CRACK CLOSURE EFFECT ON CRACK GROWTH RATE IN N18 NICKEL BASE SUPERALLOY

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Crack growth rate measurements, performed on smooth specimens, during creep fatigue of a N18 Nickel base superalloy at 650°C, reveal a strong detrimental effect of the compressive part of the loading cycle. This effect is attributed to the residual stresses in the wake of the crack, which promote crack opening. A finite element analysis is conducted in order to predict the evolution of the opening stress level as a function of the stress ratio. A good agreement is found between numerical and experimental results.

INTRODUCTION

The general framework of the present study is the modelling of crack propagation at the notch root of a nickel base superalloy for turbine disks subjected to creep fatigue cycles at 650°C. Using elasto visco plastic finite element calculations we previously evaluated the evolutions of both the local stresses and local stress ratio within the cross section of the specimen (Pommier et al., 1). This study showed that, during creep fatigue cycling, under applied nominal stresses and a nominal R ratio equal to zero, the notch root tends to be loaded under local applied strain conditions with a local negative R ratio. Introducing a semi analytical calculation of the stress intensity factor K for a semi elliptical crack in this stress gradient, it was then possible to compare, in terms of K_{max}, the propagation rate of cracks propagating at a notch root with that measured in smooth specimen. This comparison revealed that the crack growth rate is higher at the notch root than in smooth specimens if the data are plotted in terms of K_{max}.The accelerating effect of the local compression was suspected, thus, arising the need of a precise knowledge of crack closure modification by compressive stresses.

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MATERIAL AND EXPERIMENTS.

Material : The material studied is a N18 powder metallurgy Nickel base superalloy reinforced by γ' precipitation. As shown in figures 1 and 2 three type of γ' precipitates are present in the material : large primary γ' precipitates at grain boundaries triple points (1), and smaller secondary (2) and tertiary (3) γ' precipitates within the grains. The chemical composition of the alloy is given in table 1. After heat treatment a microstructure gradient appears from the skin to the heart of the discs. Grain boundaries of the "skin" microstructure (figure 2) appear to be depleted of secondary γ' precipitates whereas, at the centre of the disc, γ' precipitates can be found even along grain boundaries (figure 1). The creep fatigue crack growth rate is usually higher in the skin microstructure than in the heart microstructure (Hochstetter, (2)).

TABLE 1- Chemical composition of the N18 (Vol %) (Wlodek, (3))

C	Co	Ni	Cr	Mo	Al	Ti	B	Hf	Zr
0,015	15,7	base	11,5	5,5	4,35	4,35	0,015	0,45	0,03

The usual elastoplastic properties of the alloy, as measured at 650°C, are reported in table 2. These classical measurements have been completed by low cycle fatigue tests, relaxation and creep tests in order to evaluate the different parameters of the Chaboche's elasto visco plastic constitutive equation used in the numerical modelling (Chaboche, (4)). The material presents a strong Baushinger effect due to the presence of γ' precipitates. At 650°C, the viscous behaviour is far from being negligible. These properties have been mainly determined from heart microstructure samples.

TABLE 2- Tensile properties of the N18 superalloy at 650°C.

Young's Modulus	185 GPa
Poison's ratio	0.3
Yield stress	1050 MPa
Ultimate tensile stress	1350 MPa
Elongation	20 %

Experiments : The specimen is parallelepipedic, with a rectangular cross section of 5 x 10 mm^2. The crack growth rate is measured by the potential drop technique using an ANS apparatus. A semi-elliptical crack is initiated by room temperature fatigue precracking at 0.5 Hz. Then, the specimen is heated at 650°C and subjected to creep fatigue cycles (see figure 6) : a 10 second tension loading followed by a 300 second dwell time at the maximum stress and a final 10 second unloading to 0.05 σ_{max} for experiments conducted at $R = 0.05$ and to $-\sigma_{max}$ for experiments conducted at $R = -1$. The influence of a stress ratio change on the crack growth rate has been tested using the following procedure : the sample is first subjected to creep fatigue cycles with a stress ratio of 0,05 ; at mid life, for the same maximum stress, the stress ratio is changed to -1, and the crack is grown to rupture of the specimen. Figure 3 shows that, for a nominal applied stress of 900 MPa, the crack growth rate is nearly increased by a factor three when the stress ratio is changed from 0,05 to -1 in the heart microstructure. This effect appears also in experiments conducted at lower nominal stresses (namely 700 MPa) but vanishes for stresses lower than 500 MPa. In the heart microstructure, the detrimental effect of the compressive part of the cycle on the fatigue life of the specimen is thus clearly evidenced. Figure 4 shows that for a nominal stress of 900 MPa applied on the skin microstructure this effect is less pronounced. The effect of the compressive part of the cycle is usually attributed to a change in the crack opening level (K_{op}) so the Paris law must be plotted as a function of the effective stress intensity factor K_{eff}, where $K_{eff} = K_{max} - K_{op}$. For a stress ratio R = 0.5, the crack can be assumed to be permanently opened so $K_{eff} = 0.5\ K_{max}$. For R = 0.05, it can be assumed that $K_{op} = 0.25\ K_{max}$, as measured by G. Hochstetter (2) on CT specimens. If we assume that changing R ratio does not modify the Paris law plotted in terms of K_{eff}, the shift between the two parts of the Paris law plotted in terms of K_{max} (figure 3) gives an estimation of the value of K_{op} for R = -1. The results of the experiments conducted on heart microstructure (circles) are plotted on figure 5, for maximum stresses of 500 MPa, 700 MPa and 900 MPa.

FINITE ELEMENT ANALYSIS

To have a better understanding of these effects a finite element analysis was conducted on the software Zebulon. The behaviour of the material at 650°C is described through the constitutive equations of Chaboche (4) containing a viscoplastic law, a kinematic hardening and an isotropic hardening equations. The computations were performed in 2D, under plane strain conditions. The software was modified in order to be able to simulate a crack growth with a residual stress field generation in the crack wake. The mesh that was used for these computations was specially designed in order to keep the plastic zone of the crack within a refined meshed zone. Computed opening stress intensity factor are plotted as a function of the stress ratio R on figure 5, for a maximum stress of the fatigue cycle of 500 MPa, 700 MPa and 900 MPa. On this figure are also reported the K_{op} determined experimentaly. A good agreement is found between numerical and experimental results. K_{op} decreases with the R ratio and this effect is more pronounced for high σ_{max}, which explains the detrimental effect of the compressive part of the creep fatigue cycle on crack growth rate. For a nominal stress of 900 MPa and a R ratio of -1, the crack is fully open before the applied stress is positive. This can be explained by a change in the sign of the residual stresses. Since a unique constitutive equation was established for the material (mainly for heart microstructure) we have tried to evaluate how the variation of the constitutive behaviour could affect the results, in order to explain the different effect of the R ratio on the heart an skin microtructures.

EFFECT OF THE CONSTITUTIVE BEHAVIOUR.

The constitutive behaviour of the material can strongly affect the opening level. Two features are of major importance under creep-fatigue cycles, namely the viscous behaviour of the material and its Baushinger effect, as shown on the schematic diagram presented figure 6. The first results of our computations, for σ_{max} equal to 900 MPa, are given in table 3. The effect of the stress ratio is entirely different if the hardening is isotropic (VI) or kinematic (VK). For a stress ratio R = 0 the two cases (VI and VK) gives the same results. For a stress ratio of -1, if the hardening is isotropic, the crack opening level is approximately null (see table 3) whereas if the hardening is purely kinematic the crack opening level reaches -20 %. For a plastic material (PK), presenting a kinematic hardening law identical to that of the case VK for $\varepsilon = 10^{-3}$ s^{-1}, the effect of the R ratio is very small. This is due to the suppression of crack tip blunting during the dwell time, that occurs in a viscoplastic material. Great attention has therefore to be paid to the constitutive behaviour of the material to model the crack opening level due to plasticity at the crack tip. Relaxation, low cycle fatigue and creep test should be conducted on the skin microstructure specificaly in order to determine its viscoplastic constitutive behaviour, thus allowing to compare numerical results in skin and heart microstructure.

TABLE 3- Ratio K_{op} / K_{max} for a crack length of 210 μm

a = 210 mm	V I	V K	PK
R = 0	≈ 20 %	≈ 20 %	≈ 14 %
R = -1	≈ 0 %	≈ - 20 %	≈ 8,5 %

CONCLUSIONS

- Creep fatigue tests conducted on N18 superalloy at 650°C, have shown a detrimental effect of the compressive part of the cycle. This effect is more pronounced in the heart microstructure than in the skin microstructure.

- Finite element computations with viscoplastic constitutive equations have been performed in order to determine the opening stress intensity factor K_{op}. The numerical results are in good agreement with experimental results. They show that K_{op} decreases with the R ratio and that this decrease is more pronounced for high applied stress.

- It has also been shown that the constitutive behaviour of the material can have a great effect on the value of K_{op}, in particular the kinemetic part of the hardening and the viscosity of the alloy.

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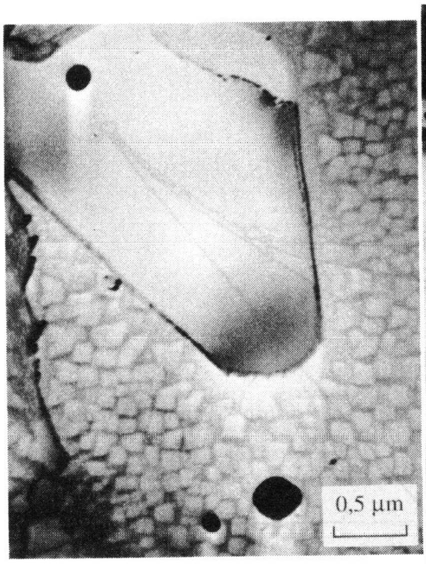

Figure 1 Heart microstructure

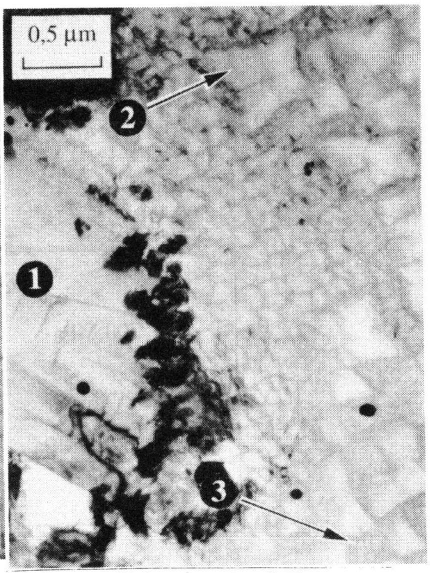

Figure 2 Skin microstructure

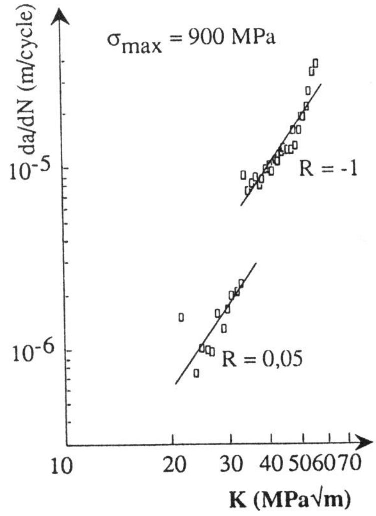

Figure 3 Creep fatigue test
on heart microstructure

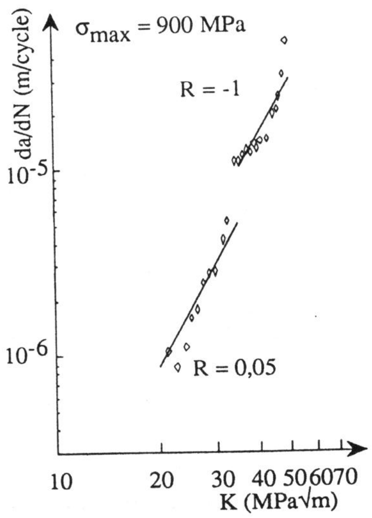

Figure 4 Creep fatigue test
on skin microstructure

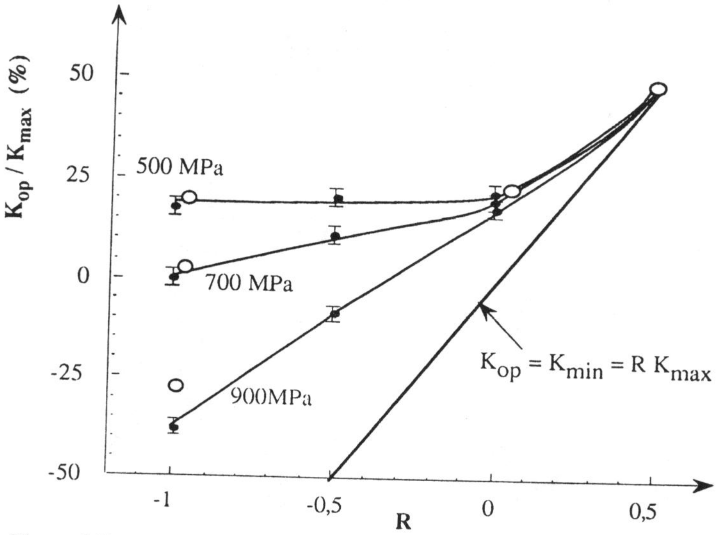

Figure 5 Experimental and numerical Kop versus R

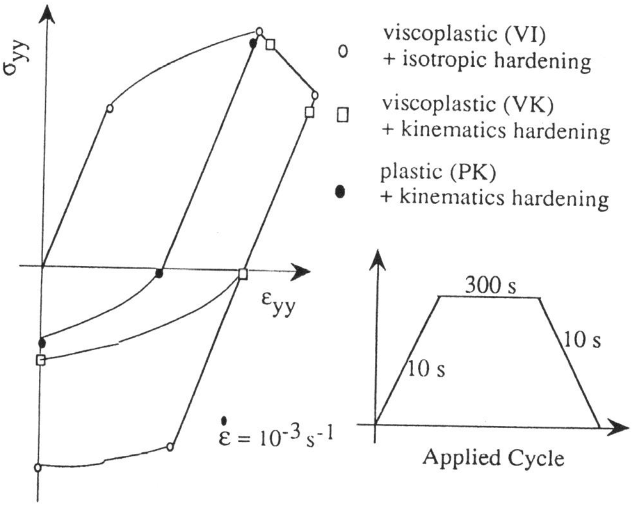

Figure 6 effect of the constitutive behaviour on Kop