the whole body and, therefore, the fracture kinetics.
One of the ways of subsequent fracture theory development, which is described in this article, is advancement of theoretical methods of fracture mechanics, experimental estimation of the thermal stressed state of finite bodies with single and multiple cracks and detection of the above-mentioned factors effect on fracture kinetics and bearing strength of a body. For the theoretical and experiment simplification ZrC, SiC, Al_2O_3 specimens in a cylinder form were used. Such specimens were exposed to the axisymmetric radial heat flux when cooling or heating the side surface (A. G. Lanin et al., 1973) or when plasma (V. S. Yegorov et al., 1972) or electron-beam heating the top surface of the cylinder (A. G. Lanin et al., 1986). For finding the thermal stresses in an axisymmetric disk cooled along the side surface and having a radial crack the force problem is solved for the case when the stresses, equal in magnitude and opposite in sign to the thermal stresses in a disk without any cracks function at the crack surfaces and then the superposition principle is used. Finally, the stated problem is reduced to solving the system of integral equations (V. S. Yegorov et al., 1981).
On the basis of equality of the stress intensity coefficient K to its critical value K_c the calculated curves of the ultimate equilibrium of the crack in the thermally loaded disk (Fig. 1) are characterized by the nonequilibrium crack growth stage becoming the quasi-static one (curves 1-3) unlike the completely catastrophic crack spread at the uniform tension. When the thermal stresses σ_0 reach the critical value σ_c, the cracks instantaneously grow up to the length l_c defined by the right branch of the ultimate equilibrium curve. The finite length l_c depends on the temperature field profile. It



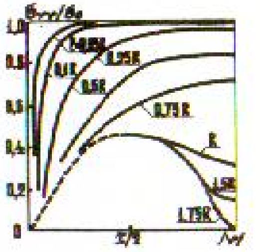
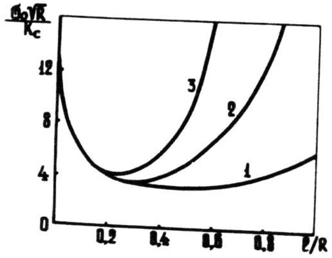


Fig. 1. The curves of the ultimate equilibrium of the edge crack in the disk cooled from the side surface with the temperature distribution along the parabola n=2 (1), n=6 (2), n=10 (3), the uniform tension - (4).

Fig. 2. The thermoelastic stresses on the contour of the disk of R-radius with the edge crack of length l at the temperature distribution along the disk radius according to the quadric parabola (n=2).

decreases with an increase of the tempereture field nonuniformity (with the n-value increase). This is obvious enough if one takes into account that in this case the tension area reduces. The increase of the finite crack length at the constant disk dimensions is connected with the $(\sigma_0\sqrt{R})/K_c$ complex increase, i.e. it takes place when the material strength increases and (or) the fracture toughness decreases. Therefore, after the critical thermal load $(\sigma_0=\sigma_c)$ has been reached, only a partial fracture becomes possible. When increasing the thermal load $\sigma_0>\sigma_c$, the crack $l>l_c$ grows quasi-statically but the disk fragmentation isn't achieved at its any finite level.
When the thermal load exceeds the critical one, the secondary microcracks appear. The location and the moment of appearance of the secondary microcracks are defined by redistribution of the stresses caused by the first crack. When the primary crack length $l<R$, the second crack can appear in the most loaded part of the disk along the same diameter with the first one. When $l>R$, two secondary cracks can appear. They are perpendicular to the first one at the point close to $\pi/2$ where the maximum stresses equal to $0,47\sigma_0$ (Fig. 2) remain on the disk contour.
The simultaneous development of two equal cracks located along the same diameter or four pair wise equal cracks located along the mutually perpendicular diameters results in a considerable change of the ultimate equilibrium curves. That determines the finite length of the stopped cracks and the critical loads for their subsequent quasi-static growth (Fig. 3).
Theoretical dependences were confirmed by test results of ZrC disks preliminarily uniformly heated and thermally insulated on their tops by cooling in room temperature waterbath. The calculation of temperature fields and stresses was performed taking into account the experimentally found dependence of



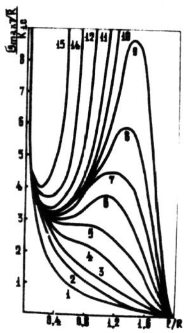


Fig. 3. The ultimate equilibrium curves for the disk having one (1), two (2) or four (3) equal edge cracks. For the parabolic temperature field (n=2).

Fig. 5. The ultimate equilibrium curves for the cylinder having an edge crack at the joint effect of the thermal stresses σ_0 and the uniform tensile (2-9) or compressive (11- 15) stresses σ directed along the normal to the side surface $\varkappa=\sigma/\sigma_0$; $\varkappa=\infty$ (1) only tension, $\varkappa=1$ (2); 0.5 (3), 0.2 (4, 15), 0.1 (5, 14), 0.05 (6, 13), 0.03 (7), 0.02 (8, 12), 0.01 (9, 11), 0 (10) - only the temperature field.

nonstationary heat exchange coefficient in water. The obtained experimental data on crack propagation in the disk without any cuts and with initial cracks confirmed existence of a nonstationary stage on the left-hand branch of ultimate equilibrium curve and quasi-static stage on the right-hand branch (Fig. 1). This allows to define fracture toughness values equal for ZrC 4+0.2 kg/mm$^{3/2}$ using one specimen many times. This agrees practically with the values K_{1c} measured by a force method. Formation of the secondary cracks in the disks considerably retards quasi-static growth of the first cracks l≥R (a shaded area in Fig. 1). At the thermal loads which are 3-3.5 times larger than the crack initiation load the set of cracks symmetric in the disk contour are formed (Fig. 4-2). Their penetration depth is lower than that of a single crack (Fig. 4-1) because of the unloading effect. If the first crack formation begins at the stresses equal to tensile strength limit σ_t the complete fracture is impossible even if the stresses σ_0 are 4-5 times larger than σ_t.

Combined influence on a body both thermal and force loads changes fracture conditions. The calculated dependence of the ultimate equilibrium of a cylindric body with a crack under joint force and thermal effect shows that when the uniform tensile stresses of 10% and more from the level of the maximum thermal elastic stresses are superimposed on each other, the sections of the quasi-static crack growth disappear (Fig. 5, curves 2-5), the crack becomes unstable, and the body fails completely. When the tension level is lower, the sections of the equilibrium crack growth are kept only up to specific load (Fig. 5, curves 6-9). But the superimposition of the

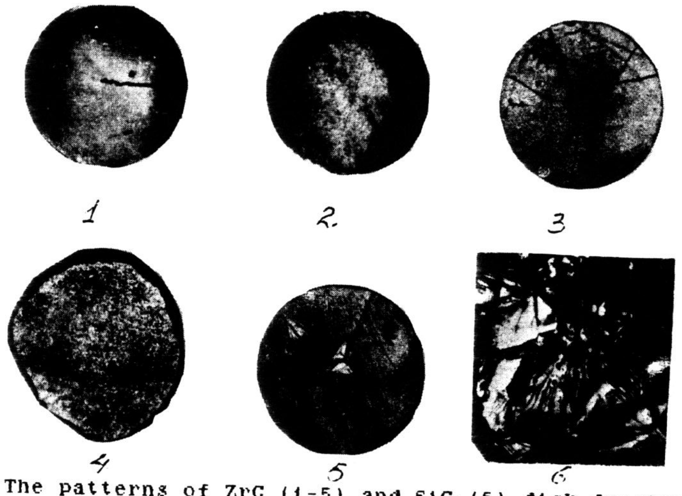


Fig. 4. The patterns of ZrC (1-5) and SiC (6) disk fracture by cooling of the side surface at $\sigma_0=\sigma_c$ (1), $\sigma_0=3\sigma_c$ (2), when heating the side surface $\sigma_0=\sigma_t$ (3), $\sigma_0>10\cdot\sigma_t$ t= 0.2 s (4), when local electron-beam heating $\omega=r/R=0.22$, $q_0=7.2$ kW/cm^2, $t_s=0.04$ s (5), 10.5 kW/cm^2, t=0.01 s (6).

compressive stresses (Fig. 5, curves 11-15) results in a marked decrease of the propagated crack length and, therefore, greater preservation of the body bearing ability. The theoretical estimations are confirmed by experimental data. When the ZrC disks are sharply heated in the melted tin, the tensile stresses arise in the central zone and the compressive stresses appear in the specimen periphery, the catastrophic fracture with fragments always occurs at moderate heat flows (Fig. 4-3). The maximum values of the tensile stresses in the disk center are only 2-2.5 times larger than the tensile material strength limit σ_t.

When the heat flow increases almost linearly with the melted tin temperature the high compressive stresses appearing in the periphery layers in the first fractions of a second at $Bio=(\alpha R)/\lambda=4$ and exceeding the tensile stresses by a factor of 9-12 in the specimen center are able to cause breaking off the disk edges (Fig. 4-4). The reason is that thermal stresses in the disk center didn't reach the tensile strength but the compressive stresses in the periphery exceeded the compressive strength limit.

The carried out calculations of the stressed state (V.S. Yegorov et al., 1972, 1975) when the top of the finite cylinder is uniformly heated show that the maximum tensile stresses appear in the axial direction at a distance from the top $\xi=z/R=1.04$ at the dimensionless time $Fo=(a\tau)/R^2=0.55$ (where λ and "a" are coefficients of thermal conductivity and thermal diffusivity, R - cylinder radius).

Distribution of the axial stresses σ_z on the radius in the

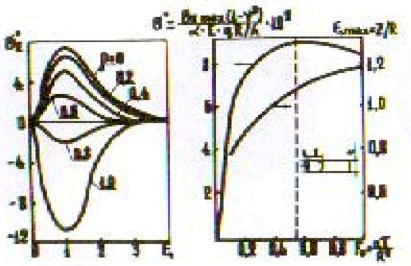


Fig. 6. Distribution of stresses along the cylinder length for different points on the radius $\rho=r/R$ at Fo=0.55 (a), change of the maximum values of the stresses σ_z and possible fracture point ξ depending on time (b).

cross-section $\xi=\xi_{max}$ is near the square parabola. The change of the tensile stresses to the compressive is in the point $\rho=0.72$. The experimentally obtained fracture coordinates and the initiation time of fracture confirmed the theoretical dependences. The curved fracture trajectory (shown schematically in Fig. 6, b) is caused by the field of the compressive stresses in the periphery layers of the cylinder. The crack forming in the centre of the cylinder zone ($\rho=0$) propagates catastrophically through the whole cylinder cross-section, overcomes the retarding influence of the compressive stresses and forms two fragments at the maximum values σ_z exceeding 2-2.5 times the material tensile strength limit.

The local heating of a part of the cylinder top area by means of an axially symmetric heat flow with an effective beam radius ω causes a complicated stress field varing according to time and defining the behaviour and conditions of fracture. The temperature field in the finite cylinder was calculated from heat equations using Laplace and Hankel transforms. Stress tensors conditioned by temperature field were calculated from the equilibrium and displacement equations converted on the basis of initial functions method to the system of differential infinite order equations brought to an algebraic equations system after corresponding substitutions (A. G. Lanin et al., 1986).

The results of their solution for specific cylinder dimensions H/R=0.2 and ω/R=0.225, obtained by an electronic computer with an error not more than 2% show (Fig. 7) that the appearing stress field (complicated and nonuniform) is specified by different localization of compression (A) and tension (B and C) zones and their change with time. When the time is small (t=0.04 s), the intensive two-axial compressive stresses in the surface layers border (at $\xi>0.3$) on a three-axial tension zone with a stress level by an order lower than the compressive stresses. From $\xi>0.7$ the compression zone is observed again. On the cylinder surface (z=0) in radial direction the compressive stresses change (at $\rho=0.2$) in the tensile ones and reach a maximum at $\rho=0.4$.

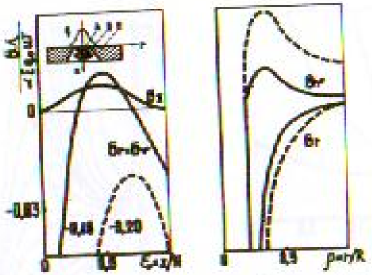


Fig. 7. Distribution of stress values along the axis at $\rho=0$ (a) and on the specimen radius at z=0 (b). Full lines for the time t=0.04 s, dash lines for t=0.023 s.

Such stress fields define the type of fracture when heating by an electron or laser beam. The high values of the tensile stresses appearing for a short period of time ($t_p<0.1$ s) (first in the zone (B) and then in the zone (C)) cause a crater in the central part of the ZrC and SiC carbide discs and then radial cracks. (Fig. 4-5). Because of the limited localization of the tensile stresses in the zone (B) and their high gradient both on the radius and along the thickness the crack incipient in the zone (B) propagates along the surface of a cone at an angle to the top of a specimen by-passing the zone (A) of the maximum compressive stresses in the central part and reaching the top surface at the point $\rho=0.2$ where the component σ_φ is a tensile one. The peak of the crater is formed at a distance of $\xi=0.3-0.5$ from the cylinder end. This corresponds to the point of appearance of the maximum tensile stresses. It is typical that in some cases the incipient crack jams in the bulk of the specimen without reaching the surface. This can be observed on the relatively transparent SiC-specimens (Fig. 4-6) (A. G. Lanin et al., 1990).

The analysis of the obtained results shows that the form of the thermal stressed state has a considerable influence on the ultimate stress level and the character of the brittle body fracture. The used fracture mechanics approach to thermally loaded bodies allows to give a more complete and precise description of the features of the crack spread in nonuniform stress fields in comparison with the existing energy concepts. Attainment of the ultimate stress intensity coefficient K_{1c} is a necessary condition for a crack motion initiation. For description of fracture of a body having extended compression areas it becomes necessary to take into account the loading history and kinetics of the stress redistribution in the bulk of a finite body at all intermediate stages of the crack propagation.

The main distinction of the body fracture when compressing from the fracture at tension is that cracks in the compressed area when reaching the critical coefficient of stress intensity K_{1c} grow quasi-statically in the direction parallel to the compression axis when the load increases continuously. The complete body fracture is possible only after a certain extent of the crack interaction and their following catastrophic growth (A. G. Lanin et al., 1985).

It's necessary to emphasize that thermal shock resistance as well as strength of a body under force loading is not a material constant. It is a complicated characteristic depending on a tested body form and external action conditions: load type, temperature and medium. When estimating the service life of a thermally loaded product: reserve of its thermal shock resistance or a bearing ability loss at thermal damage, it is necessary not be mistaken to use (when testing the specimens) the loading methods corresponding most of all to the natural stressed state like it is done in engineering practice for development of force stressed constructions.

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