STRESS INTENSITY FACTOR FOR CREEP FATIGUE CRACKS GROWING FROM A NOTCH

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Double notched specimens of nickel base superalloy N18 have been subjected to creep fatigue loading. Finite element analysis, using the elastoviscoplastic constitutive equations of N18, shows a strong stress redistribution behind the notch root. A solution for the stress intensity factor (SIF) is proposed which takes into account this cyclic stress redistribution. The "viscoplastic SIF" calculated is intermediate between an elastic solution for low applied loads and the SIF for an unnotched body for high loads.

INTRODUCTION

With the need of improvement of aircraft gas turbine performances, security components, such as turbine and compressor discs, tend to be fabricated with powder metallurgy superalloys. However their excellent mechanical properties can be deteriorated by the presence of inclusions introduced in the melt process (Denda et al (1)). Discs failures due to creep fatigue crack growth from an inclusion at firtree fixtures of turbine blades, is a key problem for engine designers (McClung (2)). Double notched specimens of N18 were subjected to a specific loading schedule corresponding to service conditions. An attempt is made to take into account the strong stress relaxation at the notch root in the calculation of the three dimensional crack propagation law.

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MATERIAL AND CONSTITUTIVE EQUATIONS.

The alloy tested, N18 is an advanced Nickel base gamma prime strengthened disc alloy. It was developped by SNECMA as a powder metallurgy alloy for service up to 700°C. Currently N18 is being used for compressors and turbine discs of the M88 engine for the new Rafale fighter. The chemical analysis of the material tested is reported in table 1. Further informations about this alloy can be found in the work of Guedou et al (8) and Wlodek et al (3). Double edge notched specimens were machined into a turbine disc as shown in figure 1 and were subjected to trapezoidal cycles (10-300-10): 10 s loading, 300s dwell time, 10 s unloading with R_S=0 at 650°C in air.

TABLE 1- Chemical composition of N18 (At %)

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 constitutive equations, proposed by Lemaitre and Chaboche (4), are built on the following hypothesis. The total strain (ε) is the sum of an elastic part (ε_e) and a plastic part (ε_p). The stress (σ) breaks up as well into two parts, the viscous stress (σ_v) and the internal stress (σ_i). σ_i itself is the sum of a kinematic hardening parameter (X) and an isotropic hardening parameter (R). The meaning of these parameters is defined in figure 2. Two more parameters are introduced : p, which represents the cumulated plastic strain and α, which is an additionnal hardening parameter. For a viscoplastic behaviour five equations describe the evolution of these parameter (see figure 2). The constant terms have been identified through stress relaxation test, tensile test, creep test and fatigue test.

FINITE ELEMENT ANALYSIS

Finite element computations have been conducted by Zebulon, the Finite Elements software developped by Ecole des Mines de Paris. Using the elasto-viscoplastic constitutive equations of N18, up to 300 cycles (10-300-10) were applied on the uncracked specimen as shown on figure 3. The notch root is highly plastified at the first loading.

Then the local stresses are redistributed into the structure and within a few cycles the tensile stresses and strains become steady and the stress-strain curve's hysteresis loop is insignificant (see figure 4). As the center of the sample remains elastic the plastic deformation of the notch root is limited, thus creep deformation during dwell time becomes quickly negligible. The results of three reckonings are presented in figure 5. On the vertical axis is plotted the local tensile steady stress (σ_{yy}) divided by the nominal tensile stress (σ_{yy}, nominal). For a nominal stress of 500 MPa, the calculated stress profile is almost "elastic", but viscoplastic results for higher nominal stresses are obviously very far from an elastic solution. The local stress at the notch root decreases and the peak stress goes deeper in the structure as the nominal stress increases. Thus stress redistribution under creep fatigue cycling should be taken into account in the crack propagation law's calculation.

DISCUSSION

Since crack initiation usualy occurs for more than 300 cycles, according to our computations, the local stress and strain at initiation can be considered as steady and the hysteresis loop (see figure 4) negligible. Thus it is reliable to use the stress intensity factor K instead of C*. An exact solution of K for a penny-shape crack subjected to a stress gradient $\sigma(y)=\sigma_0{}^*(y)^n$, has been given by R.J. Hand (5). From this solution an approximate solution (K^1) has been calculated for an elliptical crack growing under a polynomial stress distribution ($\Delta\sigma=\Delta\sigma_0\sum_{n=0}^{n=5} a_n y^n$) assuming that $\frac{K_I^1}{K_I^3}=\frac{K_I^2}{K_I^4}$ The definition of K_I^1 to K_I^4 is given in figure 6. At each point of the structure, the crack was supposed to open when the local stress, calculated on the uncracked body, becomes positive ($\Delta\sigma=\sigma\text{max}$). The polynomial's coefficients were obtained by accurately fitting a fifth degree polynomial on the computed tensile stress profile (see figure 5). Stress intensity factors (ΔK) against crack length were calculated. For crack lengths of 0.3 mm and 1 mm, we have plotted ΔK versus nominal stress (see figure 7).

Low nominal stresses give a stress intensity factor almost similar to that calculated in elasticity, whereas for higher stresses it tends to that calculated in an unotched body, for cracks subjected to a constant remote stress.

Looking at the stress profile (see figure 5) this result could be expected, since the stress concentration factor at each point of the structure is approaching one as the nominal stress increases.

CONCLUSION

(1) For creep fatigue tests performed at 650°C, with a dwell time of 300 sec, on the Nickel base superalloy N18, the Finite Element analysis conducted, using the elastoviscoplastic constitutive equations of N18, shows that a strong redistribution of stresses occurs behind the notch. (2) A solution for K_I is proposed which takes into account the cyclic stress redistribution at the notch root. The "viscoplastic SIF" calculated is intermediate between the elastic solution for a crack growing at the notch root for low nominal stresses and the solution for an unnotched body, for high stresses.

ACKNOWLEDGEMENTS

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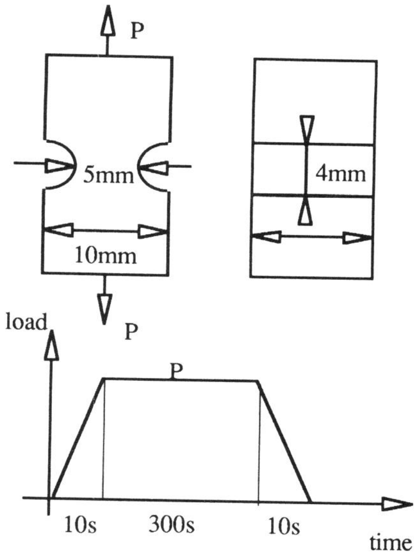
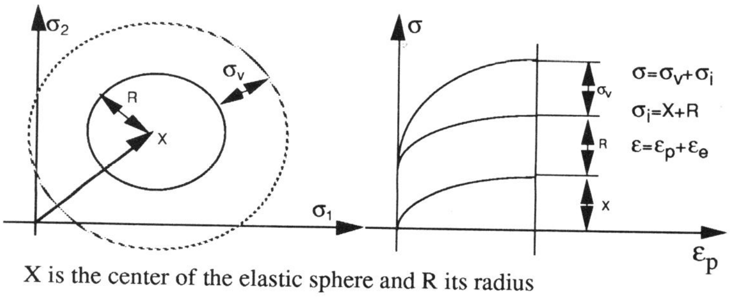


Figure 1 : Double Notched Specimens andloading schedule.



X is the center of the elastic sphere and R its radius

$$\dot{\varepsilon}^{v} = \frac{3}{2}\dot{p}\frac{\sigma'-\mathbf{X}'}{J_2(\sigma - \mathbf{X})} \qquad \dot{\mathbf{X}} = \frac{2}{3}C\dot{\varepsilon}^{v} - \gamma\mathbf{X}\dot{p} \qquad \dot{R}=b(Q-R)\dot{p}$$

$$\dot{p} = \left\langle\frac{J_2(\sigma-\mathbf{X}) - R}{K}\right\rangle^{n} \qquad \dot{\alpha}=\dot{\varepsilon}_p - \frac{3}{2}\frac{\gamma}{C}X\dot{p}$$

Figure 2 : Constitutive equations for a viscoplastic behaviour.

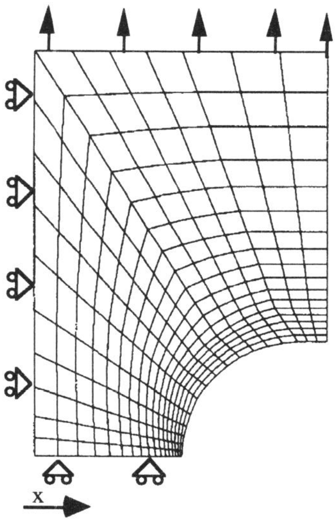


Figure3 : Finite element mesh in double notched specimen.

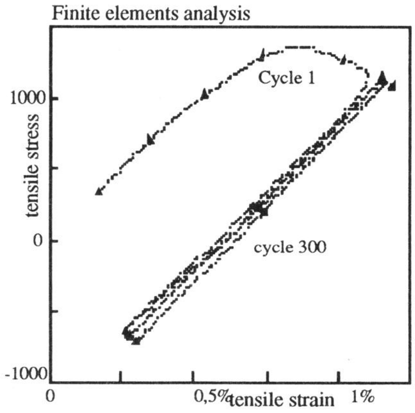


Figure 4 : Stress Strain Curve at notch root for a nominal stress of 1000MPa

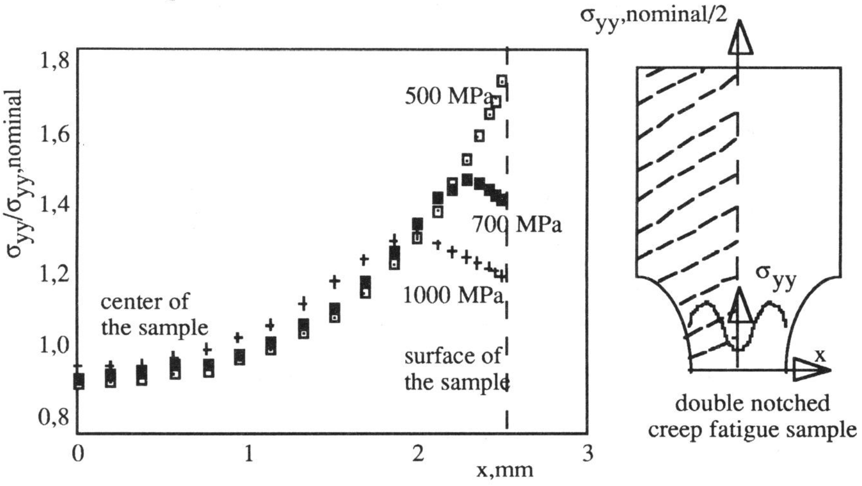
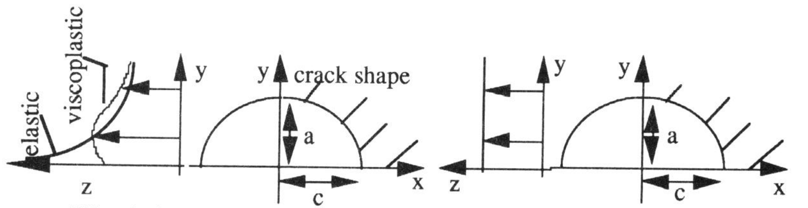
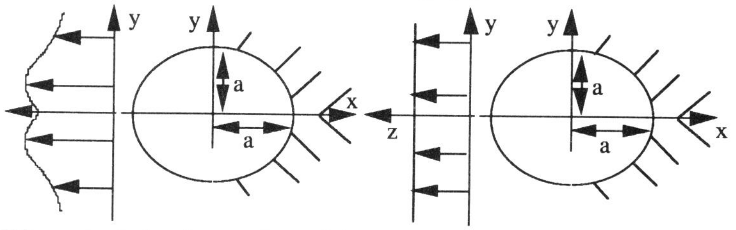


Figure 5 : Steady stress profile along the section for three nominal stresses.



K1 solution used in our propagation law

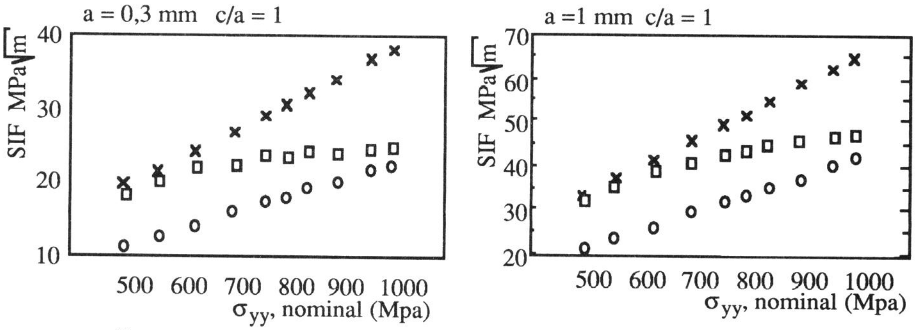
K2 was calculated by Newman and Raju (7)



K3 exact solution for a polynomial stress distribution from R.J. Hand (5) solution

K4 from Newman and Raju (7)

Figure 6 : Definition of the stress intensity factors K1 to K4. (Foth et al(6))



× elastic (crack growing from a notch)

□ elasto-viscoplastic (crack growing from a notch, with stress redistribution)

o constant stress (crack growing in an unnotched body)

Figure 7 : Comparison between the SIF calculated from elastic and viscoplastic computations of a notched sample and that for a constant stress.