FAILURE OF DISCS MATERIAL AND STRUCTURAL STRENGTH OF DISC-BLADE JOINTS UNDER NEAR-OPERATING CONDITIONS

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ABSTRACT

Results of stress-strain state estimation for several kinds of aircraft gas turbine disc-blade joints under conditions similar to those of use are presented. These results have shown that the plastic deformation can occur at dangerous points of joints causing low cyclic fatigue and rupture of discs. Investigations of BT-3-1 titanium alloy (disc material) low cyclic fatigue life under conditions of complex stress state were carried out. A criterion of fatigue life for the investigated material was obtained using the regression analysis.

KEYWORDS

Contact problem, finite element method, low cyclic fatigue, failure, fatigue life, stress concentration.

INTRODUCTION

A problem of reliability and durability increase for elements of structures subjected to complex thermo-forced loading needs the concentration of efforts on two important features. First, for the mathematical simulation of the stress-strain state of structures it is necessary to take into consideration real exploitation conditions (contact interaction, temperature gradients etc.) more closely, and, second, it is essential to use a correspondent model of material behavior and failure. In the real discs and blade tail-ends, the crack initiation occurs at points which positions can not be explained without knowing the real contact pressure distribution. Results of complex investigations for disc-blade joints in gas turbine aircraft engines are presented in this report. The operation of such joints is accompanied with non-isothermic loading and inertial forces acting on disc and blade and gas-dynamic forces acting on blade as well. The disc is loaded with blade forces by contact interaction between blade tail-end and disc slot. It must be noted that stresses at dangerous points both disc and blade tail-end significantly depend on the contact pressure distribution.

STRESS-STRAIN ANALYSIS OF THE DISC AND BLADE TAIL-ENDS AT JOINT ZONE

DKA/PC—a computer program for 2D FEM analysis has been used for the estimation of stress-strain state at a joint zone. An algorithm for solution of contact elasto-plastic boundary problems is implemented in the program (N. S. Mozharovski et al., 1989). This algorithm develops a method based on a principle of alternate satisfaction of boundary conditions. Using the parametric spline approximation the up-to-date technique for contact bodies conjunction was developed. This technique does not require obligatory presence of the opposite nodes couples on a contact surface. Such a technique was applied for friction consideration that did not make worse the convergence of main iterations. The program allows to consider variable thickness of each body, temperature gradients, inertial forces, and cyclic symmetry. The program is adapted for IBM PC/AT 286 and 386.

We used `Pic6`—a 3D solutions presentation program for FEM analysis— in postlude results processing. The program interprets the FEM mesh data in two ways: as a transparent wireframe model, and an opaque body with eliminated hidden faces. `Pic6` can cover an opaque image with function chart using both color map and isoline technique.

FEM analyses have been conducted for several kinds of disc-blade joints.

A FEM Analysis of Spruce Type Joint for the 1st Stage of the АИ-25ТЛ Aircraft Gas Turbine Jet. Disc material is ЭИ-698 ВД superalloy, blade material being ЖС-6К superalloy. Calculations have been conducted for temperature T = 567°C. It is assumed that disc and blade tail-end are uniformly heated. The disc rate of rotation is 17800 rpm.

Calculations have shown that dangerous points of the blade tail-end are located at the top and bottom hollows. At these points the effective stress exceeds the value of proportional limit of material. Dangerous point of disc slot is located in the bottom hollow and effective stress at this point exceeds that of yield limit of material, i.e. plastic deformations develops there.

A FEM Analysis of Dovetail Joint for the High Pressure Compressor 2nd Stage of the Д18-Т Gas Turbine Jet. Disc material is ВТ-9 titanium alloy, blade material being ВТ-8 titanium alloy. The temperature gradient is asserted to be from 354°C on the disc hub to 395°C on the rim. It is assumed that blade tail-end is uniformly heated to temperature 395°C. The disc rate of rotation is 9300 rpm.

As a result of calculations we have got the contact pressure distribution as well as stress fields both in disc and blade tail.

A FEM Analysis of Dovetail Joint for the Low Pressure Compressor 2nd Stage of the Д36 Gas Turbine Jet. Both disc and blade material is ВТ-3-1 titanium alloy. It is assumed that both disc and blade tail-end are uniformly heated to temperature 75°C. The rate of disc rotation is 10470 rpm.

Results of calculations for dovetail joints are similar. Effective stress field for Д36 jet is shown in Fig. 1. The distribution pattern of contact pressure has typical shape with two peaks on edges of contact zones which considerably exceed the average pressure. These peaks can cause the metal fretting both in disc and in blade tail. From the analysis of stress state of joint we can conclude, that disc is more loaded than tail-end. The maximum of the effective stress is achieved in the domain close to bottom curved boundary of the slot. For Д18-Т effective stress exceeds the yield limit for disc material. The maximum of main tensile stress is achieved at the same point.

The slot in real disc has slope in respect of disc axis. Thus, the torque we are unable to take into consideration acts on a blade. It causes extra stresses in the region of acute angle between the slot boundary and side surface of the disc. It can be stated confidently that plastic deformation appears at these points. It may cause the initiation and growth of a crack with low cyclic fatigue mechanism considering the main loading cycle lasts from start-up to shut-up of the engine.

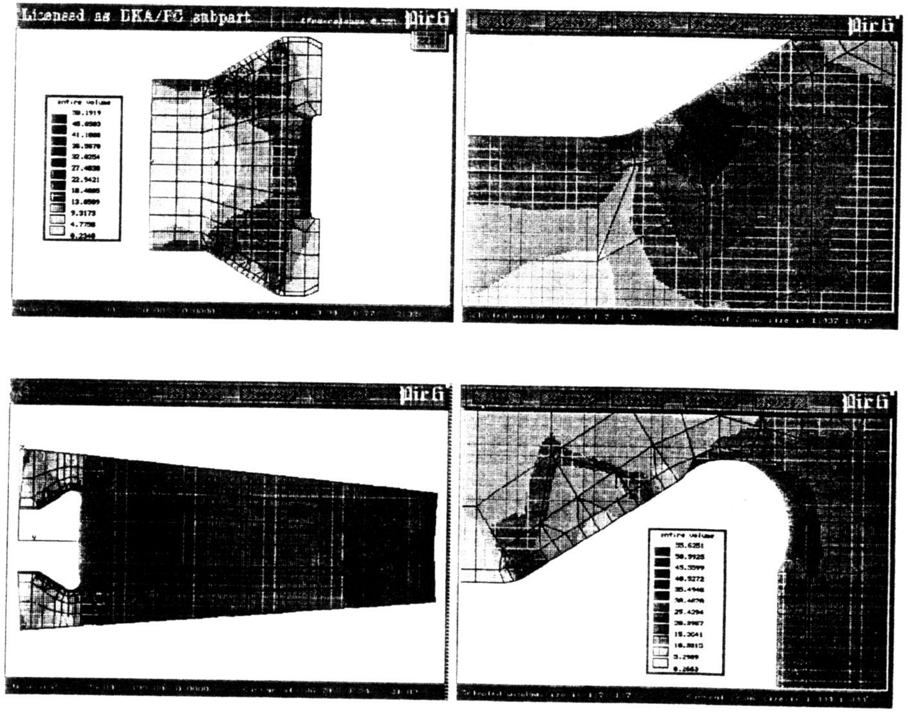


Fig. 1. Effective stress fields ($\cdot 10^{-1}$ MPa).

Analysis of the disc wrecking during exploitation shows that initiation of fatigue crack takes place at noted points. The high frequency vibrations of blade exerts influence on kinetics of crack growth. Crack propagation can cause the rupture of interslot ledge or ruin of whole disc and then destruction of engine as a result. The stress state at dangerous points is biaxial with stress concentration.

In recent time, uniaxial tests data are used for the life prediction of such elements of constructions under conditions of low cyclic loading, i.e. it is supposed that material properties do not depend on the kind of stress state. A number of authors have shown in their works that such supposition for many materials is correct only under certain conditions. That's why basing on results of FEM analysis of joints we have conducted a series of tests for the disc material—ВТ-3-1 titanium alloy—at biaxial stress state using smooth and notched tubular specimens. A statistical estimation of kind of stress state influence has been got as at uniform stress state as at stress concentration.

EXPERIMENTAL INVESTIGATION OF BT-3-1 TITANIUM ALLOY LOW CYCLIC FATIGUE UNDER THE COMPLEX STRESS STATE

All the investigations have been rendered using the self-designed equipment and techniques described in the work (N. S. Mozharovski et al, 1981). The drawings of specimens used are shown in Fig. 2. The tests were carried out at room temperature with pulsated stress-controlled cyclic loading. In a capacity of description of kind of stress state an angle of the stress vector slope in two-dimensional Ilyushin loading space was used:

$$\omega_\sigma = \arctan \frac{\sqrt{3}\,\tau}{\sigma} \qquad (1)$$

For both smooth and notched specimens the nominal stresses are defined at minimum cross-section by

$$\sigma_n = \frac{N}{\pi d \delta}; \quad \tau_n = \frac{T}{\pi d^2 \delta} \qquad (2)$$

where d and δ are the average diameter of specimen and thickness of walls at minimum cross-section.

All the tests with smooth specimens were conducted at proportional loading. The maximum effective stress of cycle is calculated by:

$$\sigma_{max}^{eff} = \sqrt{\sigma_{max}^2 + 3\tau_{max}^2} \qquad (3)$$

We determined the maximum effective nominal stress in the notched specimens. The full failure of specimens was considered as a limit state. The tests base is $5 \cdot 10^3$ cycles.

The smooth specimens were tested at three levels of maximum cycle effective stress: σ_{max}^{eff} = 970, 950 and 930 MPa at various kinds of stress state: $\omega_\sigma = 0°$ (pure tension), $\pi/6$, $\pi/3$ (tension with torsion). As a result, we derived an equation of regression establishing dependence of the number of cycles to failure upon stress amplitude $\sigma_a^{eff} = \sigma_{max}^{eff}/2$ and ω_σ:

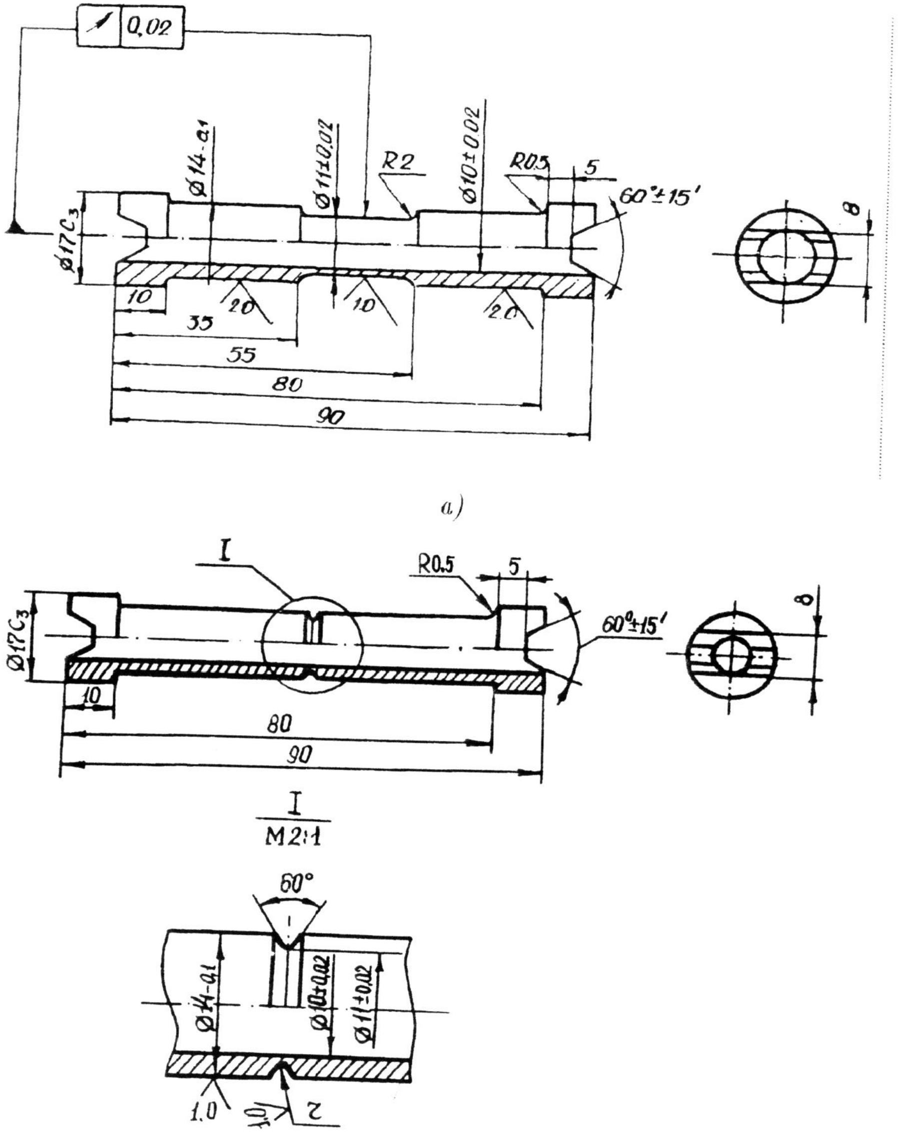
$$\begin{aligned} \lg N_f \;=\; & -236.86 + 1.03\,\sigma_a^{eff} - 3.57 \cdot 10^{-2}\,\sigma_a^{eff}\omega_\sigma + \\ & 8.51\,\omega_\sigma + 3.73 \cdot 10^{-5}\,(\sigma_a^{eff})^2\omega_\sigma - 1.12 \cdot 10^{-3}\,(\sigma_a^{eff})^2 \end{aligned} \qquad (4)$$

The low cyclic fatigue diagrams for BT-3-1 titanium alloy in semilogarithmic co-ordinates are shown in Fig. 3. Experimental results are marked with dots, those calculated with (4) being presented by solid lines. The quantitive analysis of experimental results proves evidence of influence of the kind of stress state on a fatigue life of BT-3-1 titanium alloy in investigated range of angles ω_σ. The low cyclic fatigue diagrams in semilogarithmic co-ordinates are practically parallel straight lines. The fatigue life tends to reduce when raising the shear component of the maximum effective stress in a whole investigated stress range. Taking into account the straihgtforwardness and parallelism of the low cyclic fatigue diagrams we can convert the formula (4) into

$$N_f = 10^{(18.496 - 0.0325\sigma_a^{eff} - 0.00575\omega_\sigma)} \qquad (5)$$

Basing on the orthogonal plan of experiment the regression coefficients can be found independently each other and equation (5) can be converted

$$N_f = c(\sigma_a^{eff})^m \cdot 10^{B\omega_\sigma}; \quad 0 \le \omega_\sigma \le \pi/3, \qquad (6)$$



a)

b)

Fig. 2. a) A smooth specimen; b) A notched specimen.

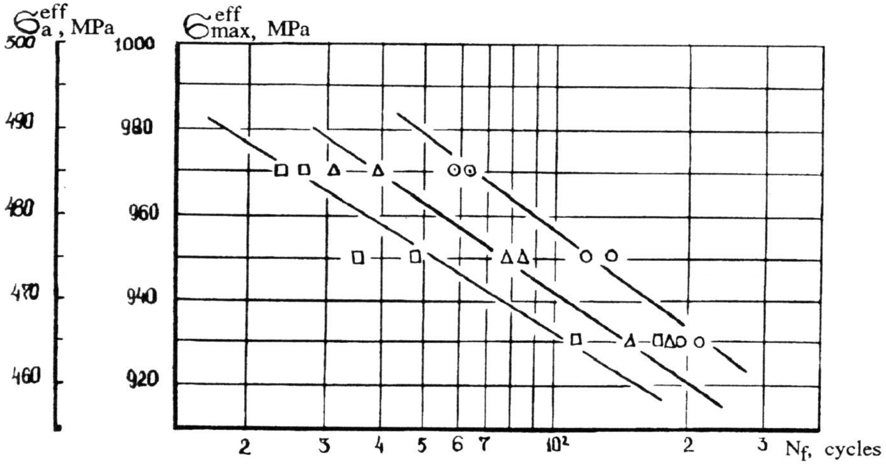


Fig. 3. The low cyclic fatigue diagrams for BT-3-1 titanium alloy.

where c and m are Coffin-Manson type coefficients determined in tension tests. B is a constant determined from the relation of fatigue lifes at pure tension and torsion. It corresponds to the multiplier at ω_σ in (5).

Fig. 4 shows an influence of a stress concentrator (V-shaped notch) on the fatigue life at various values of normal-to-shear stress relation. Using round marks the tests results for pure tension are indicated for the various curvature at tip of concentrator (κ = 0, 1.6, 10). Decrease of fatigue life for all levels of σ_{max} at tension when increasing the stress concentration factor proves the well-known fact that stress concentration has an influence on low cyclic fatigue life for design materials. If we compare the fatigue life for notched specimens at pure tension and at combined tension and torsion, we would note the fatigue life increases appreciably for combined loading at low amplitudes of maximum stresses.

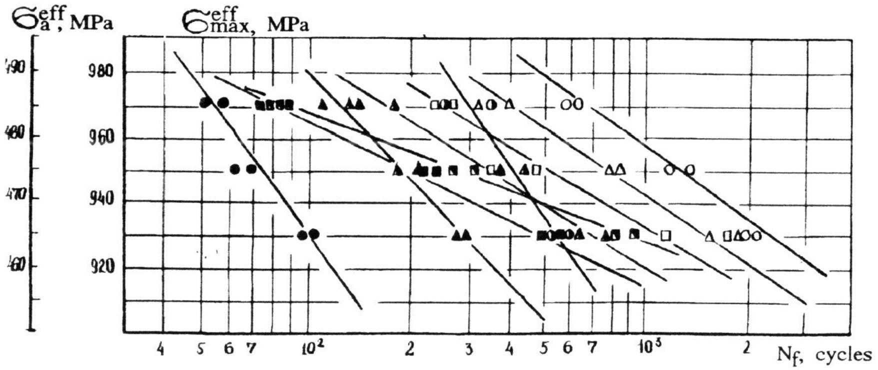


Fig. 4. An influence of the V-shaped notch stress concentrator on the fatigue life.

Moreover, this trend is enhancing while a tip of notch being sharpened. This phenomenon is most likely to be explained by decrease of the theoretical stress factor according to increase the shear deformations at stresses exceeding the yield limit of material. Moreover, as experimental results shows, the greater a curvature of notch tip, the more noticeably this phenomenon appears at equal values of nominal normal and shear stresses.

CONCLUSIONS

The numerical analysis of several kinds of disc-blade joints has shown that there is a biaxial stress state in the dangerous points with a high level of stress concentration. Besides, the plastic deformations is developed in these points that can cause the ruin of disc by the low cyclic fatigue mechanism. All of these reasons brought about a necessity of carrying out experimental investigations the low cyclic fatigue of discs materials at biaxial stress state and stress concentration.

Investigation of BT-3-1 titanium alloy fatigue life determined by full failure of specimens has shown:

— For the stress controlled cyclic loading at room temperature and under conditions of plane stress state the unique diagram of fatigue life does not exist. Moreover, lack of consideration of stress state kind could decrease the margin of safety of constructions. For taking into account such influence on the BT-3-1 titanium alloy fatigue life the regression equation is proposed.

— For uniform stress state simulated on a tubular specimen with V-shaped notch on outer surface we can see a trend to increase of fatigue life of material comparatively with pure tension at same dimensions of concentrator. So with tip curvature $\kappa = 10$ the increase took place in a whole range of investigated amplitudes of effective stress.

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