CREEP DAMAGE ANALYSIS OF SHORT CRACKS USING A NARROW NOTCH SPECIMEN MADE FROM A NI-BASE SUPERALLOY AT 700^o C

T. H. Hyde, A. A. Becker and W. Sun

School of Mechanical, Materials, Manufacturing Engineering and Management
University of Nottingham, Nottingham NG7 2RD, UK

ABSTRACT

The results of damage mechanics finite element (FE) creep analyses were used to investigate the initiation and growth of short cracks using a 2D narrow notch model, under plane strain and plane stress conditions, with a uniform tensile loading. The material properties for a Ni-base superalloy (Waspaloy) at 700^o C were used. Damage distributions and growth near the notch, with time, were used to characterise and identify crack initiation and growth and to determine the direction of growth of the high damage zone, which was used to identify the crack growth direction. It was found that under plane stress conditions, the high damage zone was formed and grew inwards along the symmetric line of the notch, while under plane strain conditions, there was a bifurcation of the high damage zone, along a direction which was inclined at an angle to the notch. This angle was found to be dependent upon the tri-axial damage parameter α, reducing from 60^o to 35^o for α increasing from 0 to 0.3.

KEYWORDS

Short cracks, creep, damage, crack growth, crack direction

INTRODUCTION

The need to estimate the life of new components, or the residual life of components already in service, which operate at elevated temperature and may contain cracks, is important. For example, in the assessment of aeroengine components, an essential requirement is to study the high temperature failure and fracture behaviour of materials and components, under creep or creep/fatigue conditions. Results of laboratory testing using uniaxial, notched, compact tension specimens etc., are usually used to obtain information regarding material failure or crack propagation behaviour. In recent years, the investigations of crack growth have resulted in various parameters (e.g. K, C*, accumulated damage, ω, and critical strain, ε_c, etc) being proposed as parameters which govern creep crack growth. Numerical analyses, for example, the finite element (FE) method, are popularly used to assist with the detailed understanding of the behaviour at the advancing crack tips.

In this paper, the results of the continuum damage mechanics FE modelling have been used to assess the creep fracture behaviour of short cracks with a simplified 2D narrow notch model, using material properties obtained for a Ni-base superalloy (Waspaloy) at 700^o C. Damage distributions and accumulation near the notch, with time, were used to identify the crack initiation and its direction of growth.

FE MODEL, DAMAGE ANALYSIS AND MATERIAL PROPERTIES

FE Model

The 2D FE model used is shown schematically in Figure 1. The width of the specimen, L, is 7 mm, with a semi-circle narrow notch of length, a_o, of 0.5 mm at the edge, which has a radius, r, of 0.2 mm. A uniform tensile stress, σ_o, is applied to the end of the specimen. The FE mesh generated for damage analyses is shown in Figure 2, with 2-D axisymmetric, 8-node isoparametric, quadratic rectangular elements with reduced Gauss integration points (2×2). Local mesh refinement is used in the area near the notch.

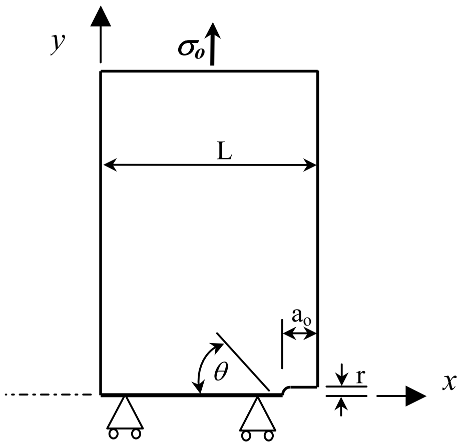

Figure 1: Schematic diagram of the short crack specimen (symmetrical half)

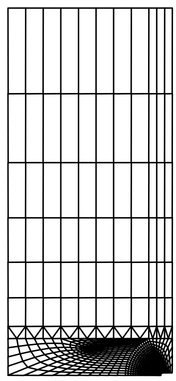

Figure 2: FE mesh of the narrow notch model

FE Damage Analyses

Creep damage constitutive equations of the type [1]

$$\dot{\varepsilon}^c_{ij} = \frac{3}{2} A \left[\frac{\sigma_{eq}}{1-\omega} \right]^n \frac{S_{ij}}{\sigma_{eq}} t^m \qquad (1)a \qquad \text{and} \qquad \dot{\omega} = \frac{M \sigma_r^{\chi}}{(1+\phi)(1-\omega)^{\phi}} t^m \qquad (1)b$$

in which $\sigma_r = \alpha\sigma_1 + (1 - \alpha)\sigma_{eq}$ were used in FE analyses to obtain the damage distributions, where σ_{eq}, σ_1 and σ_r are the equivalent, maximum principal and rupture stresses, respectively, ω is the damage variable and A, m, n, M, ϕ and χ are material constants. α is a material constant ($0 < \alpha < 1$) which describes the effect of the tri-axial stress state on the rate of damage of the material. FE creep damage calculations were performed using the user's material subroutine, UMAT, facility within the ABAQUS FE code [2, 3].

It should be noted that very high stress and strain concentrations occur at the notched region due to the small width of the notch. However, since the stress values in the high stress region will quickly reduce due to redistribution during creep, the local plastic behaviour was not taken into account in the current creep damage modelling.

Creep Properties

The material constants used in the FE analyses were related to the creep properties of a Ni-base superalloy (Waspaloy) at 700^o C, which is used in the manufacture of aeroengine turbine discs [4]. The material constants, in equations (1), for the Waspaloy superalloy are given in Table 1. Young's modulus and the yield stress for the material at 700^o C are 178×10^3 MPa and 860 MPa, respectively.

TABLE 1
MATERIAL CONSTANTS FOR THE NI-BASE SUPERALLOY (WASPALOY) AT 700^o C [4]

A	n	m	M	ϕ	χ	α
9.226×10^{-34}	10.647	0.0	1.184×10^{-25}	13.0	8.133	0.15

RESULTS

Creep damage calculations were performed using the FE model shown in Figure 2, under both plane stress and plane strain conditions, using the material properties given in Table 1, with an applied stress, σ_o, of 400 MPa. Calculations were also performed with a range of other α values, in order to investigate the effect of the tri-axial stress state damage parameter on the damage behaviour of the specimen. Since the main purpose of this work was to identify the main factors affecting creep crack growth, an arbitrary damage level of 50% was chosen to represent the crack growth behaviour.

Stress, Strain and Damage Distributions and Direction of Damage Growth

The stress, strain and damage contours obtained from the FE analyses are used to illustrate the general behaviour of the specimen. The contours (near the notch) for the strain in loading direction, ε_y, rupture stress, σ_r, and damage at $\omega = 0.5$ under the plane stress condition, at different creep times, are shown in Figures 3(a) to 3(c), respectively. The corresponding results obtained from the plane strain analyses are shown in Figures 4(a) to 4(c), respectively. In all cases, it was found that the stress, strain and damage levels near the notch are significantly higher than those remote from the notch. The behaviours (strain, stress and damage distributions) illustrated by Figures 3 and 4 are consistent, i.e. in general, the high damage area is associated with the high strain area. When the damage level is high, the stress values in these areas reduce and the high stress regions move inwards to the region near the ends of high damage zones (similar to the behaviour at the tip of a crack), resulting in further growth of the high damage zones.

Results obtained under plane stress conditions, show that high damage initially occurs at the notch root, and then moves inwards, along the plane of symmetry of the notch, with increasing creep time, Figure 3(c). However, under the plane strain condition, the high damage zone, which initially occurs at the notch root, moves inwards along the plane of symmetry of the notch for a very short distance, before bifurcating and then continuing to grow in a direction inclined at an angle, θ, of about 45^o to the plane of symmetry of the notch, Figure 4(c).

Effect of the Tri-axial Stress State Damage Parameter, α

High damage growth direction

Calculations were also performed with α values (keeping the other material parameters in equations (1) the same), in the range of $0 < \alpha \leq 0.5$, in order to investigate the effect of the tri-axial stress state damage parameter on the distributions and growth of the high damage zones in the specimen. Results obtained from the calculations using the Waspaloy properties have shown that changing the α value in general will not change the trend of high damage growth for the plane stress specimen. However, for the plane strain case, increasing the α value will significantly reduce the inclination of the high damage zones to the plane of symmetry, θ, as illustrated in Figure 5.

Growth of the high damage zone

The variations of the crack growth, a, as indicated by the growth of the high damage zone, with the creep time, t, for a range of α values, under the plane stress condition, are shown in Figure 6. The results given in Figure 6 were obtained from the symmetric centre line of the specimen, at a damage level of $\omega = 0.8$ ($\omega = 0.5$ was used for most of the analyses presented), in order to obtain high accuracy. The crack length, a, was defined as the extent of 0.8 damage zone along the centre line, starting from the notch root.

Failure life estimation

Failure life was estimated, using the times at which the high damage ($\omega = 0.5$) zones reached a significant length (≥ 1 mm), compared to the width of the specimen. The lives, estimated in this way, with different α values, are presented in Table 2. In general, the failure lives estimated reduce with increasing α, which is similar to the behaviour indicated by calculations for a Bridgman notch bar made from the same material [4].

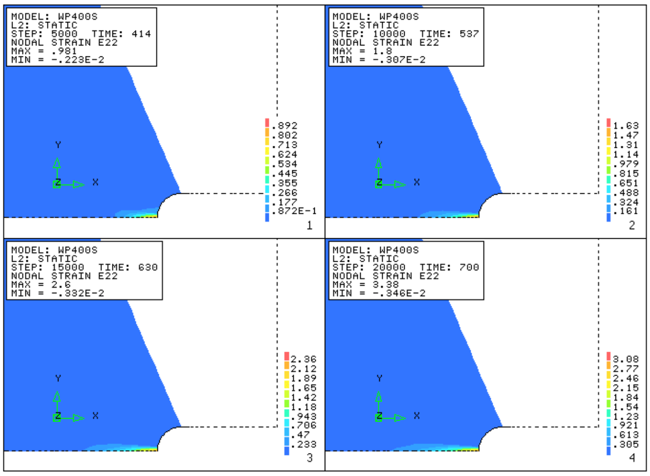

Figure 3(a): Distributions of axial strain, ε_y, for different times: plane stress case, $\alpha = 0.15$

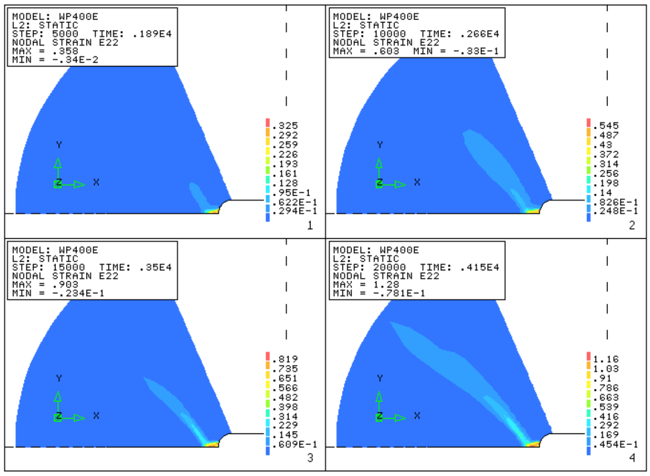

Figure 4(a): Distributions of axial strain, ε_y, for different times: plane strain case, $\alpha = 0.15$

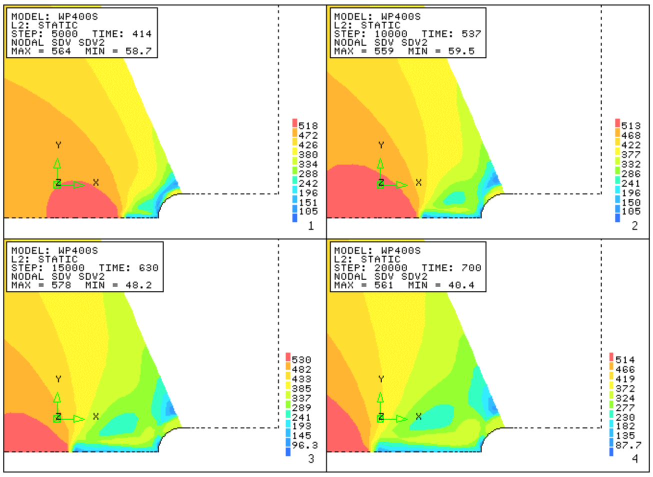

Figure 3(b): Distributions of rupture stress, σ_r, for different times: plane stress case, $\alpha = 0.15$

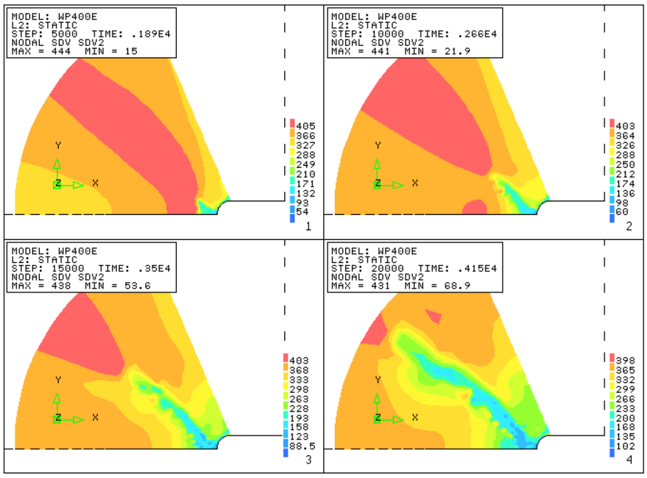

Figure 4(b): Distributions of rupture stress, σ_r, for different times: plane strain case, $\alpha = 0.15$

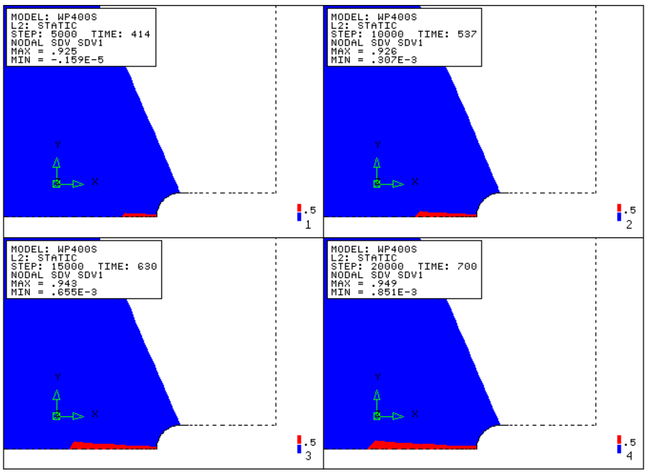

Figure 3(c): Distributions of damage, ω, for different times: plane stress case, $\alpha = 0.15$

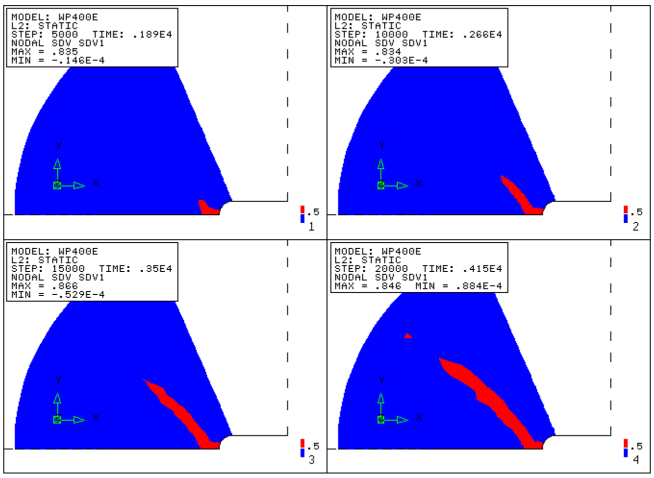

Figure 4(c): Distributions of damage, ω, for different times: plane strain case, $\alpha = 0.15$

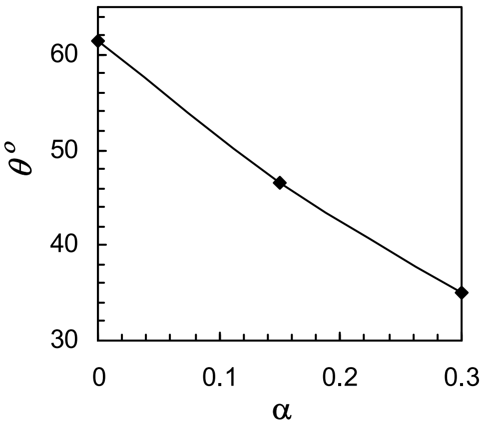

Figure 5: Variation of θ, with α, under the plane strain condition (σ_o = 400 MPa)

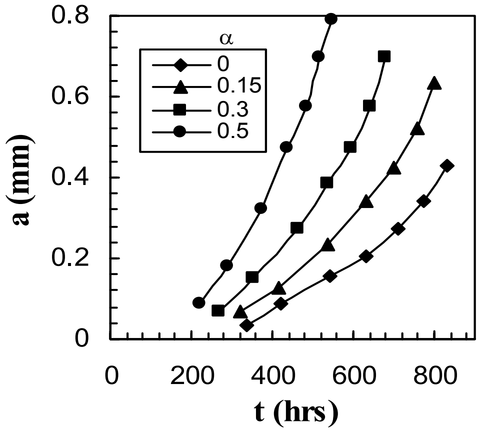

Figure 6: Variation of a, with t, for a range of α, under the plane strain condition (σ_o = 400 MPa)

TABLE 2
ESTIMATED FAILURE LIVES, t_f (hrs), FOR A RANGE OF α VALUES

α	Waspaloy (σ_o=400 MPa) P Strain	P Stress
0.0	7063	1022
0.15	5665	634
0.3	----	773
0.5	----	612

The failure life obtained for a uniaxial specimen, using the Waspaloy properties at 400 MPa, is 5809 hrs. Therefore, it is obvious that under plane stress conditions, the existence of the narrow notch results in a significant reduction in life, while the failure lives of the narrow notch specimen under plane strain conditions are similar to those of the uniaxial specimen.

DISCUSSION AND CONCLUDING REMARKS

The results of the damage mechanics FE modelling have been used to assess the creep fracture behaviour of short cracks by using a 2D narrow notch model. The material properties used were related to a Ni-base superalloy (Waspaloy) at 700° C. Damage distributions and accumulation near the notch, with time, were used to identify the crack initiation and its direction of growth. Since the main purpose of this work was to identify the trends of the crack growth, an arbitrary damage level of ω = 0.5 was chosen to represent the trends of crack growth and an arbitrary damage level of ω = 0.8 was used to obtain the crack growth with time. Failure life was roughly estimated using the times at which the high damage (ω = 0.5) zones reached a significant length (≥ 1 mm). These simplifications for crack growth and life estimate will not affect the general behaviour of the specimen.

The results obtained have shown that, under plane stress conditions, the high damage zone would be formed and would grow inwards along the plane of symmetry of the notch. Under plane strain conditions, bifurcating cracks would be formed, i.e. the high damage zone would grow in a direction inclined at an angle of between 35 and 60° to the plane of symmetry of the notch, for α-values in the range of 0 to 0.3. The growth direction angle reduces significantly with increasing α, see Figure 5, and the inclined angle reduces to zero, when α → 1.

The results of the crack growth behaviour obtained, under plane strain conditions, Figure 6, have clearly shown the trends of the crack growth with time, i.e. crack growth occurs more rapidly with increasing time. It can be also seen that the failure lives estimated, Table 2 and Figure 6, reduce with increasing α, which is similar to the behaviour indicated by results obtained for a Bridgman notch bar made from the same material [4]. However, in addition to this similarity, bifurcation behaviour was not observed in the damage modelling of the axisymmetric Bridgman notch model, where the failure damage initiated and grew along the minimum notch section, perpendicular to the direction of the applied axial load.

Although the local plastic behaviour was not taken into account and the crack growth was described by creep continuum damage modelling, the forms of the crack growth directions, obtained from the simplified plane stress and plane strain models, were found to be similar to the patterns of the plasticity zones, ahead of crack in a plate of finite thickness, subjected to tensile loading [5]. In this case, the stress state near the two free surfaces is close to that of plane stress and the stress state near the centre is close to plane strain [5]. Therefore, the difference in the crack growth direction between the plane stress and plane strain conditions is caused by the difference in the stress state or the creep strain constraint near the crack.

References

1. Hayhurst, D. R. (1983) In: *Engineering Approaches to High Temperature*, pp. 85-176, Wilshire, B. and Owen, D. R. J. (Eds). Pineridge Press, Swansea.
2. Moberg, F. (1995) Implementation of constitutive equations for creep damage mechanics into the ABAQUS finite element code, SAQ/FoU-Report 95/05.
3. Sun, W., Becker, A. A. and Hyde, T. H. (1999) 2D functions of ABAQUS UMAT damage code for creep continuum damage mechanics analyses, Internal Report, University of Nottingham.
4. Hyde, T. H., Xia, L. and Becker, A. A. (1996) *Int. J. Mech. Sci*. 38, 385.
5. Knott, J. F. (1973) *Fundamental of Fracture Mechanics*, Butterworths, London.