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CREEP MODELLING AND LIFETIME PREDICTION FOR NICKEL-BASE SINGLE CRYSTALS AT HIGH TEMPERATURES

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ABSTRACT

The one and three dimensional creep behavior of nickel-base single crystals can be described by a modified Burgers-model within its primary and secondary creep stage. In order to include damage, a Kachanov/Rabotnov damage variable has been introduced, which enables the model to describe monotonous creep behavior in the whole range up to rupture. By integrating the relevant parts of the evolution equations a rule for the time-to-rupture prediction is derived.

1 INTRODUCTION

For the designer of turbine blades, life estimation under creep loadings is one of the main challenging tasks. Under high temperatures, nickel-base superalloys show some remarkable features under creep tests:

1) the secondary creep phase exists only in a tangential sense, i.e. the tertiary creep almost immediately starts after finishing the primary phase;
2) the ultimate creep deformations before rupture can be rather high, in some cases more than 20 %;
3) the creep deformations are extremely nonlinear with respect to the applied stress;
4) the whole creep behavior varies greatly with the orientation of the crystal in the specimen, see [1,2,3]. The same holds for temperature changes, too.

The purpose of the present paper is the modelling of the behavior of these materials taking these features into account. Moreover, for industrial applications one needs simple rules for the estimation of lifetime for creep applications. Naturally, such rules have to be rather limited to ideal conditions, because too many parameters influence the damage behavior. As a first step, creep under constant loads for constant temperature and for fixed orientations will be modeled, before we try to generalize it to three dimensions and thus give it an orientation dependent presentation. As little is known about the anisotropic damage behavior, lifetime predictions for fully three-dimensional non-proportional loads is still beyond our present possibilities.

2 UNIAXIAL MODEL

The starting point for our present contribution is a set of two evolution or differential equations

which are derived from the well-known Burgers model and, hence, constitute a material model:

$$\dot{\varepsilon}(t) = \frac{1}{C+K}\left[\dot{\sigma}(t) + \left(\frac{C}{D} + \frac{C}{L} + \frac{K}{L}\right)\sigma(t) - \frac{C}{D}\tau(t)\right] \qquad (1)$$

$$\dot{\tau}(t) = \frac{K}{C+K}\left[\dot{\sigma}(t) + \frac{C}{D}(\sigma(t) - \tau(t))\right] \qquad (2)$$

Herein, σ denotes the stress, ε the total strain, τ an inner variable with the same dimension as σ, C and K elastic constants, and D and L viscosities. All of these four material constants or functions are assumed to have positive values in their entire ranges. The non-linearity in the applied stress is induced by the viscosities D and L, which are assumed to be functions of σ. It turned out by our identification procedure, that both dependences are quite similar, namely

$$\begin{aligned} D &= d(1 + k_1\sigma) \\ L &= l(1 + k_1\sigma) \end{aligned} \qquad (3)$$

where d, l, and k_1 are material constants depending on the orientation and on the temperature. This simple model is already capable to describe the primary and secondary creep behavior in a fairly large load and temperature range.

A complete three-dimensional generalization of this model by means of tensor-funtion-representations has been given in [4,5]. It has been implemented in the finite-element-code ADINA [6]. Calibrations of this model to experiments and numerical results will be presented in a fourthcoming paper [7].

In order to include tertiary creep, which is related to a manifold of different mechanisms in crystal physics, among them void growth and diffusional creep, we introduce a damage variable δ in the sense of Kachanov/ Rabotnov, that relates the effective cross section F_E to the current one F_A by

$$\frac{F_E}{F_A} = 1 - \delta \quad , \qquad 0 \le \delta \le 1 \quad . \qquad (4)$$

At the beginning, δ is zero. During the creep process, δ continuously grows. In analogy to the above evolutions equations (1) and (2), we set

$$\dot{\delta} = C_1\sigma + C_2\dot{\sigma} + C_3\tau + C_4\delta \quad . \qquad (5)$$

It turned out (see [8], [9]), that only few terms of this growth law are really significant, namely C_1 and C_2 , depending on the temperature. At 760 °C, for example, the simplified law

$$\dot{\delta} = C_1\sigma \qquad (6)$$

gave good results. In Fig. 1 experimental results for the nickel-base superalloy SRR99 at 760 °C are shown together with the calculated creep curves by means of our model. It shows a fairly good approximation in the entire creep regime up to the ultimate measure points immediately

before rupture.

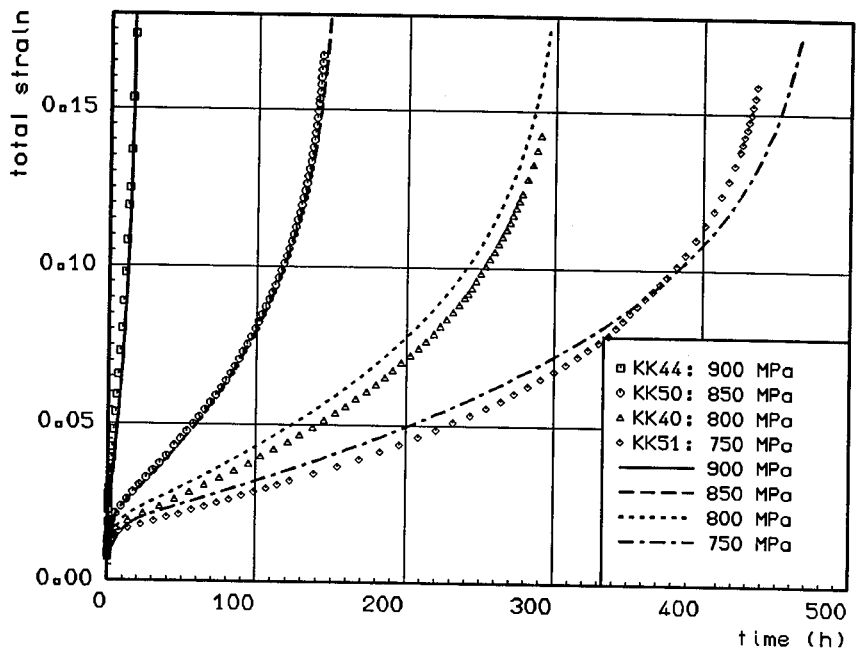

Fig. 1: Experimental data and predictions of creep tests at 760 °C.

3 TIME-TO-RUPTURE PREDICTION BY THIS MODEL

In our model, C and K represent the instantaneous elastic response, whereas D dominates the primary creep. These constants are of little if any influence on the time-to-rupture. Only the viscosity L, which governs the secondary creep, will be therefore taken into account for our lifetime estimation. Combination of the resulting differential equations, the assumption of volume-preserving creep deformation, and elimination of σ and ε leads to

$$\left[\frac{\ddot{\delta}\,(1-\delta)^2}{\dot{\delta}}\right] = 0 \quad . \tag{7}$$

For more details see [8]. By integrating this differential equation twice and determining the integration constants by suitable initial conditions, one obtains finally

$$t = \frac{-\delta}{K_2} + \frac{K_1}{K_2^2}\ln\left[\frac{K_2(1-\delta) - K_1}{K_2 - K_1}\right]$$

$$= \frac{1}{\sigma_o C_1 K_4}\left[-\delta + \left(1 + \frac{1}{K_4}\right)\ln(1 + \delta K_4)\right] \tag{8}$$

where the abbreviation

$$K_4 = \varepsilon_o + \frac{1}{C_1 L} \tag{9}$$

has been used. Rupture occurs, if δ grows to values near one.

Therefore, the time-to-rupture can be assessed by the limit of t in the above equation as δ tends to 1. This time is given by

$$t_{\infty n1} = \frac{1}{\sigma_o C_1 K_4}\left[\left(1 + \frac{1}{K_4}\right)\ln(1 + K_4) - 1\right] , \tag{10}$$

a rather complicated nonlinear formula. By expanding the logarithmic function into a power series

$$t_{\infty n1} = \frac{1}{\sigma_o C_1 K_4}\left(\frac{K_4}{2} - \frac{1}{6}K_4^2 + \ldots\right)$$

$$= \frac{1}{2\sigma_o C_1} - \frac{1}{6\sigma_o C_1}\left(\frac{1}{C_1 L} + \varepsilon_o\right) + \ldots \tag{11}$$

a first order approximation

$$t_{\infty 1} = \frac{1}{2\sigma_o C_1} \tag{12}$$

can be obtained which contains only one constant. This result coincides with the geometrically linear theory neglecting reductions of the cross section due to lateral strains. In Fig. 2 the two versions of the derivated time-to-rupture rule has been plotted against σ.

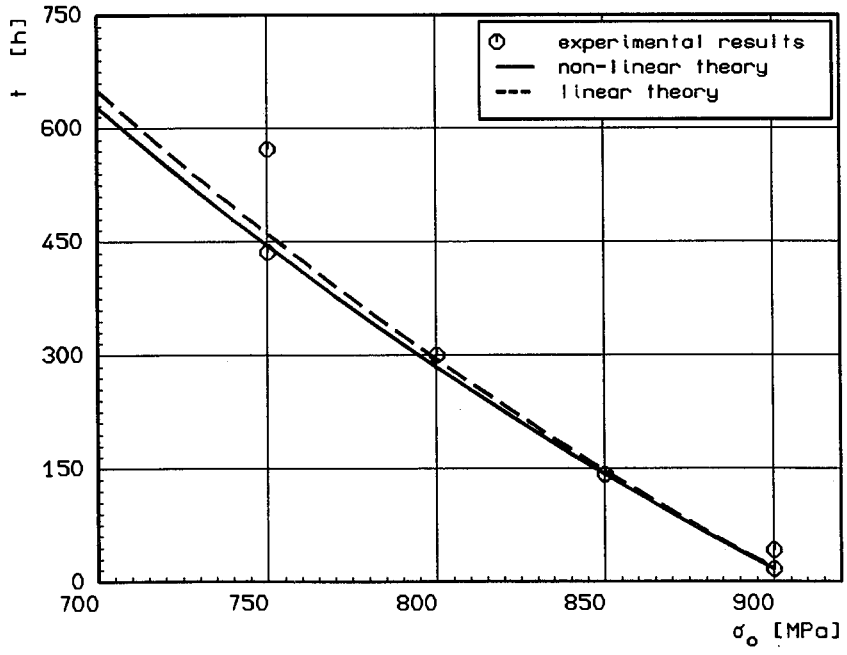

Fig. 2: Time-to-rupture of SRR 99 at 760 °C

The difference between the two curves turns out to be rather small and neglegible if compared with the scatter of the experimental results, which are indicated by the symbols.

4 CONCLUSIONS

The suggested model is capable to describe the monotonous creep behavior in all its stages for the class of material under consideration. By integrating the relevant parts of the evolution equations one obtains a simple rule for the prediction of time-to-rupture. A three-dimensional generalization of this model exists only for the primary and secondary creep phase, as too little is known about the 3-D damage behavior of single crystals.

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