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NUMERICAL SIMULATION OF NONISOTHERMAL PLASTICITY AND THERMOMECHANICAL FATIGUE OF TURBOMACHINERY COMPONENTS

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Abstract. Model of cyclic stress-strain curve and corresponded damage model are developed for simulation of nonisothermal cyclic loading and for estimating life time of turbomachinery components. Material cyclic model describes change of Bauschinger's effect, Young's module and parameters of hardening as functions of accumulative plastic strain. Model of damage is based on reaching value of accumulative plastic strain ultimate state at cyclic loading. Simulation of nonisothermal plasticity of turbomachinery components based on FE code which uses for calculation theory of strain plasticity, that was generalized to cyclic noniosthermal loading. Results of calculation of turbine engine details under cyclic loadings (discs, high-loaded concentrators of blade locks and turbine blades) are presented.

1 INTRODUCTION

Turbomachinery components work under nonisothermal and transient loading, which generates alternating plastic strain under strain cycling into stress concentrator. Therefore problem of mathematical simulation of stress-strain state is actual to describe influence of plasticity and creep under nonisothermal cyclic loading. Particularly this problem is actual on the design stage of GTE parts with the stress concentrators (discs with holes, turbine blades and etc.) for estimating of low cycle fatigue. These stress concentrators are local whose change stresses and strains from the nominal values in the some local regions of parts. Therefore in most cases stresses and strains in these regions practically have not influence on the common stress-strain state of the part. Common stress-strain state can be describe by calculating of kinetics of stresses and strain in the structure. It is possible on the base of the technology of multidisciplinary simulation that allows to create virtual model of part or engine [1-3]. This virtual model determines the kinetics of thermal state, pressures, nominal displacements, strain and stresses in the parts of structures by the simultaneously calculating gas flow in the cavities of the engine, transient thermal conductivity and deformable solid mechanics. Results of that analysis determines temperatures and boundary conditions (displacements and stresses) for the improvement of the selected region around the concentrator. For example Fig. 1a shows displacements of the HPC rotor at the takeoff regime. Kinetics of the variation of the gap in the labyrinth seal 1 between rotor and stator is performed on the Fig. 1b.

Based on results of this research it can be determine kinetics of displacements and forces on the boundary of the local subregion which includes concentrator (region of bolt joint 2 or region of lock joint 3 in Fig. 1a). In most cases this research may be carry out in elastic state or in simple plastic state without effects of unloading and alternating plastic strain in elastoplastic case.

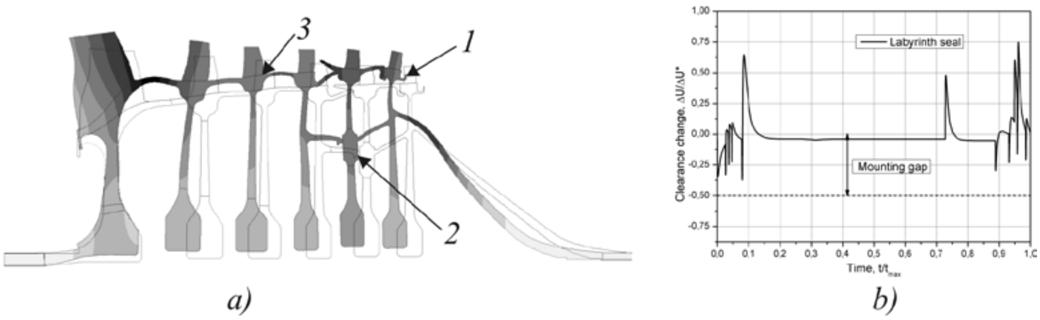

Figure 1: HPC rotor: *a)* - deformed rotor on the takeoff regime, *b)* – kinetics of the variation of the gap in the labyrinth seal

Transition to research of region of concentrator requires more accuracy analysis of elastoplastic state. In that case it is necessary to take into account features of nonisothermal cyclic loading. Cyclic stress-strain curve presents a conception about these features. These curves were acquired for the some materials at the room temperature under uniaxial loading of specimens. Number of experimental results for structural materials under isothermal cyclic uniaxial tests at elevated temperatures is essentially lower because to provide a stable temperature in the specimens is needed Nonisothermal experiments are more complexity problem because it is necessary to provide fixed program of variation of the temperatures and loadings in the specimen. Results of these experiments are significance because it allows to verify various versions of nonisothermal plastic models, programs of simulation structures, models of estimating life prediction of parts. However number of these experiments is so small. Generally these experiments are carried out with the loading program which is similar to kinetics stresses and temperatures in the most loaded points in parts. Results of these experiments is impossible to transfer to parts which have another loading program. In addition stress-strain state in the regions of the concentrators substantially multiaxial. However number of experiments under multiaxial nonisothermal loading is very low. Therefore for the simulation of structures and parts under nonisothermal loading plasticity models are used which can be generalize limited experimental data to common loading conditions of structures. There are a lot of these models. This paper dedicates to one of these approaches to solve this problem and to describe of models to solving of kinetics of stress-strain state and life prediction of low cycle fatigue of region of concentrators. Models of plasticity, which are used in work are based on approximation cyclic stress-strain curve by 3 parameters (Bauschinger effect, scale of transformation of nonlinear part of stress-strain curve and Young's modulus)which depend on total cumulative plastic strain. [4]. Nonisothermal loading is considered by the conception of thermomechanical surface [5], which is generalized on nonisothermal cyclic loading.

2 MODEL OF NONISOTHERMAL CYCLIC STRESS-STRAIN CURVE

Three parametric model [4,6,7] which is used to simulation elasto-plastic stress-strain response under isothermal cyclic loading is generalized to case of nonisothermal conditions. This makes it possible to describe dependence of Bauschinger effect, nonlinear part of stress-strain curve and Young's modulus versus total cumulative plastic strain under nonisothermal cyclic loading.

Such approach at fixed temperatures was confirmed [4,6,7] for description cyclic stress-strain curve several structural materials.

Let us consider the thermomechanical surface under cyclic or complex loading. Part of this thermomechanical surface (Fig. 2) which is located between isothermal cyclic stress-strain curves at temperatures T_1, T_2 and at current value of cumulative plastic strain $\chi = \int \left| d\varepsilon^p \right|$ is described by relations:

$$\sigma^* = F(\varepsilon_p^*, T),\ F = (1-\lambda) f_1 + \lambda f_2,\ \lambda = \frac{T - T_1}{T_2 - T_1}, \tag{1}$$

$$f_i = \begin{cases} E(T_i)\cdot d(\chi, T_i)\cdot \varepsilon^*, \\ E(T_i)\cdot d(\chi, T_i)\cdot \varepsilon_s^* + d(\chi, T_i)\cdot b(\chi, T_i)\cdot \left[f\left(\varepsilon_S + \dfrac{\varepsilon^* - \varepsilon_S^*}{b(\chi, T_i)}, T_i \right) - \sigma_S(T_i) \right], \end{cases} \tag{2}$$

$$i = 1, 2,\ \sigma_s^*(T) = a(\chi, T)\sigma_s(T), \varepsilon_s^* = a(\chi, T)/d(\chi, T)\varepsilon_s$$

where σ* and ε* are stress and strain in local coordinate system (Fig. 2a); $a(\chi, T)$ is a size of elastic zone of loading surface; $b(\chi, T)$ is a transformation coefficient of nonlinear part of initial stress-strain curve; $d(\chi, T)$ is a coefficient of variation of Young's modulus; ε_S and σ_S are the initial yield stress and strain; ε_p is a plastic; strain; E is a initial Young's modulus; $f(\varepsilon, T)$ is a stress-strain curve at the first halfcycle; f_i is a cyclic stress-strain curve at temperature T_i [4,6,7].

It should be noted that parameters $a(\chi, T_i)$, $b(\chi, T_i)$ and $d(\chi, T_i)$ depend on cumulative plastic strain χ and characterize cyclic stress-strain curve at temperature T_i.

For simulation under nonisothermal cyclic loading it is nessesary to calculate isothermal stress-strain curve f_i^{k+1} for temperature T_i on the each $k+1$ halfcycle (Fig. 2a). Also it is necessary to take account of plastic strain χ^k accumulated in previous halfcycles. Then thermomechanical surface F_i^{k+1} is calculated for the $k+1$ halfcycle (Fig. 2b). Nonisothermal cyclic stress-strain curve on the $k+1$ halfcycle is located on this surface in stress-strain-temperature coordinates. Determining parameters of this surface is occurred with taking into account of direction of loading.

Material parameters $a(\chi, T)$, $b(\chi, T)$, $d(\chi, T)$ which are used for simulation of variation of cyclic curves under isothermal loading are depended as function on cumulative plastic strain. For various temperatures these parameters are determined from experimental isothermal stress-strain curves under hard or soft loading.

For determining material parameters as function of cumulative plastic strain it is necessary to define from experimental data dependence of similar material parameters and cumulative plastic strain on numbers of halfcycles.

Parameter $a(\chi, T)$ which is defined dimension of elastic zone on each halfcycle is determined by relationship between current yield stress in local coordinates and initial yield stress: $a(k, T_i) = \sigma_S^*(k, T_i) / \sigma_S(T_i)$.

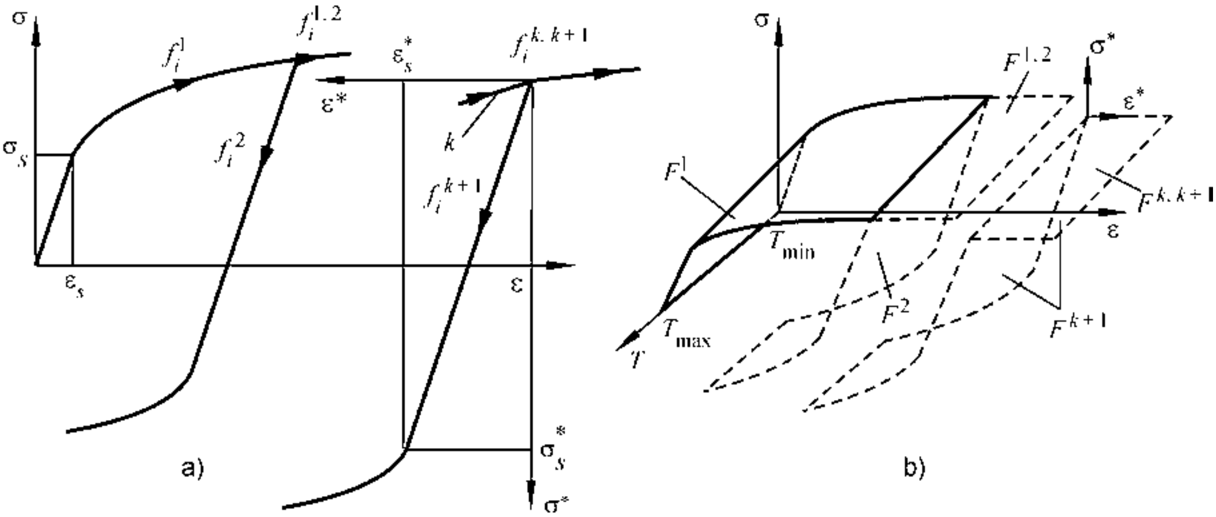

Figure 2: Model of thermomechanical surface: *a)* - stress-strain curve for isothermal cyclic loading; *b)* - part of thermomechanical surface at various halfcycles

For determining parameter $b(\chi, T)$ which is responded of transformation of nonlinear part of initial stress-strain curve on each halfcycle least-squares method is used.

In the case of soft loading following approximate relationship may be used for determining transformation coefficient: $b(k, T_i) = \Delta\varepsilon_p^0 / \Delta\varepsilon_p^k$ where $\Delta\varepsilon_p^0$ is plastic strain on initial halfcycle and $\Delta\varepsilon_p^k$ is plastic strain on halfcycle with number k.

Parameter $d(\chi, T)$ which is simulated influence of cumulative plastic strain on Young's modulus is determined by relationship between Young's modulus on current halfcycle and initial Young's modulus: $d(n, T_i) = E(n, T_i) / E(1, T_i)$.

After determining $\chi(n, T)$, $a(n, T)$, $b(n, T)$, $d(n, T)$ for each temperature it may be possible to determine required relations $a(\chi, T)$, $b(\chi, T)$ and $d(\chi, T)$ for required temperature and cumulated plastic strain range.

3 MODEL VERIFICATION

Based on equations (1) - (2) a program for simulation of specimen test under nonisothermal cyclic loading was developed. Verification of this program under isothermal and nonisothermal loading was performed in work [8].

Experimental results of nickel based superalloy under isothermal and nonisothermal cyclic loading were presented in [9]. Frequency of isothermal and nonisothermal loading was 0.0025 Hz (400 seconds per cycle). Influence of creep strain was neglected. Temperature of all experiments was in range from 571°C to 823°C. Type of loading cycle was hard. Stress-strain curves and material parameters were defined from isothermal tests. Material parameters *a*, *b* at temperatures 571°C, 700°C, 823°C of that alloy is shown on Fig.3.

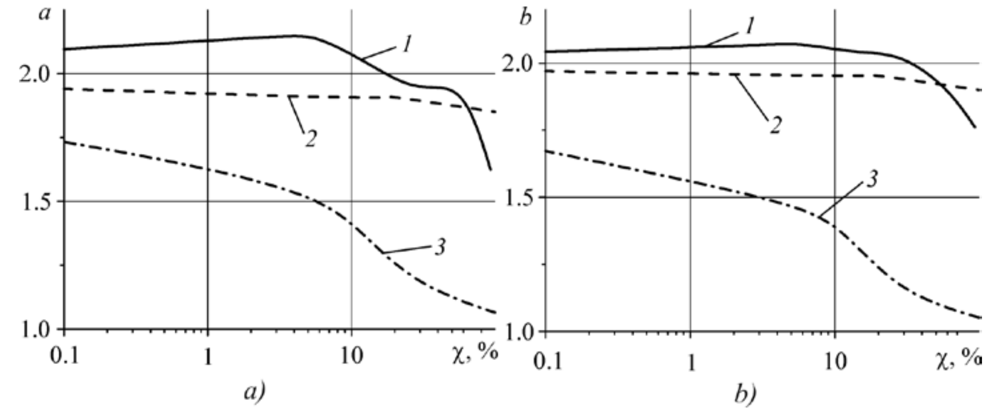

Figure 3 Material parameters: *a)* – parameter a; *b)* – parameter b (*1* - 571°C, *2* - 700°C, 3 – 823°C)

Comparison of experimental data of stable hysteresis loop and results of simulation of in-phase test is shown on Fig. 4a. Strain amplitude was equal 0.6%. Temperature was equal 823°C at maximum of tension and temperature was equal 571°C at maximum of compression. Simulation and experimental results of stable hysteresis loop of out-phase test are shown on Fig. 4b. Parameters of out-phase test were equivalent to parameters of in-phase test. Stable hysteresis loop is identical 67 and 68 halfcycles for all types of loading. In both cases of the simulation loops for 1 - 3, 10 - 11, 30 - 31 and 67 - 68 halfcycles are shown on Fig. 4.

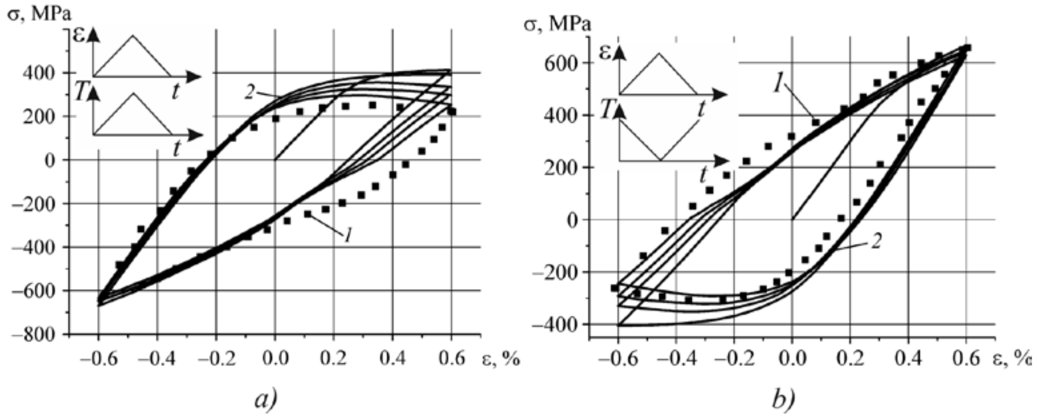

Figure 4 Hysteresis loops under nonisothermal loading: *a)* – in-phase test; *b)* – out-phase test (*1* - experiment, *2* - simulation)

4 DAMAGE MODEL

In [4,6,7] based on experimental results it was determined that at room temperature number of halfcycles to failure for several structural materials under various loading programs (soft loading, hard loading, random loading) n_f depends on ultimate value $\chi_{\max}$ by next relation:

$$n_f = \left(\chi_{\max} / \delta\right)^{\gamma} \tag{3}$$

where δ and γ is material constants.

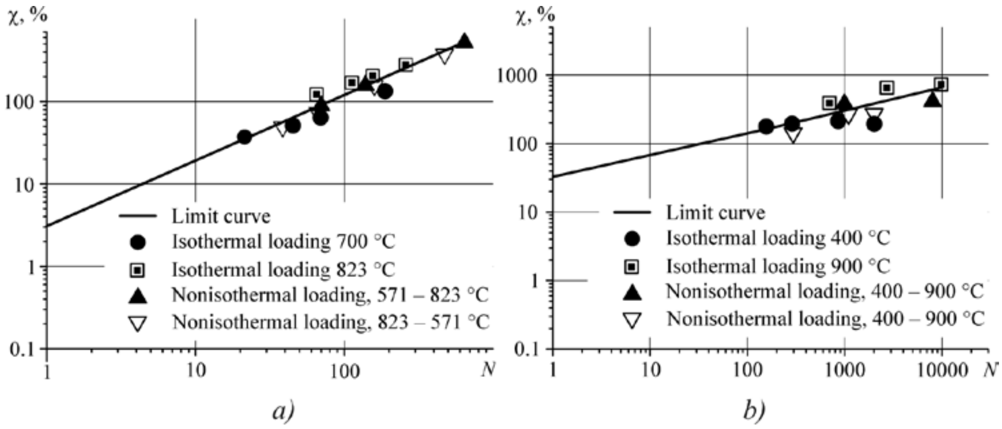

Figure 5 Relation between cumulated plastic strain to failure χ_{max} and number of halfcycles to failure: *a)* – for nickel-base superalloy, *b)* – IN738LC

LCF isothermal experimental data at temperatures 700°C and 823°C [9] allows with least-squares method to calculate material parameters of damage model δ and γ. Cumulative plastic strain as function of number cycles to failure was calculated by the model (1 - 2). For comparison on Fig. 5a experimental results of LCF are shown by points and result of damage model (3) is shown by limit curve that is calculated by parameters δ and γ.

Similarly based on LCF experimental data of IN738LC [10] in temperature range 400°C - 900°C applicability of damage model was verified. Based on isothermal data at 400°C and 900°C parameters of LCF model were calculated by least-squares method. Experimental results of LCF are shown on Fig. 5b by points. Limit curve on Fig. 5b is calculated by parameters δ and γ that were defined form experimental data.

5 FINITE ELEMENT ANALYSIS

Consider cyclic deformation which load vector $\{F\}$ is applied to component by the following program

$$0 \to \{F_{\max}\} \to \{F_{\min}\} \to \{F_{\max}\} \to \ldots$$

If strain and stress vectors in body points $\{\varepsilon\}_k$ and $\{\sigma\}_k$ correspond to end of the k^{th} halfcycle of loading and ones $\{\varepsilon\}_{k+1}$ and $\{\sigma\}_{k+1}$ correspond to end of the $(k+1)^{\text{th}}$ halfcycle, then for each halfcycle a variational relationship is carried out

$$\int_{\Omega}\{\sigma\}_q^T\{\delta\varepsilon\}\,d\Omega-\int_{\Omega}\{F_\Omega\}_q^T\{\delta u\}\,d\Omega-\int_{S}\{F_S\}_q\{\delta u\}\,dS=$$
$$=\int_{\Omega}\{R_\Omega\}_q^T\{\delta u\}\,d\Omega+\int_{S}\{R_S\}_q^T\{\delta u\}\,dS \tag{4}$$

where $q=k,k+1$ – halfcycle number, $\{F_\Omega\},\{R_\Omega\},\{F_S\},\{R_S\}$ – vectors of volume loads and misalignment surface loads and misalignment respectively. Suppose that $\{R_\Omega\},\{R_S\}$ are equal zero on k+1 halfcycle and subtract from relation Eq.4 at $q=k+1$ similar one at $q=k$ get that a problem of stress-strain condition simulation by change from loading halfcycle to unloading one is came to solution next problem

$$\int_{\Omega}\{\Delta\sigma\}_{k+1}^T\{\delta\varepsilon\}\,d\Omega-\int_{\Omega}\{\Delta F_\Omega\}_{k+1}^T\{\delta u\}\,d\Omega-\int_{S_F}\{\Delta F_S\}_{k+1}\{\delta u\}\,dS=$$
$$=\int_{\Omega}\{R_\Omega\}_k^T\{\delta u\}+\int_{S}\{R_S\}_k^T\{\delta u\} \tag{5}$$

If specify a relation form $\Delta\sigma(\Delta\varepsilon)$, then Eq.5 by well-known method will be came to finite element problem

$$[K]_{k+1}\cdot\{\Delta U_{k+1}\}=\{\Delta F_{k+1}\}+\beta\{F_0\} \tag{6}$$

where $[K]_{k+1}$ – stiffness matrix of the ($k+1$)th halfcycle, defined by step-by-step approach; $\{\Delta U_{k+1}\}$ and $\{\Delta F_{k+1}\}$ – vectors of increments of displacement and loading at halfcycle, correspondingly, β – correcting multiply, $\{F_0\}$ – correcting vector.

In that case for displacement vector at the ($k+1$)th halfcycle it is rightly.

$$\{U_{k+1}\}=\{U_k\}+\{\Delta U_{k+1}\} \tag{7}$$

while strain and stress in a calculated point are related by similar relations

$$\{\varepsilon_{k+1}\}=\{\varepsilon_k\}+\{\Delta\varepsilon_{k+1}\}$$
$$\{\sigma_{k+1}\}=\{\sigma_k\}+\{\Delta\sigma_{k+1}\}, \tag{8}$$

Equations (6) – (8) shows self – corrected algorithm for the problem solution.

It can be considered to various models of plasticity depending on features of cyclic loading.

For the most parts of turbomachine processes of force and temperature variation are synchronous. In this case it can be assumed that variations of stresses and strains are proportional.

These conditions are described by strain plasticity theory which was generalized on cyclic loading [11]. Plastic strains appear in the local region by the influence of elastic displacements of the all structure on the boundary which validates this assumption. This type of loading is similar to "hard". In this case it can be possible to consider large values of increments of loads, temperatures, stresses, strains and displacements and each step is considered as one half-cycle.

6 EXAMPLES AND RESULTS

Example 1.

Let us consider the simulation of the overspeed test of the discs (Fig.6a).

Strain plasticity theory which was generalized on cyclic loading is applied in the simulation because experiments were carried out at constant temperature.

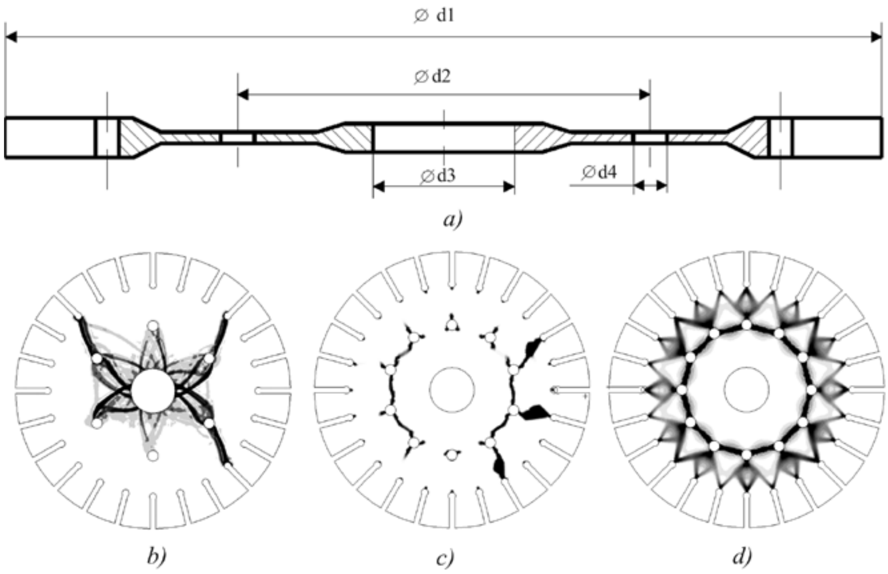

Figure 6 Overspeed test: a) – disc scheme; b) – fracture of disc with 6 holes; c) – fracture of disc with 10 holes; d) – fracture of disc with 12 holes

Generalized planar stressed state was simulated in discs. All computations were carried out by FEM analysis. For the improving of accuracy of analysis and for stability kinematic boundary conditions was defined in integral form. In the simulation of the overspeed tests rotation frequency increased to fracture initiation, which was determined by non-stop node displacement increasing after fracture some finite elements. On each halfcycle damage failure level $D=\chi(n)/\chi_{\max}(n)$ is determining in the process of analysis. If damage failure level in an element verge towards unity the element is excluded from analysis with technology "died" elements [11].

On Fig.7 relations of the radial displacements of the points of disc hub and of the rim disc versus disc revolution are shown. Displacements sharply increase at the critical revolution and fracture initiation of disc is beginning.

On the Fig.6 possible types of disc fracture with various number of holes are shown. Disc with six holes failed at the crack propagation at the meridional direction(Fig. 6b). Disc with ten holes begins to fail at the cylindrical direction then crack propagation continues at the radial direction (Fig. 6c). Disc with twelve holes failed at the crack propagation at the cylindrical direction(Fig. 6d).

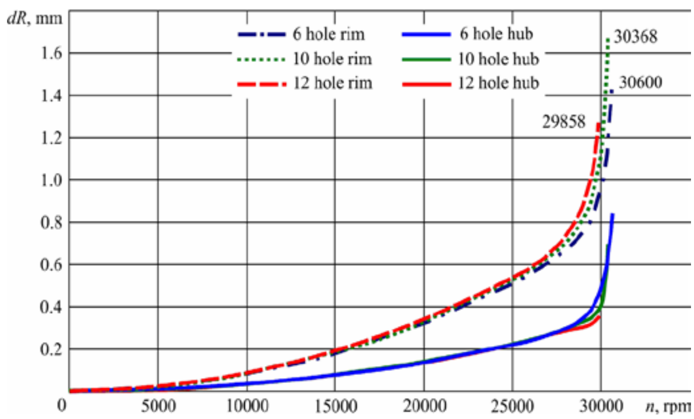

Figure 7 Displacements of points of hub and of the rim at the radial direction versus revolution

Results of simulation of regions of plasticity show that types of disc fracture correspond to model of limiting state which can be developed based on method of characteristics for rigid-plastic body.

Simulation of cyclic loading leds to the similar pictures of failure. However maximal rotation frequencies into the cycle are defined the values of number of cycles to failure. Therefore this model can be applied to the analysis of discs LCF.

Example 2.

Let us consider the turbine disc lock and equivalent notched specimen (Fig. 8). All research was based on experimental results of low cycle fatigue of notched specimens under isothermal loading at the various temperatures are preformed, that were carry out by T.K. Bragina in CIAM [12].

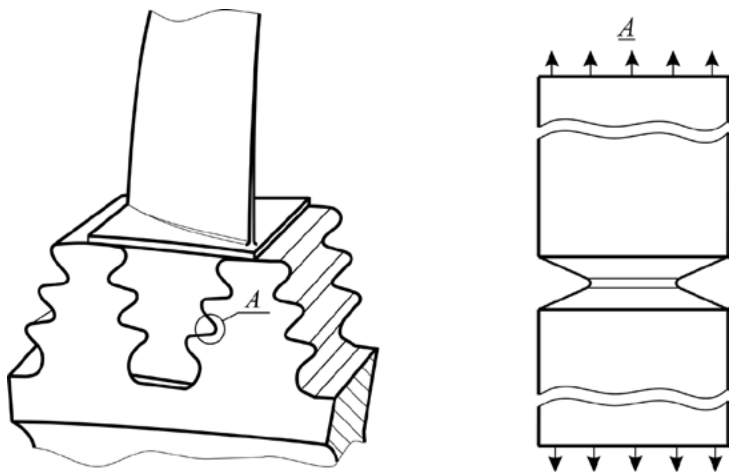

Figure 8 Concentators: a) – in turbine disc lock b) – equvalent specimen

Specimen material is nickel alloy AI698. Temperature of experiments was 20°C, 400°C и 650°C. Type of loading was zero-to-compression stress cycle. Axisymmetric stress state was simulated in notched specimens.

Material parameters of cyclic model at 20°C and parameters of LCF model were performed in works [11]. Material parameters of cyclic model at the temperature 600°C was caclulated by the processing experimental data from work [13]. Stress-stain state is shown on Fig. 9.

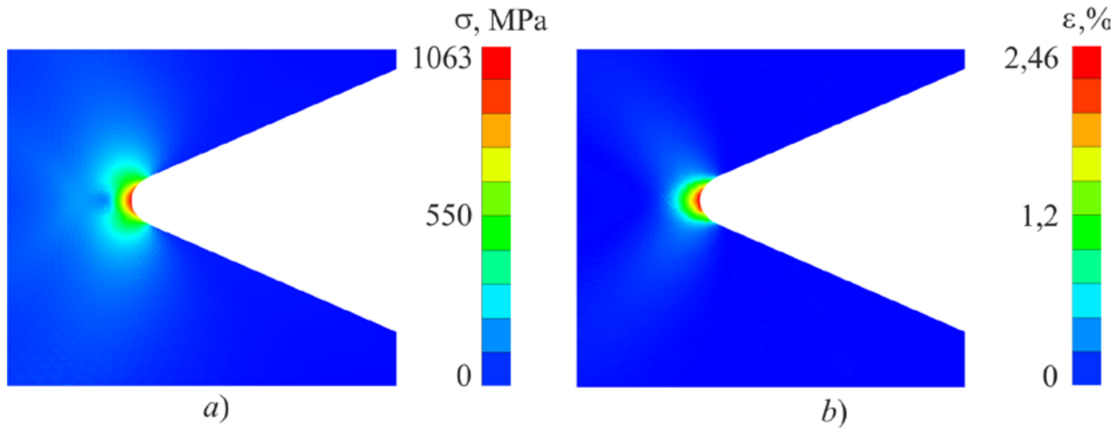

Figure 9 Notched specimen at crack initiation at the stress amplitude 300 MPa and temperature 20°C: *a*) – efficient stresses, *b*) – efficient strains

Based on simulation results of the cyclic loading LCF curves of the notched specimens with various stress amplitudes was calculated for notched specimens at the temperature 20°C (Fig. 10a) and 650°C (Fig. 10b). Simulation results are shown by lines and circles. Experimental results are shown by squares.

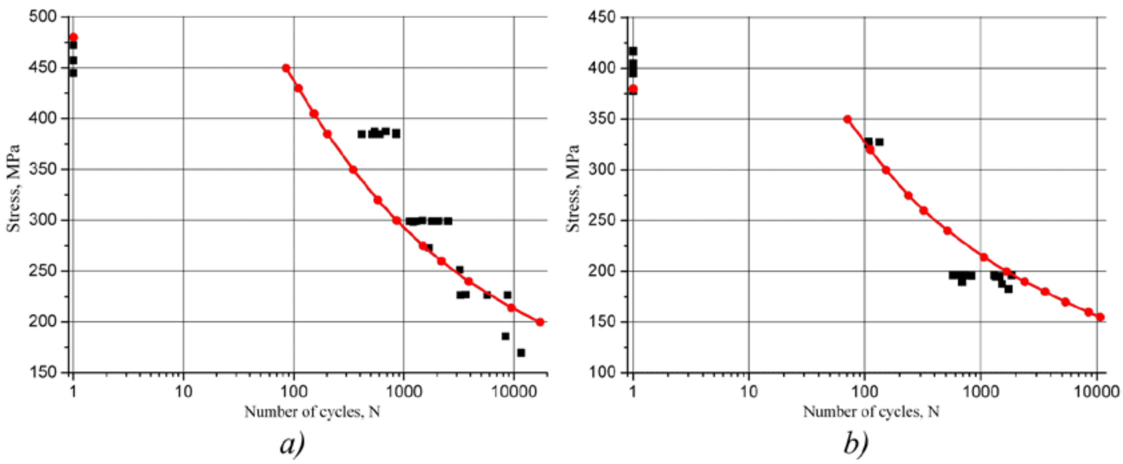

Figure 10 LCF curve of AI698 for notched specimens: *a*) – at 20°C, *b*) – 650°C

Example 3. LCF simulation of turbine blade.

The turbine blade (Fig. 11a) works under nonisothermal cyclic loading (temperature range 20°C - 800°C in point A). Material of turbine blade is a nickel based superalloy.

There are holes for emission a cooling gas on the external surface in point A in the blade. Structural FEM analysis shows that maximum values of stress and plastic strain are located in the point A near the hole. Behavior of cyclic stress and cyclic strain near hole with strain amplitude $\Delta\varepsilon = 1,5\%$ is shown on Fig. 11b. Modifying parameters of temperature and loading it is possible to estimate admissible strain near the hole and to calculate LCF curve (Fig. 11c). Process of crack grown and estimate of crack extension velocity are simulated by included "died" element model (Fig. 10d).

On the Fig. 11d the position 1 accords to the crack initiation in the hole for emission a cooling gas. The position 2 shows excepted from analysis ("died") elements which damage failure level was equal unity which is located in the middle of crack grown process. The position 3 accords to moment which crack involves all volume between holes.

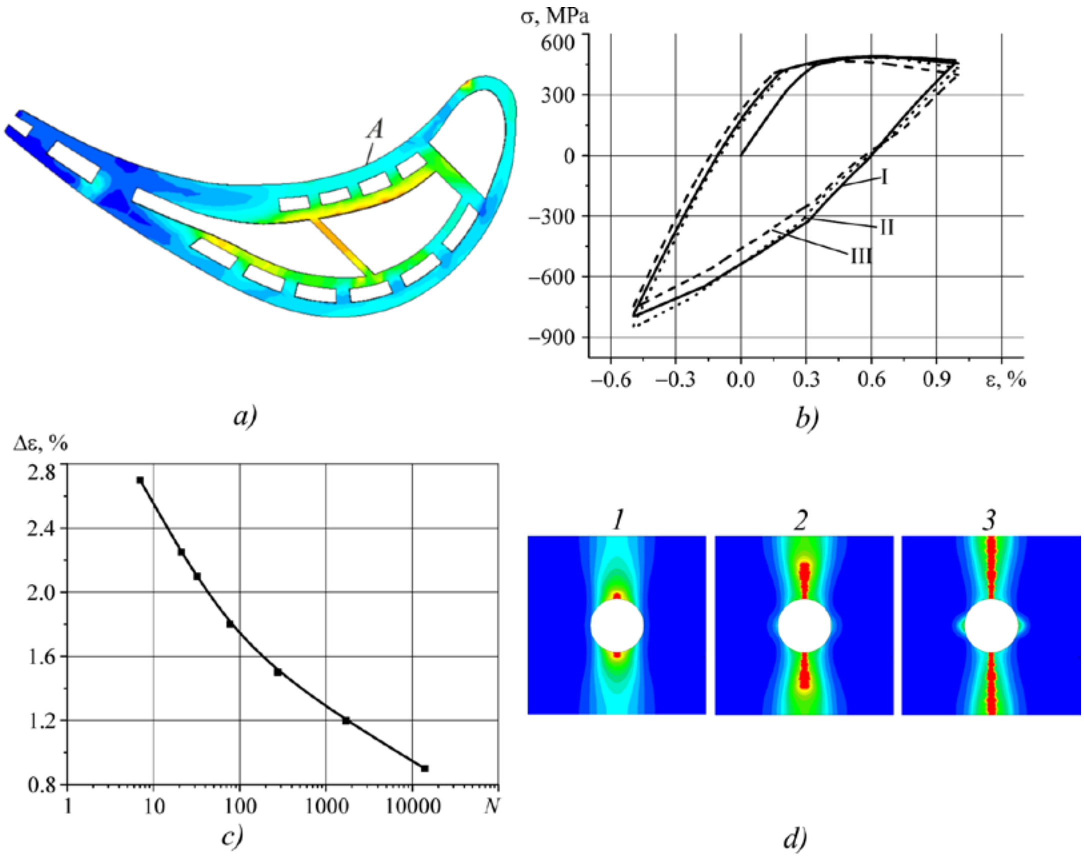

Figure 11 FEM analysis: a - stress-strain state of the turbine blade; b - cyclic stress-strain curve of the critical point (I - 1-2-3 halfcycles, II - 10-11 halfcycles, III - 50-51 halfcycles); c - LCF curve; d – crack grown in the critical point

8 CONCLUSION

Presented results indicate a probability application nonisothermal cyclic stress-strain curve model, that generalized theory of strain deformation plasticity on cyclic nonisothermal loading and damage model for calculation stress-strain state and life time prediction for high stressed engine structures under proportional loading.

For the complex loading influence of forces and temperatures on the stress-strain state can be estimate if the time steps q are small and relation between stresses and strains is determined by theory of plastic flow, that can be generalize on nonisothermal cyclic loading [14].

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