NUMERICAL OPTIMIZATION OF CRUSIFORM SPECIMENS GEOMETRY FOR PERFORMED THROUGH AND SEMI-ELLIPTICAL FATIGUE CRACKS UNDER BIAXIAL CICLIC LOADS AND CRACK GROWTH SIMULATION.

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ABSTRACT

Several variants for the stress-state calculation were considered on the basis of the FEM analysis to optimize the cruciform specimens sizes for tests under biaxial cyclic loads for through and semi-elliptical cracks. The optimization was performed to locate in the center part of the specimen uniform biaxial stress-state for the specimen thickness 2mm, 5mm, and 10mm. The 3D analysis was used to calculate stress-state ahead of a crack tip for elliptically shaped crack.

The fatigue crack growth simulation was performed on the basis of the new model, which used the size of the stretched zone performed under an overload to estimate the crack increment. The results of the crack growth simulation under the biaxial cyclic loads in this case are discussed.

1 INTRODUCTION

Many aircraft components in flight have experienced a biaxial stress-state resulting from external loads [1]. The fatigue crack growth in this case can be considered on the basis of the well-known criterion for the determination stress intensity factors from knowledge of plastic zone sizes when various external loads are applied to a component [2].

The stress intensity equivalent factor, K_e, has been introduced to describe fatigue crack growth in components on the basis of this criterion plus a synergistic approach [1], [3]:

$$K_e = K_I [1+\sum_{i=1}^{k} f(X_i)]^{1/2} = K_I F(X_1, X_2 ... X_i) \qquad (1)$$

There are X_i parameters of external cyclic loads in eqn (1) that increase or decrease crack growth compared with the standard situation of a uniaxial tensile load with R=0 when the stress intensity factor K_I has been determined. The equivalent stress intensity factor K_e is that which gives the same value of the fatigue crack growth rate. In the case of biaxial cyclic loads with various R-ratios it should give the same crack growth rate for the cyclic loading parameters l_1, R_1 and l_2, R_2. Hence the correction function is constant and equal to 1 under equivalent conditions. This indicates the possibility of describing the crack growth rate at different l, R values with one kinetic curve according to which the growth rate depends on the value of an equivalent stress intensity factor $l, R\, K_e = K_I F(l, R)$, where $F(l, R)$ is dimensionless correction function of the stress intensity factor for various biaxial stress-state.

The function correction $F(l, R)$ in fatigue tests must to be determined under uniformly biaxial cyclic loads. That is why, the specimen sizes optimization was performed to realize the central part with a permanent l -ratio within a several tens millimeters diameter on the basis of the finite element analysis.

The semi-elliptic fatigue crack growth is not the same that discovery for the through crack [4]. It pierces through the specimen section in the depth direction and simultaneously growth by the specimen face. The specimen thickness for the crack size in the depth direction have to be enough for the crack size in several tens millimeters on the specimen surface. This situation can be exceeded for the thick specimen with the thickness more than 10mm. At the same time for the specimen grip ends have to be used more thickness that for the central part of the specimen to realize the enough level of the maximum principal stress of the regular cyclic loads.

Fatigue crack growth after an overload depends on the overload level, principal stress level, stress intensity factor, $R-$ratio, specimen thickness and other parameters [1]. However, all well-known models of fatigue crack growth, which have been developed for the case of uniaxial overloads, can be expressed in the following form:

$$(da/dN) = \tilde{N}_t \; (da/dN)_0 \tag{2}$$

In the Eq.(2) the factor $\tilde{N}_t$ includes all parameters influencing the growth rate after an overload as a result of cyclic loads interaction effects, and $(da/dN)_0$ correlates to the crack growth rate without an overload. The stress intensity factor K_e takes into account many factors influencing growth rate at a regular cyclic load, i.e. frequency, temperature, environment and others.

But in the case of very frequently introduced overloads the dominant role for interaction effects of cyclic loads played the process of the plastic deformation material at the crack tip, which influenced the crack increment. The model of fatigue crack growth simulation under irregular biaxial cyclic loads has to use knowledge about this process.

The paper presented FEM-analyses for cruciform specimens from Al-based alloys, which were used for cyclic loads tests under biaxial loads. Investigations carried out for regular and irregular biaxial cyclic loads of D16T and AK6 Al-alloys. A model of crack growth under cascade of cycles with overloads in the case of biaxial loads is proposed. The main idea of the discussed model is about dominant role of the plastic deformation process at a crack tip, which influenced the crack increment during overload.

2 FEM OPTIMIZATION OF THE CRUCIFORM SIZES FOR THROUGH CRACKS

To investigate the through fatigue crack growth under biaxial cyclic loads usually used cruciform specimens. One of the problems for specimen geometry to optimize specimen dimensions in such a way that a permanent biaxial stress state was obtained in the central part within as much diameter as possible. The second problem must be resolved for specimen thickness. It is need to be done for the case of the specimen cyclic loading under the biaxial tension-compression.

Both problems were resolved on the bases of the FEM calculation for cruciform specimens of 1.5mm and 5mm in the thickness with different central notches used for through fatigue cracks growth investigations. An elastic stress analysis was carried out for the cruciform specimen using the general program for the finite element method-calculation ANSIS. Material's constants of Young's modulus, Poisson's ratio and Yield stress are $E = 70\,GPa$, ν=0.3, $s_{0.2}$=350MPa, respectively for D16T Al-alloy.

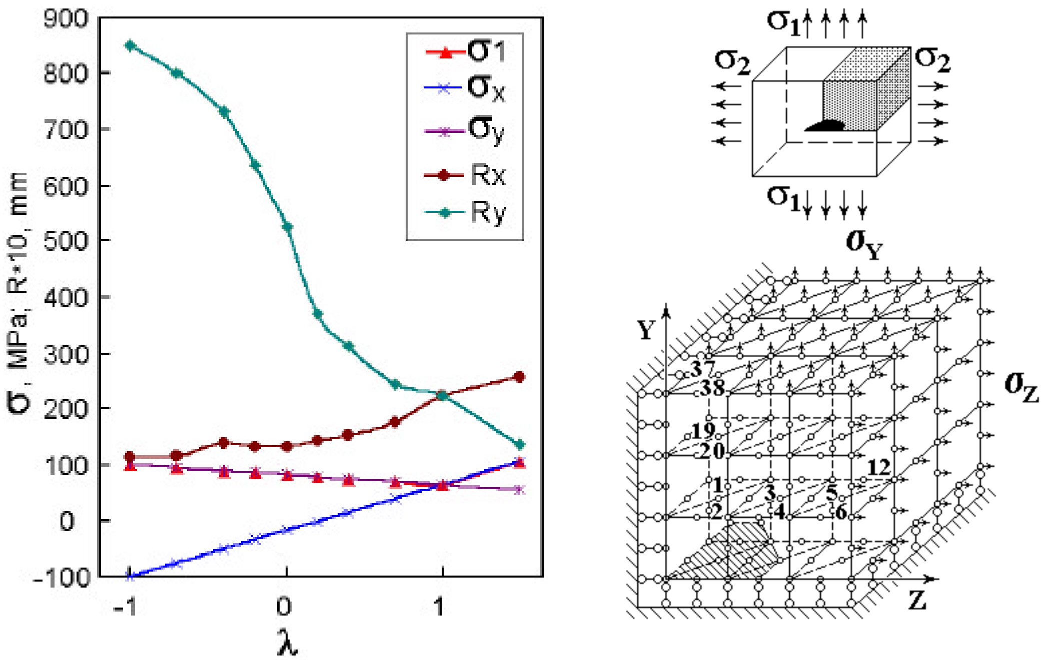
High stress region was built up in the central region of the specimen by reducing the thickness for crack not to originate at the corners. Then stress analysis was carried out for the cruciform specimen with t =5mm in thickness at the center by means of the three dimensional elastic FEM. The eight node-isoparametric elements of which numbers are 604 and 1014 in the mesh element and the node were used. The stress analysis was performed for the specimen of t =5 mm under the tensile equi-biaxial stress condition of $s_1 = s_2$= 100MPa, where $s_1 = s_2$ are the stresses applied at the grip ends in the X-and Y- directions in Fig.1, a. The similar calculation was performed for the specimen of t =1.5 and 2mm under the tensile equi-biaxial and the tension-compression stress condition of s_1= 56MPa.

The results of calculation have shown the permanent biaxial stress-state within a 20 mm and 40 mm diameter for specimens with thickness 1.5 mm and 5 mm respectively. The differences between the stresses at the center and radius 10mm and 20mm for specimen thickness 1.5mm and 5.0mm, respectively was less 2.5 percent of the ones at the center, which holds under equi-biaxial loading conditions other than $s_1 = s_2$= 56MPa or 130MPa.

2.1 Semi-elliptical cracks

A finite-element approach was employed to numerically determine the stress-state a plate that involves a semi-elliptical fatigue crack. The calculations were done in two steps. Steps one using two-dimensional plane FEM to describe the general stress-state of the plate. Steps two was to calculate the stress-state of a metal volume at a crack tip; here we used three-dimensional FEM. The idea was that the solutions, obtained in terms of two- and three-dimensional FEM, would coincide at the outer border of this volume.

Tetrahedral finite elements with linear approximation of displacements are utilized. 1/8 part of a periodicity cell is divided into parallelepipeds. Each one of them in its turn is divided into six tetrahedrons by three cross-sections, parallel to coordinate axes and containing side diagonals. The example of cell's discretisation is shown in Fig.1,b, (periodic cells) for one of the fatigue crack position.



a) b)

Figure 1: Results of FEM analysis (a) for stress-state estimation and radius R_x, R_y for uniformly stress state of the cruciform specimen in 5 mm of the thickness, and (b) periodic cells used in the cruciform specimen of the 10 mm in the thickness for the semi-elliptical crack.

3 CRACK GROWTH SIMULATION UNDER IRREGULAR BIAXIAL CYCLIC LOADS.

The crack growth simulation was performed for cruciform specimens of 5.0mm in the thickness. In the middle part of the test specimen with this thickness, the crack plane does not deviate too far from the horizontal plane at any l -ratio. That is why the crack growth simulation is done without taking consideration the deviation of the fracture plane from the horizontal plane for various l -ratio. So, the first step of numerical analysis for the fatigue crack growth modelling was performed taking

consideration the functional correction $F(l, R)$ in the case of through cracks growth [3]. It used to calculate the stress intensity factor by the eqn (1).
The plastic zone size, a_D, within which the load interaction effect after an overload can be seen, can be calculated on the basis of the maximum tensile deformation theory by the next relation [1]:

$$a_D = (a_D)_0 [0.25 l^2 - l + 1][1.5 - R] \qquad (3)$$

The crack growth simulation must be derived from eqn (3) for various R ratios in the range $0.1 < R < 0.5$ and $0 < l < 0.7$.
The crack simulation was developed by the relations taken from the reference [1] when the crack increment, Δ_f, during one-cycle estimates without calculation of the stretched zone. The reviewed relations were introduced for the fatigue crack simulation in the case of a number of cycles between overloads, which are enough to cross by the crack the plastic zone performed under an overload. But in reality sequence of cyclic loads, which reproduced, for instant, the aircraft loading by flight, can be performed with permanent increasing of the maximum stress level from one cycle to another.
That is why there was introduced two-parametric model for loads interaction effect, when a size of the stretched zone, d_{st}, was used to estimate the fatigue crack increment under an overload, as shown in Fig.2, a. There was examined a block of cyclic loads that have been discovered from the stress-state analysis in several flights for one of the wing area of the civil aircraft Yak-42, Fig.2, b. The biaxial stress ratio was in the range of $-0.2 < l < +0.5$ for 55 cyclic loads of the schematised block for one flight.
The earlier performed measurement have shown correlation between the stretched zone size and the stress equivalent value, K_e, in the range of $-1.0 < l < +1.0$ and $0.1 < R < 0.8$ [3]. On the basis of these measurements can be introduced the next relation for the mean value, d_{st}, of the stretched zone:

$$d_{st} = C_o + C_1 K_e \qquad (4)$$

The sequence of events during one cycle of loading used for simulation fatigue crack growth was the next: a) during uploading the crack increment takes place because of the stretch zone formation; b) during unloading the crack increment takes place because of material fracture [1]. As a result, it allowed to us to estimate the crack increment in one cycle of loading from the next relations:

$$\begin{aligned} (\Delta_f) &= d_{st} + a_d \qquad \text{for } (K_e)_{i+1} \geq (K_e)_i \\ (\Delta_f) &= a_d, \qquad \text{for } (K_e)_{i+1} \leq (K_e)_i \end{aligned} \qquad (5)$$

The fatigue crack growth simulation by the eqns (1)-(5) have shown that for the biaxial cyclic loads the crack increment because of stretch zone formation is dominant for the cyclic loads sequence, shown in Fig.2. In the case of biaxial tension-compression the crack growth period under the principal stress s_1= 70 MPa decreases on 4.5% (209 blocks of cyclic loads) in comparison with the case of l =0 for the crack interval 10-20mm. In the case of biaxial tension the crack growth period under the principal stress s_1= 70 MPa increases on 3.5% (160 blocks of cyclic loads) for the same crack growth interval.

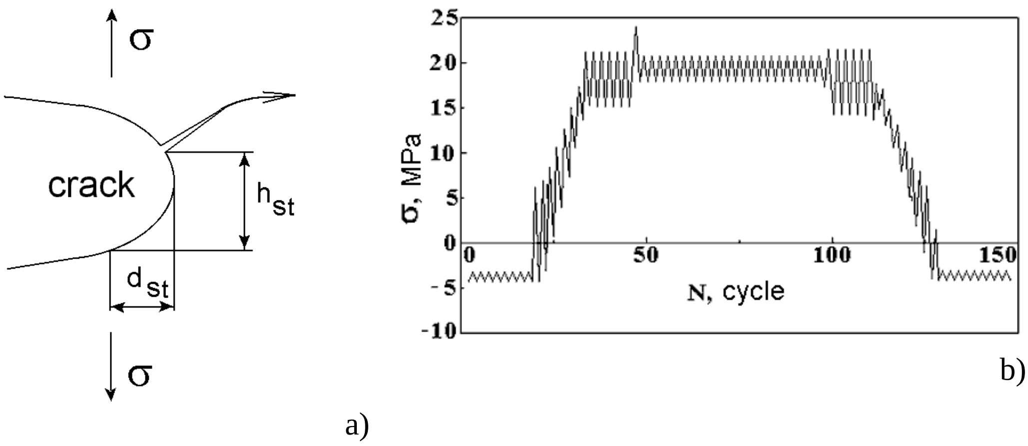


Figure 2: Parameters (a) for schematized stretched zone, and (b) schematized block of cyclic loads by flight, which was discovered in the wing of the aircraft Yak-42.

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