A STUDY OF RATE DEPENDENT DEFORMATION AND FRACTURE OF α-TITANIUM USING FINITE ELEMENT ANALYSIS

G. Shatil and D.J. Smith

Results are presented of finite element (FE) simulations of the deformation response of precracked compact tension (CT) specimens of α-Titanium at room temperature subjected to different displacement rates. A simplified approach was used in the FE analyses, which did not require using a rate-dependent constitutive equation. For a given rate the uniaxial stress strain curve was obtained and used as the material response in the FE simulations. These simulations are found to agree well with the experimental deformation response of precracked CT specimens, particularly when results are normalised to take into account ductile crack growth.

INTRODUCTION

Many investigators have examined the effects of strain rate and temperature on material behaviour, for example Hartley and Duffy (1). Work by Kujawski et al (2) and Smith and Jones (3) has illustrated that in some materials there are rate effects below "quasi-static" rates. There has been only limited attention on the influence of strain rate on ductile fracture characteristics, particularly at low temperatures where significant creep effects are not expected.

The influence of rate dependent plasticity on the ductile crack growth resistance (R)-curve has been investigated by a number of workers (3-6). Commercial purity α-Titanium has been shown to be strain rate sensitive at room temperature (3,6), and in particular sustained load crack growth was observed to take place in pre-cracked specimens (6).

Department of Mechanical Engineering, University of Bristol, Bristol. BS8 1TR

In this paper a simple approach is adopted to evaluate rate dependent behaviour without having to introduce numerically stiff rate dependent equations. The deformation response of pre-cracked fracture mechanics specimens is simulated using a finite-element analysis for a range of displacement rates. The results are compared with experimental data with brief reference to complementary experimental studies (7).

ANALYSIS

Uniaxial Deformation Response

Earlier work (3) on α-Titanium demonstrated that the post-elastic deformation response is strain rate sensitive, and for a given constant strain rate a unique uniaxial stress-strain curve is obtained. If the strain rate is suddenly changed the subsequent stress strain curve matches the curve for the new strain rate. This deformation response was shown (3) to be well described by a constitutive equation developed by Cernocky and Krempl (8). The equation is a single non-linear differential equation based on an overstress model, where the total strain rate $\dot{\varepsilon}$ is given by

$$\dot{\varepsilon} = \dot{\varepsilon}^{e} + \dot{\varepsilon}^{in} \qquad (1)$$

Where $\dot{\varepsilon}^{e}$ is the elastic strain rate, $\dot{\sigma}/E$ where E is the modulus of elasticity, and $\dot{\varepsilon}^{in}$ the inelastic strain rate is given by

$$\dot{\varepsilon}^{in} = \frac{\Sigma}{Ek[\Sigma]} \qquad (2)$$

The square brackets denote function of, so that $k[\Sigma]$ is defined as a relaxation function which is a function of the overstress Σ. The overstress is defined as the stress that exceeds an "equilibrium" stress-strain curve defined by the function $g[\varepsilon]$, so that

$$\Sigma = \sigma - g[\varepsilon] \qquad (3)$$

For α -Titanium at room temperature Smith and Jones (3) found from stress relaxation tests the relaxation function to be given by

$$k[\Sigma] = \exp(6.55 - 0.544\Sigma) \qquad (4)$$

For a given applied strain rate the stress strain response is obtained by numerical integration of Eq [1]. Experimental and simulated uniaxial stress strain curves for a range of constant strain rates are shown in Figure 1.

Finite Element Model

To simulate the rate-dependent deformation behaviour of an FE specimen the compact tension (CT) specimen was chosen, the dimensions of which (width, W = 40mm, total thickness B_t = 20 mm and crack length approximately 24mm) were selected to match those used for an experimental programme on rate-dependent ductile crack growth in α-Titanium (7). Due to symmetry a 2-D model of one half CT specimen was constructed. The experimental tests used side-grooved CT specimens, and consequently the FE model was given an effective thickness.

A simplified approach was adopted to model the material rate dependent behaviour. For a given load point displacement rate $\dot{\Delta}(=d\Delta/dt)$ the applied overall strain rate was assumed to be $\dot{\Delta}/W$. This rate was used as the control parameter in Eq (1) to simulate the appropriate stress strain curve. Subsequently the stress strain curve for the given strain rate was used as the material model for an elastic-plastic FE analyses. Displacements were applied gradually up to 2mm total load point displacement. In this way the experimental clip gauge displacement control was closely simulated. Three displacement rates, 10^{-6}, 10^{-4} and 1mm/s, corresponding to the experimental displacement rates were performed, and examined for plane stress and plane strain conditions.

RESULTS

Without crack growth

The FE results in terms of load and load point displacement, for the three applied load point displacement rates are shown in Figure 2 for displacements up to 1mm. The FE simulations were carried out at initial crack lengths corresponding to experimental tests. The experimental results are generally bounded by the plane strain and plane stress FE simulations. It is notable that good agreement in all three cases shown in Figure 2 exists between the average of the plane stress and plane strain FE results and the experimental results.

With crack growth

The experimental studies (7) consisted of obtaining ductile fracture resistance curves at the three displacement rates, using a multi-specimen technique. In the following the deformation response of these specimens are compared with the FE results using the key curve procedure which aims to remove the effects of instantaneous crack growth from the experimental results.

Ernst et al (9) developed a dimensional analysis which removes the dependency of the measured variables on crack length. This method was also applied to rate-dependent studies using an approach given by Jones and Davies (10) to determine resistance curves. The normalised load P_n is related to the plastic displacement Δ_p by

$$P_n = \frac{PW}{B(W-a)^2 \exp\{0.522(W-a)/W\}} = K\left(\frac{\Delta_p}{W}\right)^n \qquad (5)$$

where P is the applied load and K and n are material constants. For a given load the total displacement is the sum of the elastic and plastic displacements.

FE simulations for the three displacement rates were carried out at five crack lengths for plane stress and plane strain conditions. Normalising the load and displacement from the FE simulations to produce P_n and Δ/W respectively, yielded crack length independent curves. Average curves are shown in Figure 3 for each strain rate. Also shown are experimental results for each rate. Each data point represents a single test, where the final load, displacement and measured crack length were used to obtain P_n and Δ/W. At all three displacement rates there is good agreement between the simulations and experiments, up to normalised load point displacements of about 0.04. This corresponds to ductile crack growth of about 1mm for each displacement rate.

CONCLUDING REMARKS

In the FE analyses no account is taken of rate dependent behaviour with the exception of adopting the uniaxial elastic plastic stress strain curve for a given strain rate simply derived from integration of Eq (1). The agreement between the average of the plane stress and plane strain FE simulations and the experiment load and displacement response is somewhat unexpected. Not only do the average FE results agree with an individual experimental test for a given displacement rate (Figure 2) but they are also in general agreement with the experimental multi-specimen results expressed in terms of normalised load and displacement (Figure 3).

ACKNOWLEDGEMENTS

This work was supported by the Defence Research Agency, (MOD), Holten Heath. We are grateful for DRA for supplying the experimental data for this work, and in particular Richard Jones and John Galsworthy for their advice and support.

References

(1) Hartley, K.A. and Duffy, J. Inst. Phys. Conf. Ser. No703rd Conf. Mech.Prop High Rates of Strain, Oxford, 21, 1984.

(2) Kujawski, D., Kallianpur, V.V. and Krempl E., J. Mech. Phys. Solids 28, 129, 1980.

(3) Smith, D.J. and Jones, R.L.., Mechanics of Materials, 8, 219-235, 1989.

(4) Smith, D.J. and Garwood, S.J., In Non-Linear Fracture Mechanics, Time Dependent Fracture, ASTM STP 995, 242 - 273, 1989.

(5) Tsuru, S. and Garwood, S.J. Some aspects of time dependent ductile fracture of line pipe steels, Welding Inst. Res. Rep 92, 1979.

(6) Smith, D.J. and Jones, R.L., Fatigue Fract. Engng Mater. Struct. 14,10, 979-989, 1991

(7) Jones, R.L. and Smith D.J. Unpublished research 1992.

(8) Cernocky, E.P. and Krempl. E. Int. J. Non-Linear Mech, 14, 183, 1979.

(9) Ernst,H, Paris P.C, Rossow, M and Hutchinson, J.W., Fracture Mechanics, ASTM STP 677, 581 - 599, 1979.

(10) Jones, R.L. and Davies P.C. Fatigue. Fract. Engng Mater. Struct, 12, 5, 423-437, 1989.

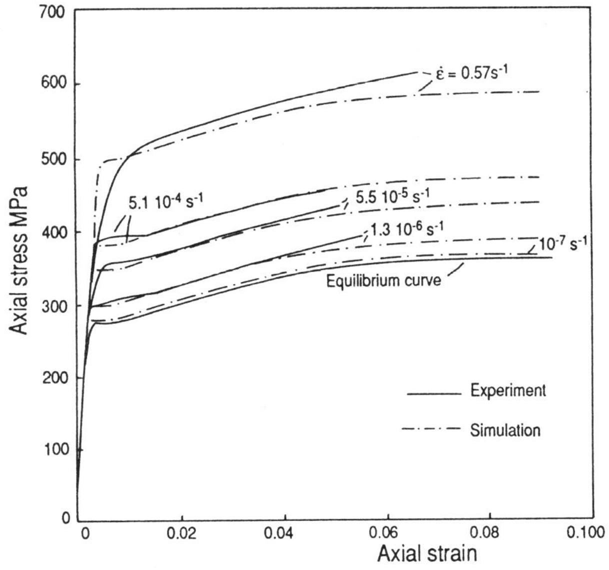

Figure 1 Experimental and simulated stress-strain curves at constant strain rates for α-Titanium at room temperature

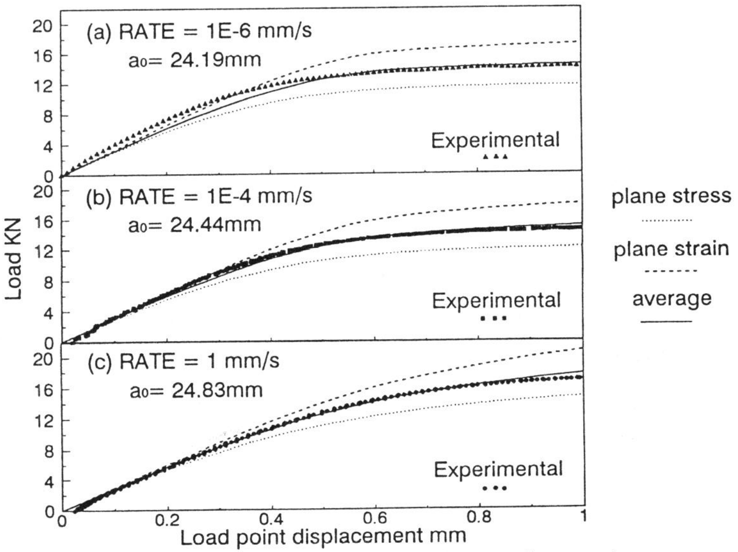

Figure 2 Finite element simulations and experimental load and displacement curves

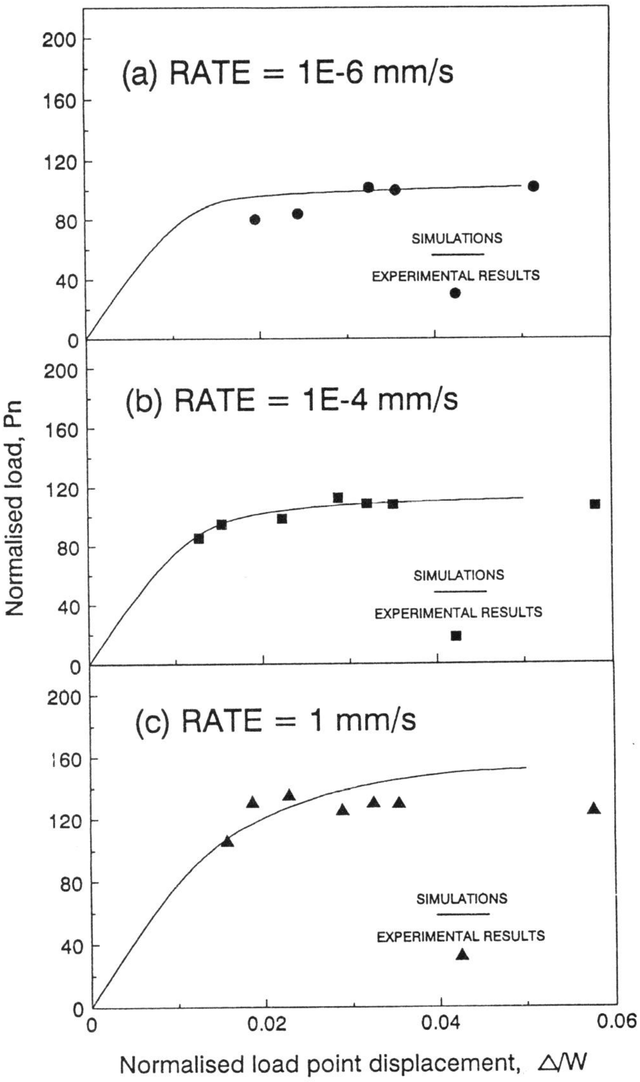

Figure 3 Key curve simulations compared to experimental results