CRACK-RESISTANCE TESTS OF MATERIALS: STATE AND OUTLOOKS

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ABSTRACT

The paper considers problems of analysis of fracture toughness and resource for complex three - dimensional up-to-date structures operating under high loadings (static and cyclic ones) and temperatures in which structurally - homogeneous and bimetallic materials are applied. The paper presents results for material test under combined loading, investigations of structurally - inhomogeneous materials as well as application of methods developed to estimate fracture toughness and resource of structure elements

KEYWORDS

Fracture mechanics criteria, structiral - mechanical inhomogeneity of properties, self - heating at crack-tip

INTRODUCTION

Crack resistance assessment for structure elements is a highly complex problem of which solution calls for special investigations being at the joint of fracture mechanics and experimental mechanics. This work includes the following studies:

- development of fracture mechanics criteria and testing techniques for combined loading patterns;
- development of experimental methods to obtain the fracture mechanics parameters of three-dimensional components of cracked structures undergoing combined loading;
- development of criterial approaches and testing methods for materials exhibiting a structural-mechanical inhomogeneity of properties;
- analysis of damage distribution regularities at a tip of a crack and along the path of its probable propagation;
- development of a method to assess an influence of self-heating at a crack-tip zone during cyclic deformation on the crack growth kinetics.

The paper presents results of scientific - methodical developments in the field of calculational, experimental and analytic - experimental methods to investigate the parameters with taking these factors into account.

CRITERIAL RELATIONSHIPS

Criterial relationships for the problems concerning a crack under a combined loading are being formed in the frames of the linear fracture mechanics. However even in this case when external force action for a crack tip zone is characterized only by stress intensity factors K_I, K_{II}, K_{III} (elastic stress state) a fracture process can occur according to numerous and multiform mechanisms. A simplified classification of macroscopic fracture mechanisms in the frames of the linear fracture mechanics is proposed (Table I). The arrows on the schemes show a relative displacement of crack edges. The meanings f_1 are represented as correction functions for the K_I value. In the case when $K_I = 0$ the values of K_σ, K_τ are to be defined through the meaning of K_I and a fracture of the function at parameter p.

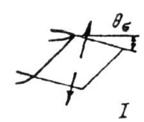
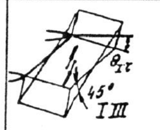
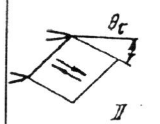
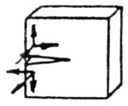
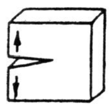
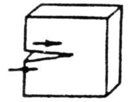
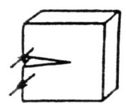
If according to the Table I an ultimate state is determined in terms of the criteria of the maximum tensile and tangential stresses then a similar approach can be developed for any of the known criteria of the fracture mechanics (Fisher,1984; Makhutov and Koksharov, 1991) which will define only a kind of the function f_1. On this base a notion of equivalent stress intensity factor is used which can be found in terms of the expression $K^Э = K_i f_i$ where f_i is a function obtained according to the chosen criterion (Makhutov and Koksharov, 1991).

The numerous computations made for a plate with an inclined crack (Fisher,1984; Makhutov and Koksharov, 1991) showed the series of criteria to give the similar assessments of breaking-down stresses within the accuracy being acceptable for engineering estimations. An important aspect both for cracks of normal separation and for cracks of a mixed kind presents a problem of short cracks for which an account of nonsingular terms of elasticity theory problems turns out to be significant.

Two-parameter approaches to the fracture mechanics developed according to this foundation when two parameters are being introduced into the equation of the ultimate state for example ultimate strength δ_c and fracture viscosity K_c, do not give breaking-down stresses exceeding the ultimate strength; as distinct from the singular approach. For ductile materials it is more expedient to consider the problem of mixed loading in the frames of the strain criteria of the fracture mechanics (Makhutov,1981).

Below we present the results of the tests aimed to determine the ultimate meanings of K_{IIc} and performed on specimens of Al-alloys AMr6 (σ_p = 170 MPa, σ_c = 351 MPa, e_c = 21%, K_c^I = 41 MPaM$^{1/2}$) and D19AT (σ_p = 365 MPa, σ_c = 476 MPa, e_c = 13,5%, K_c = 54 MPaM$^{1/2}$) with fatigue cracks. Fig.1 presents results of tests performed on specimens in which pronounced plastic strains at a range between crack tips occurred before fracture. Plastic

Table 1. The criterional relationships of linear fracture mechanic for mixed-mode loading cracks

Macromechanisms of fracture					
Limiting values of SIF		K_c^I	K_c^{I-III}	K_c^{II}	K_c^{III}
Characteristics of loading					
K_I K_{II} K_{III}	 I+II+III	$K_\sigma < K_c^I$, $K_\sigma = K_I \cdot f_\sigma\left(\frac{K_{II}}{K_I}\right)$	$K_{I\tau} < K_c^{I-III}$, $K_{I\tau} = K_I\, f_{I\tau}\left(\frac{K_{II}}{K_I^H}\right)$	$K_\tau < K_c^{II}$, $K_\tau = K_I\, f_\tau\left(\frac{K_{II}}{K_I}\right)$	$K_{III} < K_c^{III}$
K_I	 I	$K_I < K_c^I$	$K_{I\tau} < K_c^{I-III}$ $K_{I\tau} = \beta K_I$ $\beta = 0{,}446$ (plane stress)	$K_\tau < K_c^{II}$ $K_\tau = 0{,}385 K_I$	
K_{II}	 II	$K_I < K_c^I$ $K_\sigma = 1{,}15 K_{II}$	$K_{I\tau} < K_c^{I-III}$ $K_{I\tau} = \beta K_I$ $\beta = 0{,}065$ (plane stress)	$K_{II} < K_c^{II}$	
K_{III}	 III				$K_{III} < K_c^{III}$

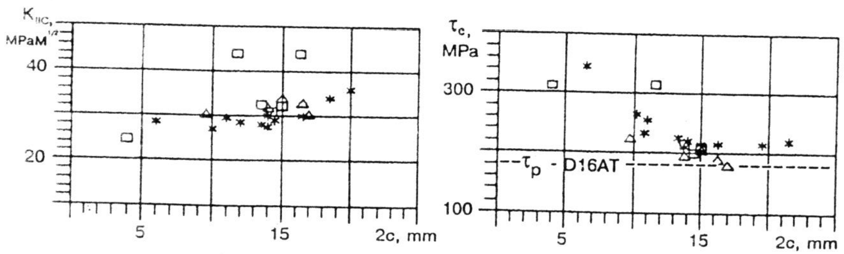
$$f_\sigma\left(\frac{K_{II}}{K_I}\right) = \frac{1}{2}\left((1+\cos\Theta_\sigma) - 3p\sin\Theta_\sigma\right)\cos\frac{\Theta_\sigma}{2},$$

$$f_{I\tau} = 2^{-\frac{9}{4}}\left[\cos\frac{\Theta_{I\tau}}{2}(3-\cos\Theta_{I\tau}) + p\sin\frac{\Theta_{I\tau}}{2}(3\cos\Theta_{I\tau}-1) - A\left(\cos\frac{\Theta_{I\tau}}{2} - p\sin\frac{\Theta_{I\tau}}{2}\right)\right],$$

$$f_\tau\left(\frac{K_{II}}{K_I}\right) = \frac{1}{4}\left[\sin\frac{\Theta_\tau}{2} - \sin\frac{3}{2}\Theta_\tau + p\left(\cos\frac{\Theta_\tau}{2} + 3\cos\frac{3}{2}\Theta_\tau\right)\right],$$

$$\Theta_\sigma = 2\,\mathrm{arctg}\left[\frac{1-\sqrt{1+8p^2}}{4p}\right], \quad \cos\frac{\Theta}{2} + 3\cos\frac{3}{2}\Theta - p\left(\sin\frac{\Theta}{2} + 9\sin\frac{3}{2}\Theta\right) = 0\Big|_{\Theta=\Theta_\tau},$$

$$\Theta_{I\tau} = \Theta_\sigma + \frac{\pi}{2}, \quad A = \begin{cases} 0 \text{ - plain stress} \\ M \text{ - plain strain} \end{cases}, \quad p = \frac{K_{II}}{K_I}$$



□,* - D16AT: □ - shear under tension
* - shear under compression

△ - AMr6: shear under tension

Fig. 1. Test results of AL-alloys to determine the ultimate meanings of K_{IIC}

deformation of the specimens was accompanied by slow growth of cracks. Ultimate fracture took peace at high rates of crack propagation and was accompanied by "clap" characteristic of brittle fracture according to the Model 1. Due to the presence of pronounced plastic strains at the whole section we must consider a longitudinal characteristic K_C^{II} only as a conventional one in the frames of the fracture mechanics. The Fig.1 presents also breaking-down stresses which did not exceed an accepted yield stress τ_p = 0,5.σ_p. With increased tip-to-tip distance the increased ultimate values of K_C^{II} and reduced tangential stresses are observed. The similar test on specimens with cracks (w = 80 mm, t = 5 mm, 2c = 14-18 mm) being made of low-carbon steel permitted to obtain conventional characteristics of K_C^{II} = 51,6 MPa M$^{1/2}$ and breaking-down tangential stresses τ_p = 329 MPa. When the temperature was lowered to -120°C these characteristics were increased to correspondingly 65,3 MPa M$^{1/2}$ and 367 MPa which fact is due to increased plasticity value for low temperatures.

EXPERIMENTAL FRACTURE MECHANICS METHODS

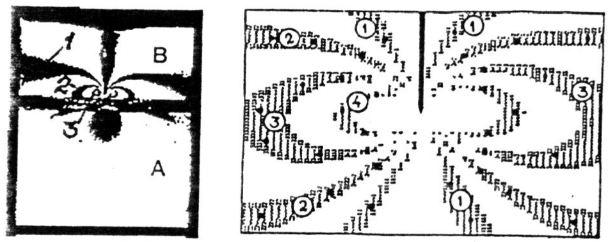
The fracture mechanics stated the new tasks to be achieved and encouraged development of experimental mechanics methods in the corresponding directions. These methods can be in essential classified into two categories:

- methods to measure length of a propagating crack (optical, magnetic and other techniques);
- methods to analyse a stressed-strained state of cracked structural components (photo-elasticity, holography, moire, caustic - method and so on).

The methods related to the second category give opportunity to obtain directly on full-scale objects and on specimens

the parameters being necessary to analyse brittle strength of cracked structures. At the same time the holographic interferometry and micromoire methods which permit to perform direct measurement, to determine displacement fields at a crack tip zone within an accuracy up to 0,1 mkm open roads to deeper knowledge of crack formation mechanism (Vogel,1991). The photoelastisicity method that permits to perform experimental investigations for a general case of loading of three-dim cracked objects. Variety of the problems being solved with high accuracy of data being obtained including ones for the zones of high gradients of stresses give efficiency of the polarization - optical methods in solving general-purpose methodical and practical problems of the fracture mechanics.

As of now a package of procedures have been developed to determine stress - intensity factors K_I,K_{II} and K_{III} in terms of results of polarization - optical measurements, made by use of the least - square methods, on plate, three-dim optical models and photoelastic coatings (Makhutov and Razumovsky, 1989). Those developments can
be used to study piece - uniform structures with cracks (Fig.2) as well as to define nonsingular terms for analytical representation of the stress field at a crack zone alongside with stress intensity factors. This fact is of importance for estimation of short cracks on a basis of the two - parameter approaches.



a) band pattern for a crack tip (slice of 3D optical model)

b) computer-plotted image of a band pattern

a) b)

A - main material; B - corrosion proof austenite steel

Fig. 2. Investigation of SIF distribution along a front of edge of semi-elliptic crack in bimetal shell on "frozen" optical method

INVESTIGATIONS OF PIECE-HOMOGENJOUS BODIES AND WELDED JOINTS WITH CRACKS

Use of piece - homogencous bodies of bimetals and welded joints - type in high loaded structure components stimulated development of analytical and experimental methods to assess their crack - resistance with due regards for mechanical and structural inhomogeneity. Solution of problem on edge and central cracks in layeredmaterials promoted development of the stated directions being connected with determination of stresses, strain and displacements near a crack edge free of loading in two - layered elastic medium and creation of local fracture criterion (Kuliev and Nasibov, 1983).

Successful development of fracture mechanics of piece - homogeneous cracked bodies was favoured by investigations of crack retardation at the boundary of two different elastic mediums (V.D.Kuliev et al., 1978). It is of particular importance for the cases when the cladding layers have reinforcing effect. As it was shown for two - sided cladding band of main metal (width 2l), with central crack (size 2a) a rational choice of strength and stiffness parameters of cladding layers can provide a stable crack growth in three - layered material with sufficiently high values of defects (α = a/L) within α = 0,6 ... 0,95. The results obtained promoted development of theoretical foundations for bimetal crack - resistance test methods and gave opportunity to realize the new mechanical - technologic methods to increase loading capacity of structure components with crack - like defects (Parton et al.,1977).

For structurally and mechanically inhomogeneous bodies of welded junctions type it is of significant interest to determine crack - resistance in terms of tradditional mechanical characteristics of materials (ψ,E,μ) and structural parameter ρ (V.V.Panasiuk et al., 1977). Due to the fact that in bimetals, welded junctions and other structurally and mechanically inhomogeneous cracked bodies. a combined fracture can be observed it is expedient to apply the continuous fracture model being based on conception of fracture dimorphism in local volumes (Chizik, 1979).

Deformation and fracture of bimetals due to damafe accumulation in elasto - plastic loaded structure components of transient zones and layers can result in significant increase of local inelastic strains. The latter ones will result not in local stress increase at crack zones but in strain intensity factor decrease which makes expedient to use in this case the strain criteria of fracture based on strain diagram parameters and founded characteristics of mechanical properties (Makhutov, 1979).

Use of the mentioned relations gave opportunity to perform a detailed analysis of crack stability in bimetals with due regards for local elastic and strength characteristics of separate structure components of transient zone which is really formed between the main metal and a cladding layer. Besides it turned out to be very important to take into consideration the mechanisms of mechanical microdamage accumulation (according to V.V.Bolotin) which were used as a basis for physico - mechanical model of bimetal fracture (Makhutov et al., 1991).

THERMO-RELATED DEFORMATION OF BODIES WITH CRACKS

Combination of cyclic elasto - plastic strains and increased loading frequencies permits to realize so-called thermo - related deformation condition (self - heating up) being

characteristic in particular for the zones of sharp strain concentrators of a crack type. Various approaches to this problem are being developed laterly.

The finite-element method (FEM) presents the most wide possibilities to solve the related thermo-mechanical problems. Use of this method in combination with the experimental procedure of temperature field variation recording (ASEMA-782 unit, measurement accuracy within ±0,1° C) is the most general and efficient technique to solve complex practical tasks, to consider nonisotermic , physically and geometrically monlinear deformation of body.

In the pachage of programs FEM which had been developed at Mechanical Engineering Research Institute (Academy of Sciences of Russia) the equations of nonisothermic flow theory with combined strengthening (isotropic +kinematic) are used as the basic equations. The yield surface can depend on strain strengthening, temperature and time. The program also provides for solving the problem in geometric monlinear statement. The methodologic approach mentioned was used to develop procedures to analyse longevity of structure components at thermo-related deformation on a basis of a notion of elasto-plastic strain intensity factor. The methodology permits to determine the upper and lower boundaries of durability for the given growth of a crack. The obtained results being in a good agreement with the corresponding experimental investigations show the efficiency of related thermomechanical deformation with local heat release near a crack tip to be taken into consideration when increased cyclic loadings with frequencies of 5÷10 Hz and higher are

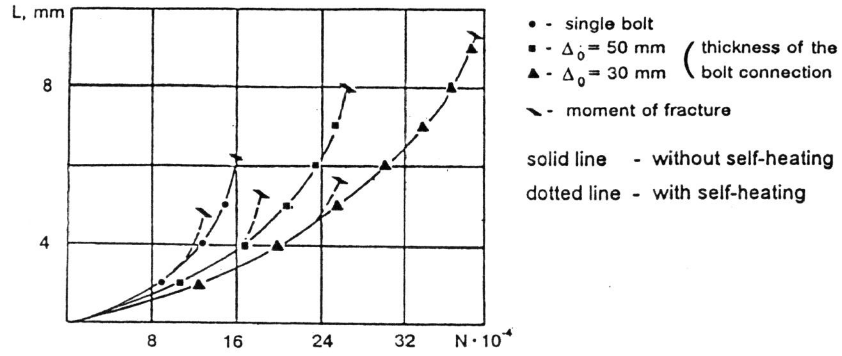


Fig. 3. Curves of crack growth in bolt connections

present. Fig.3 shows an example of analytical results. For this analysis a bolt was simulated by a solid cylinder (diameter d = 27 mm) having a ring crack (R = 2,0 mm). The loading conditions were the following: σ_T = 0,3; σ_1 = σ_{max} = 0,9 σ_T; frequency γ_o = 60 Hz. The material was XI8H10T.

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