CHARACTERISTICS OF FATIGUE-Crack RESISTANCE OF ALUMINUM ALLOYS IN COMBINED MODES OF FAILURE UNDER BIAXIAL LOADING

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The article contains a complex quantitative evaluation of the effect of the state of stress and of the angle of orientation of the initial crack on its growth rate for eight aluminum alloys subjected to combined modes of biaxial extension. A new dimensionless parameter of fatigue-crack resistance is introduced and substantiated.

It is established that there exists a single dependence of the crack growth rate on the suggested parameter for all the investigated aluminum alloys with different mechanical properties.

Most structural elements operate under conditions of complex state of stress, having variously oriented initial crack-type defects. It is therefore of particular interest in practice to obtain information on the effect of the kind of state of stress in combination with arbitrary orientation of the initial crack on crack resistance when the conditions of real operation of thin-walled structural elements are modeled. The solution of such problems in crack mechanics comes under the heading of combined modes of failure. However, the evaluation of the effect of biaxiality of loading on the characteristics of fatigue-crack resistance is ambiguous even in the case of symmetric failure. The available information is contradictory and incomplete.

The aim of the present work is a complex quantitative evaluation of the effect of the kind of state of stress on the characteristics of fatigue-crack resistance of aluminum alloys with a broad range of properties under conditions of combined modes of failure.

As a rule, aluminum alloys are used as material of thin-walled structural elements for which cyclic loading is decisive from the point of view of load bearing capacity. In the present work I therefore confine myself to the conditions of plane state of stress in plates with through cracks with arbitrary orientation in a field of variable biaxial stresses of unequal intensity.

The investigation of crack development under biaxial cyclic loading has a number of traits distinguishing it from the already specified tests of specimens in uniaxial symmetric extension. One of the main methodological problems in these investigations is the selection of the geometry of the specimens for the realization of fields of biaxial nominal stresses with specified ratios. The geometry of the specimens and the arrangement of loading them have to ensure a uniform state of stress and strain (SSS) in the working part, which, in turn, has to suffice for measurements of crack growth.

The authors of [1-6] prefer flat cross-shaped specimens with central notch for these purposes. In the present work I chose specimens with eight lobes (Fig. 1) which ensure a larger zone of uniform SSS than the cross-shaped specimens without longitudinal through grooves in the loading lobes in consequence of the change of their geometry in dependence on the specified ratios of the nominal biaxial stresses. This is confirmed by the results of an analysis of the SSS of specimens with eight lobes by the finite element method (FEM) [7]. The authors of [7] also presented the K-calibration of a specimen for equibiaxial extension ($\eta = 1$).

It is known that for cracks not coinciding with the axes of symmetry of the external load and of the geometry of the structure in plane state of stress two forms of failure are realized: they are characterized by the corresponding stress intensity factors (SIF) of normal detachment ($K_1$) and of transverse shear ($K_2$). The main peculiarity of tests of materials with an initial inclined crack is that the crack does not develop in the initial direction and has a curved path. This creates difficulties of an experimental and numerical nature connected with the measurement of the position of the crack tip on the path of its development and with the calculation of the SIF for these positions. The approach based on the concept of a rectilinear crack
made it possible to overcome these difficulties, and as a result the authors of [8] suggested a method of interpreting the results according to the characteristics of fatigue-crack resistance with combined modes of failure. This method was used in the present work for processing the results of tests concerned with the crack growth rate. Within the framework of this method the FEM yielded K-calibration functions of the SIF for specimens shown in Fig. 1a, and it was also suggested to use the parameter of strain-energy density introduced in [9] as the equivalent SIF:

$$S = a_i K_i^2 + 2a_{i2} K_i^2 + a_{i3} K_i^2,$$

where

$$K_i = \frac{\sigma \sqrt{2}}{2} [(1 + \eta) - (1 - \eta) \cos 2\alpha]; \quad K_i = \frac{\sigma \sqrt{2}}{2} (1 - \eta) \sin 2\alpha, \quad \eta = \frac{\sigma_{xy}}{\sigma_{yy}};$$

$$a_{i1} = \frac{1}{16G} (\chi - \cos \theta) (1 + \cos \theta); \quad a_{i2} = \frac{2}{16G} (\cos \theta - \chi + 1) \sin \theta;$$

$$a_{i3} = \frac{1}{16G} [(\chi + 1) (1 - \cos \theta) + (3 \cos \theta - 1) (1 + \cos \theta)];$$

$$G$$ is the shear modulus; $$\chi = (3 - \nu)/(1 + \nu); \quad \nu$$ is the Poisson ratio. Besides that it was suggested to coordinatize the position of the crack tip on the crack development path by the pair of equations [8]:

$$a_i = a_{i-1} + \Delta a_i \Delta a_i \cos (\alpha - \theta_{i-1});$$

$$a_i = a_{i-1} + \arcsin \frac{\Delta a_i \sin (\alpha - \theta_{i-1})}{a_i},$$

where $$a_{i-1}, \alpha_{i}, \alpha_{i}$$ are the preceding and subsequent length and slope of the crack, respectively; $$\Delta a_i$$ is the increase of the crack length within the cumulated number of load cycles $$\Delta N_i$$. The angle in Eq. (2) at which the crack further propagates was determined, in distinction to the traditional method according to any desired criterion, from the approximation of the experimental dependences $$(-\theta^* - \alpha)$$ by Lagrange polynomials for each investigated material with the specified kinds of nominal biaxial state of stress. This is so because at present, as shown in [10], there are no universal criteria of the direction of crack growth. The use of the strain-energy density S as parameter controlling crack growth under the conditions of combined modes leads to the following regularity of the crack growth rate [11]:

$$\frac{da}{dN} = \left( \frac{da}{dN} \right)^* (S_{max}/S^*)^n,$$

where $$\frac{da}{dN}$$ is the crack growth rate; $$S^*, \ n$$ are experimental constants; $$\left( \frac{da}{dN} \right)^* = 10^{-7} \text{ m/cycle}$$.  

Fig. 1. Geometry of the specimens for biaxial (a) $$\eta = 0.5$$, (b) $$\eta = 1$$ and uniaxial (c) extension. (The dashed line indicates the boundary of the zone of uniform SSS.)