

THE EFFECT OF NOTCHES ON HIGH TEMPERATURE CREEP BEHAVIOUR OF CMSX-4 SUPERALLOY SINGLE CRYSTALS

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ABSTRACT

This paper deals with the effect of notches on creep strength of the hi-tech high temperature material, CMSX-4 superalloy single crystals. Cylindrical bars of the orientation <001> with circumferential notches were tested at 850 °C under constant loads. Two types of notches with different notch geometry and therefore with different notch acuity and different degree of stress triaxiality were used. The notched specimens exhibit a longer creep lifetime than the smooth specimens for the same net-section stress. This can be attributed to the strain constraint caused by the stress triaxiality. Stress-strain analysis of the notched specimens was performed using the general purpose finite element system ANSYS. The creep data of smooth specimens and the average value of the calculated steady-state creep strain rate was found. Thus a modified Monkman-Grant relationship is valid both for smooth and notched specimens. This offers a basis for the evaluation of the notched creep life solely on the basis of the smooth creep data.

KEYWORDS

Superalloys, CMSX-4, multiaxiality, notch effect, Monkman-Grant relationship

INTRODUCTION

Single-crystalline superalloys are nowadays extensively used as structural alloys in hot section components like first stage turbine blades in gas turbines of power stations or in aero engines applications. Blade axis direction corresponds to crystal orientation therefore the creep behaviour of <011> - oriented single crystals has been extensively investigated.

Defects such as notches are very frequent in structural components. An understanding of the effects of the notches is essential for the prevention of failure. Generally, notches produce stress concentrations and they change the stress state from uniaxial to multiaxial. Moreover, under creep loading conditions, the stress fields redistribute with time. The initially high axial stress components existing due to the notch relax during high temperature creep. All these factors influence the lifetime of notched bodies.

The effect of notches on fracture under creep loading has been studied in several papers, e.g. [1, 2] or in [3]. Comparison of fracture behaviour of smooth and notched specimens for the same net section stress shows that the effect of a notch on the service life of a structure can be either positive (notch strengthening) [4] and [5] or negative (notch softening) [6] and [7]. The

available data show both notch strengthening and notch softening in dependence of material, notch geometry, temperature, applied load and surrounding environment.

Lifetime estimations of notched specimens under creep conditions are sometimes based on the value of elastic stress concentration factor [8], but this approach is too simplified. The damage mechanics can be also used [9], but it is too complicated and unsuitable for engineering practice.

The aim of this paper is to propose a simple engineering procedure for the estimation of lifetime of notched bodies under creep loading.

Material and specimens

Testing was carried out on <001> - oriented CMSX-4 single crystals. The chemical composition of superalloy CMSX-4 is given in Table 1.

Cr	Мо	W	Со	Та	Re	Hf	Al	Ti	Ni
6.5	0.6	6.4	9.7	6.5	2.9	0.1	5.7	1.0	bal.

Table 1. Chemical composition of CMSX-4 (weight %).

The rough material was delivered as cast bars in fully heat treated condition.

Three types of the test specimens were manufactured. Smooth cylindrical specimens with gauge length of 50 mm and gauge diameter of 3 mm were used to obtain basis creep data. Two types of notches were investigated. Circumferential V – notch with depth 0.5 mm, wedge angle of 60° and notch root diameter 0.2 mm was refined on the specimen's gauge length with diameter 3 mm. For this specimen the elastic stress concentration factor is $K_t = 2.54$. Circumferential U – notch with diameter 5 mm. Elastic stress concentration factor is $K_t = 1.61$.

Methods of treatment

Two methods had to be used to reach the aim mentioned above: (i) smooth and notched specimens were creep tested and (ii) stress strain analysis of the specimens was performed.

Experimental procedure

All the creep tests on smooth and notched specimens were performed in air at a constant temperature of 850 °C under constant load regime in tension using standard creep machines. In the case of smooth specimens the applied stresses laid between 400 MPa and 600 MPa. As for the notched specimens range, the net stresses (load divided by the minimal cross-section) laid between 600 MPa and 750 MPa for the U-notch specimens, and between 650 MPa and 800 MPa for the V – notch specimens. During the tests the elongation and elapsed time were continuously measured and registered. Time to fracture of smooth and notched specimens in dependence on the net stress can be seen in Fig. 1.

Strong notch strengthening effect is evident. At the same value of the net stress, the time to fracture of notched specimens are greater then that of smooth one, namely the lifetime is one order of magnitude longer in case of U-notch at 600 MPa. A slightly more expressive notch

strengthening effect for the V-notch then for the U-notch can be seen (Fig. 1.). The notch strengthening effect can be attributed to the existence of multiaxial stress state in the specimen.



Fig. 1. Creep life curves for smooth and notched specimens.

To obtain basic creep data four smooth specimens were tested. Creep curves were registered and analysed and for all the test specimens the similar dependences between strain rate and elapsed time were found Fig. 2. There is short primary stage, the strain rate decreases and reaches minimal value. Steady state is very short and most of the time to fracture appertains to the third stage of creep, where the strain rate increases. Nevertheless, the minimum creep rate can be determined from the creep test data record. Data evaluation leads to exponential function between strain rate and net section stress (1).

$$\dot{\varepsilon}_{\min} = Ae^{B\sigma}$$
, (1)
where A = 1.67x10⁻¹³ s⁻¹ and B = 2.12x10⁻² MPa⁻¹.



Fig. 2. Differentiated creep curve of smooth specimen tested at 500 MPa.

Numerical analysis

Time-dependent elastic-plastic calculations were used to obtain stress and strain distributions in the crept bodies. Due to the rotational symmetry of specimen geometry, boundary conditions, loading and isotropic material properties, only two-dimensional model of one quarter of the specimen was used. Calculations were performed using the general purpose finite element system ANSYS. The creep equations in ANSYS were integrated with an explicit Euler forward algorithm with the automatic time stepping algorithm, see [10] for details.

Based on the experimentally obtained material data for CMSX-4 superalloy, the distributions of stress, strain and displacement were numerically determined for different types of notched specimens. The results of creep calculations provide the distributions of stress, strain and displacement in the specimen as functions of time. Directly after loading the stress state corresponds to elastic solution. As creep occurs in a notched body, the initial stress field redistributes at the rate, which is controlled by the geometry of the notch and the specimen, the level of the applied stress and material properties. Fig. 3. shows distribution of one stress component, namely σ_{zz} as a function of distance from the notch root both U-notch and V-notch. σ_{zz} is normalized by nominal net section stress σ_{nom} .



Fig. 3. Stress components σ_{zz} as a function of the distance from the notch root. (a) V-notch, $\sigma_{nom} = 650$ MPa; (b) U-notch, $\sigma_{nom} = 600$ MPa.

A detailed knowledge of the stress and strain distribution generated due to the existence of a notch makes it possible to study the influence of stress state on creep rupture and on lifetime of notched bodies.

Creep behaviour of the smooth specimens is usually characterized by the minimum creep strain rate and its stress dependence. Creep failure of notched specimens is due to plastic flow in the whole notched section of the specimen; therefore to describe the creep strain rate of the notched specimens, the application of the mean value of the steady-state strain rate

component $\overline{\dot{\epsilon}}_{_{77}}$ was suggested.

$$\bar{\varepsilon}_{zz} = \frac{\iint \dot{\varepsilon}_{zz} \, dS}{S_0},\tag{2}$$

where S_0 is initial net section.

The stress multiaxiality due to existence of the notch is quantified by the coefficient of the stress triaxiality α ,

$$\alpha = \left(\sigma_{xx} + \sigma_{yy} + \sigma_{zz}\right) / \sigma_{eff} , \qquad (3)$$

where σ_{ij} are the values of the stress components and σ_{eff} is corresponding von Mises effective stress.

The mean value of the stress triaxiality coefficient α can be defined as

$$\overline{\alpha} = \frac{\iint \alpha \, dS}{S_0},\tag{4}$$

where S_0 is initial net section.

DISCUSSION

Estimation of creep life of notched specimens based on creep strain rate Monkman and Grant in the fifties of the last century related the creep life of smooth specimens with the minimum creep rate. They have found relation in the form

$$\dot{\varepsilon}_{\min} t_f^n = const.\,,\tag{5}$$

where the exponent *n* lies near to 1. For the notched specimens it is necessary to use a value of the creep rate characterizing the notch specimen instead of $\dot{\varepsilon}_{\min}$. For that purpose the value defined by equation (2) will be used. Fig. 4. shows the Monkman-Grant plot both for the notched specimens and for the smooth ones. Not only that Monkman-Grant relation can be used also for the notched specimen, but moreover the experimental points for smooth specimens and for notched ones fall into one scatter band.



Fig. 4. Monkman - Grant plot for smooth and notched specimens.

Estimation of creep life of notched specimens based on stress triaxiality factor

The numerical and measured results were used to find a correlation between the time to fracture of smooth and notched specimens and level of the stress multiaxiality in the specimen. With the aim to eliminate the influence of applied stress level, the time to fracture for notched specimens was divided by the time to fracture of the smooth one for the same loading conditions $t_f/t_{fsmooth}$. The notched specimens were tested at higher stresses then smooth ones. Therefore the relationship between creep lifetime and applied stress for smooth specimen was used for extrapolation of lifetime at high stresses. The normalized value $t_f/t_{fsmooth}$ was then correlated with corresponding values of the mean value of stress triaxiality $\overline{\alpha}$ calculated for stationary state (6).

$$t_f / t_{f,smooth} = \overline{\alpha}^c, \qquad (6)$$

where c is constant.



Fig. 5. Correlation between normalized time to fracture and stress triaxiality parameter.

The calculated dependences shown in Fig. 4, 5 make it possible to predict the creep lifetime of the notched specimens solely on the basis of creep data obtained on smooth specimens combined with the above outlined computation of stationary state.

Conclusions

Cylindrical bars of the orientation <001> with circumferential notches were tested at 850 °C. Strong notch strengthening effect was detected for both notch geometries.

The distributions of stress, strain and displacement were calculated using the general purpose finite element system ANSYS for notched specimens with different notch geometry and with different level of stress triaxiality.

The mean value of creep strain rate component $\overline{\dot{e}}_{zz}$ was used to characterize the notched specimens. The stress triaxiality was quantified by means of the mean value of the stress triaxiality coefficient calculated for stationary state.

The correlation was found between the creep lifetime of the notched specimens and the mean value of calculated creep strain rate. For both notches the creep life curves of this type were found to be identical within scatter with the life curve for smooth specimens expressed in terms lifetime versus steady state creep rate. The modified Monkmam-Grant relationship is valid both smooth and notched specimens.

Moreover the correlation between the normalized time to fracture and the stress triaxiality factor was found.

Based on the obtained results the lifetime of the notched specimen can be estimate on the basis of creep data obtained on the smooth specimen.

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