Crystallographic orientation and delay time influence on thermal fatigue strength of single-crystal nickel superalloys

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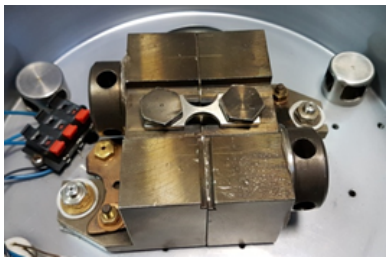
Abstract

The influence of a delay time at the maximum temperature on the number of cycles before the macrocrack initiation for three thermal loading programs was investigated for single-crystal nickel-based superalloy ZhS32. An analytic approximation of a delay time influence was proposed. Comparison of the computational results and analytic formula on the basis of constitutive equations with the experimental data was performed for single-crystal nickel-based superalloy ZhS32 and showed a good accuracy. The influence of crystallographic orientation of the corset sample on the thermal fatigue durability with delay times was investigated for various thermal loadings.

1 Introduction

Single-crystal nickel based superalloys [1] are used for production of gas turbine engines (GTE). These materials have a pronounced anisotropy and temperature dependence of properties. Cracking in the turbine blades is caused often by thermal fatigue [2]. For the investigation of thermal fatigue durability under a wide range of temperatures with and without delay times the experiments are carried out on different types of samples, including corset (plane) specimen [2] on the installation developed in NPO CKTI [3] (see Fig. 1 a). Fixed in axial direction by means of two bolts with a massive foundation the corset sample (see Fig. 1 b) is heated periodically by passing electric current through it. The fixing of sample under heating leads to the high stress level and inelastic strain appearance. The local strain and stress concentration is observed in the central (working) part of sample. The FE simulation is required for the computation of inhomogeneous stress and inelastic strain fields.

The aim of the research is to study systematically the effect of delay at maximum temperature on the thermal fatigue durability on the base of the deformation



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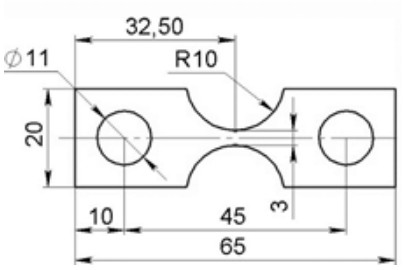


b)

Figure 1: a) Setup for thermal fatigue experimental investigations, b) Geometry of corset sample for thermal fatigue experiment.

criterion [4, 5, 6] for single crystal superalloys using the results of finite element (FE) simulation of full-scale experiments and results of analytical formulae and to study systematically the effect of crystallographic orientation on the thermal fatigue durability. The results of simulation and their verification are obtained for single-crystal nickel-based superalloy ZhS32.

2 Results of thermo-elasto-plastic analysis

Modeling of inelastic deformation in the corset samples has been performed with taking into account of the temperature dependence of all material properties, anisotropy of mechanical properties of single crystal sample, inhomogeneous temperature field, mechanical contacts between bolt and the specimen, between specimen and foundation, temperature expansion in the specimen.

Two FE formulations for the thermomechanical problem have been considered:

- with taking into account of equipment;
- without taking into account equipment (simplified formulation [7] for the sample only).

The validity of the simplified formulation is based on the comparison with the results of full-scale formulation (with taking into account equipment), as well as on the comparison with the displacements of two markers measured in experiments. The problem was solved in a three-dimensional, quasi-static formulation. As boundary conditions the symmetry conditions were set: zero displacements on the y-axis on the xz plane and zero displacements on the x-axis on the yz plane. On the lower side of the equipment zero displacements along the x and z axes were set. Tightening force was applied on the bolt cap. The temperature field distributions were set from the experimental data at maximum and minimum temperature with linear interpolation in time. The results of finite element heat conduction simulations [8] consistent with experimental temperature field distributions.

The mechanical properties for alloy ZhS32 were taken from [3] are presented in Table 1. The mechanical properties of bolts are taken for pearlitic steel [9].

Table 1. Mechanical properties of ZhS32 used in simulations [3]:

T	∘C	20	700	900	1000	1050
E_{001}	MPa	137000	110000	99800	94800	92300
ν	-	0.395	0.425	0.43	0.435	0.436
α	1/K	$1.2\cdot10^{-5}$	$1.6\cdot10^{-5}$	$1.8\cdot10^{-5}$	$2.2\cdot10^{-5}$	$2.4\cdot10^{-5}$
σ_Y^{001}	MPa	919	904	895	670	580
n	-	8	8	8	8	8
A	$MPA^{-n}c^{-1}$	$1\cdot10^{-42}$	$2\cdot10^{-31}$	$2\cdot10^{-28}$	$6\cdot10^{-27}$	$7\cdot10^{-26}$

In simplified formulation (see Fig. 2) we consider only the sample without equipment, in which zero displacements on the symmetry planes xz and yz were set, the outer face of the sample parallel to the symmetry plane xz was fixed in the direction of the axis x. To exclude solid body motions, a number of points on this face were also fixed in the direction of y and z axes.

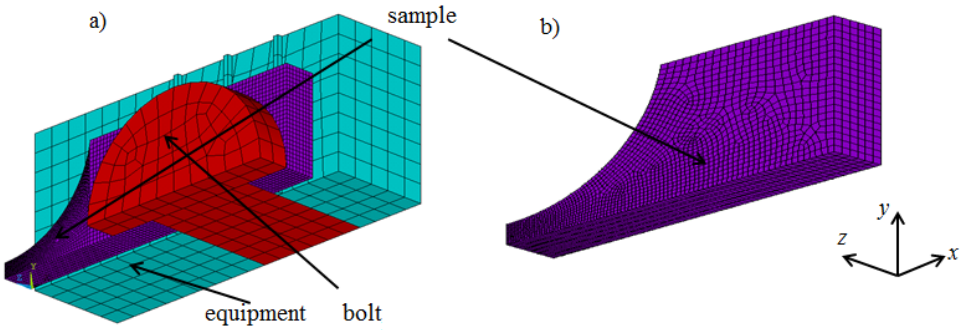


Figure 2: Finite-element models in mechanical problem: a) with taking into account equipment, (1/4 of structure due to symmetry) b) without taking into account equipment (simplified formulation), (1/4 of structure due to symmetry).

Fig. 3 shows distributions of plastic strain intensity for two different temperature loading programs after 7 cycles.

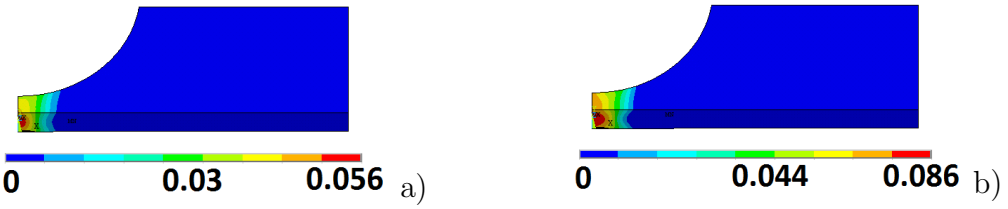


Figure 3: Distributions of plastic strain intensity for a) superalloy ZhS32, T = $150 \div 900 \circ C$; b) superalloy ZhS32, T = $700 \div 1050 \circ C$ after 7 cycles.

The full effective length for superalloy ZhS32 for several temperature modes was 45 mm [8]. In the FE simulations the full length of the specimen for all alloys was taken to be 40 mm.

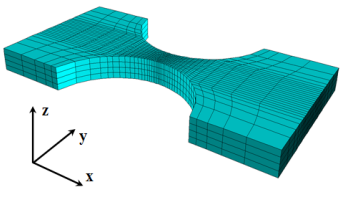
3 Simulation and an analytical approximation for delay influence on thermal fatigue strength. Influence of crystallographic orientation

Simulation of inelastic cyclic deformation of corset samples were performed with using of the FE program PANTOCRATOR [10], which allows to apply the micromechanical (physical) models of plasticity and creep for single crystals [11]. The micromechanical plasticity model accounting 12 octahedral slip systems with lateral and nonlinear kinematic hardening was used in the FE computation for single crystal alloy. FE computations were carried out for a part of a corset sample (simplified FE model with half-effective length of sample equal 20 mm, see Fig. 3b). The temperature boundary conditions were set from the experimental data at maximum and minimum temperature with linear interpolation in time.

The influence of the delay at maximum temperature and the influence of crystallographic orientation on the number of cycles to the formation of macrocrack is analyzed in the range from 1 min to 1 hour for the cyclic loading regimes (see, for example, Fig. 4 b) with:

- maximum temperature of $900 \circ C$ and a temperature range of $750 \circ C$;
- maximum temperature of $1000 \circ C$ and a temperature range of $500 \circ C$.

The heating times in the cycle were 10s and 25s, the cooling times were 14 s and 75s for ZhS32. The mechanical properties for alloy ZhS32 were taken from [3]. The problem was solved in a quasi-static 3-dimensional formulation. The boundary conditions were zero displacements in the direction of the x-axis on two side faces of the sample with the normal along the x-axis. To exclude solid-state motions, a number of points on these faces in the direction of the y and z axes were also fixed. Finite element model in simplified formulation and temperature evolution in central point of sample with and without delay for thermal loading program $T = 150 \div 900 \circ C$ are presented in Fig. 4.



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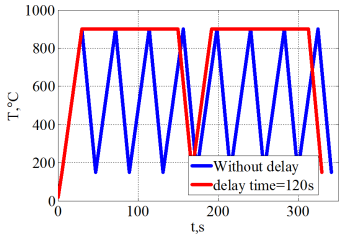

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Figure 4: a) Finite element model of sample (simplified formulation) for analysis of delay influence, b) temperature evolution in central point of the sample with and without delay for $T = 150 \div 900 \circ C$.

Damage calculation and estimation of the number of cycles before the formation of macrocracks were made on the basis of deformation four-member criterion [4, 5, 6]:

$$D = \sum_{i=1}^{N} \frac{(\Delta\varepsilon^{p}_{eq_i})^{k}}{C_1(T)} + \sum_{i=1}^{N} \frac{(\Delta\varepsilon^{c}_{eq_i})^{m}}{C_2(T)} + \max_{0\le t\ge t_{max}} \frac{\Delta\varepsilon^{p}_{eq}}{\varepsilon^{p}_{r}(T)} + \max_{0\le t\ge t_{max}} \frac{\Delta\varepsilon^{c}_{eq}}{\varepsilon^{c}_{r}(T)}, \qquad (1)$$

where the first term takes into account the range of plastic strain within the cycle, the second term is the range of creep strain within the cycle, the third term is accumulated plastic strain (ratcheting), the fourth term is accumulated creep strain. The number of cycles before the formation of the macrocrack N is determined from the condition D = 1. Usually it takes the values k = 2, m = 5/4, $C_1 = (\varepsilon_r^p)^k$, $C_2 = 3/4 \cdot (\varepsilon_r^c)^m$ where ε_r^p and ε_r^c are ultimate strains of plasticity and creep under uniaxial tension. In the FE computations the values of ultimate strain $\varepsilon_r^p = \varepsilon_r^c = \varepsilon_r$= 0.13 and 0.18 for ZhS32 were used.

Analytic approximation is offer to enter for describing of delay time influence on thermal fatigue strength. We consider the principle of deformation additivity [12] in case of uniaxial loading:

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_c + \varepsilon_t = \varepsilon_0, \tag{2}$$

where ε is the full initial strain, $\varepsilon_e = \frac{\sigma}{E}$ is the elastic strain, ε_p is the plastic strain, ε_c is the creep strain and ε_t is the temperature strain. Differentiating (2), using $\dot{\varepsilon_p} = \frac{\dot{\sigma}}{H}$, where H is the hardening modulus, Norton law $\dot{\varepsilon_c} = A \cdot \sigma^n$, taking into account $E + H = E_T$ is the tangent modulus and dividing the equation by σ^n we put:

$$\sigma^{-n}\dot{\sigma} = -AE_T \tag{3}$$

Splitting variables, integrating from t_0 to time t and using $\dot{\varepsilon_c} = A \cdot \sigma^n$, we put:

$$\dot{\varepsilon_c} = A({\sigma_0}^{1-n} + (n-1)AE_T(t-t_0))^{\frac{n}{1-n}} \tag{4}$$

Using variables changing $\tau = {\sigma_0}^{1-n} + (n-1)AE_T(t-t_0)$ and integrating from t_0 to time t we obtain:

$$\Delta\varepsilon_c = \frac{\sigma_0}{E_T}(1 - (1 + A(n-1)E_T{\sigma_0}^{n-1}(t-t_0))^{\frac{1}{1-n}}) \tag{5}$$

Using simplified deformation criterion with taking into account creep deformation terms:

$$\frac{{\varepsilon_c}^{accumul}}{\varepsilon_r} + N\left(\frac{\Delta\varepsilon_c}{\varepsilon_r}\right)^m = 1, \tag{6}$$

where ε_r is the ultimate strain of creep under uniaxial tension, N is the number of cycles of macrocrack initiation we obtain:

$$N = \left(\frac{\varepsilon_r}{\frac{\sigma_0}{E_T}(1 - (1 + A(n-1)E_T{\sigma_0}^{n-1}(t-t_0))^{\frac{1}{1-n}})}\right)^m \cdot \left(1 - \frac{{\varepsilon_c}^{accumul}}{\varepsilon_r}\right), \tag{7}$$

where we use $\sigma_0 = (\alpha_{20-T_{max}} \cdot T_{max} - \alpha_{20-T_{min}} \cdot T_{min}) \cdot E_T \cdot 0.9$, $\alpha_{20-T_{max}}$ and $\alpha_{20-T_{min}}$ are the coefficients of linear thermal expansion, $E_T = 9.48 \cdot 10^4$ MPa / $9.98 \cdot 10^4$ MPa, $A = 2 \cdot 10^{-28}$ / $6 \cdot 10^{-27} MPa^{-n}s^{-1}$, $\varepsilon_r = 0.13/0.18$ for alloy ZhS32, multiplier $(1 - \frac{{\varepsilon_c}^{accumul}}{\varepsilon_r})$ is picking up to correlate one point with experiment.

Comparison of results of FE simulations and experiments concerning the effect of the delay time at the maximum temperature on the thermal fatigue durability for single-crystal superalloy ZhS32 for two temperature modes is given in fig. 5.

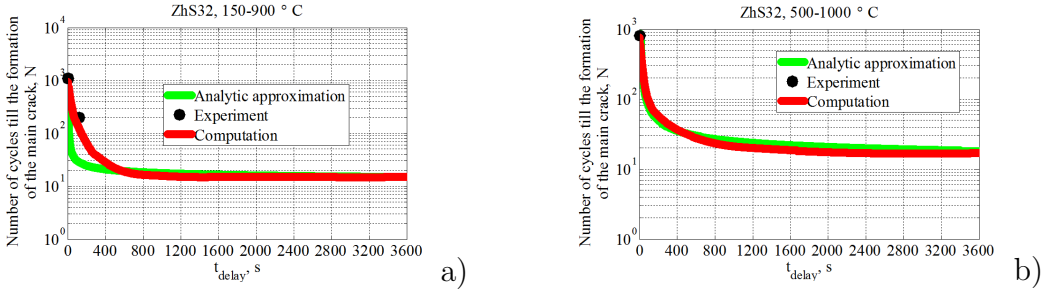

Figure 5: Comparison of results of FE simulation and experimental data for alloy ZhS32: a) T = 150 ÷ 900 ∘ C, heating time is 25s, cooling time is 75s, ε_r= 0.13, b) T = 500 ÷ 1000 ∘ C, heating time is 10s, cooling time is 14s, ε_r = 0.18.

Influence of crystallographic orientation (CGO) on thermal fatigue strength for superalloy ZhS32 for two temperature modes is presented in fig. 6.

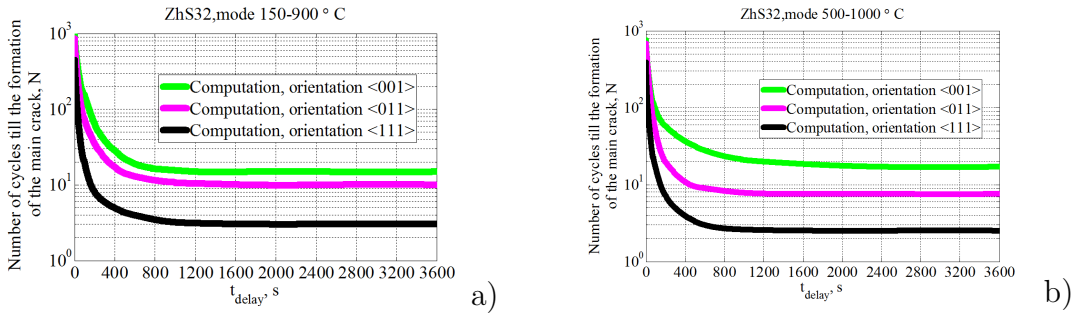

Figure 6: Influence of crystallographic orientation on thermal fatigue strength for superalloy ZhS32: a) T = 150 ÷ 900 ∘ C, heating time is 25s, cooling time is 75s, ε_r= 0.13, b) T = 500 ÷ 1000 ∘ C, heating time is 10s, cooling time is 14s, ε_r= 0.18.

4 Conclusions

Computational results of thermal fatigue durability showed a good agreement with the experiment, which suggests that the finite-element and analytical computations in combination with deformation criterion (1) can be used to predict the thermal-fatigue strength of single-crystal superalloys. Researching of CGO influence has showed that thermal fatigue durability of specimens with crystallographic orientation <001> is the highest among all considered variants and specimens with crystallographic orientation <111> is the weakest among all variants of orientations.

Acknowledgements

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