SIMULATION OF ROOM TEMPERATURE SUSTAINED LOAD CRACKING OF COMMERCIAL PURITY TITANIUM

G. Shatil* and D.J. Smith**

Experimental results and finite element (FE) simulations of the deformation and fracture of commercial purity titanium (CP Ti) at constant load and room temperature are presented. Results are shown for two batches of CP Ti having different equivalent oxygen (O_{eq}) contents 14 and 19%. The FE analysis used a unified visco-plastic material model. The simulations are compared with experimental results. At a given load CP Ti with a 14% equivalent oxygen content gives a shorter failure time than for 19% O_{eq} CP Ti. This is confirmed by the FE simulations.

INTRODUCTION

Previous work (1) on commercial purity titanium (CP Ti) at room temperature demonstrated that the rate dependent deformation of uniaxial specimens could be described using a material model developed by Cernocky and Krempl (2). Experiments (3) have also determined the crack growth resistance of CP Ti when subjected to constant load at room temperature. These experiments demonstrated that time dependent (sustained load) failure could occur at room temperature at relatively high loads. The rate dependent material model was used earlier in a finite element (FE) analysis to simulate crack growth in compact tension (CT) specimens subjected to different load point displacement, (4,5).

In this paper results for sustained load fracture of CP Ti, with different oxygen equivalent content, are reported and finite element simulations of the experiments are presented.

* Faculty of Engineering, University of the West of England, Bristol BS16 1QY
** Department of Mechanical Engineering, University of Bristol, Bristol BS8 1TR

EXPERIMENTS

Uniaxial Behaviour

Room temperature experiments were carried out using two batches of the commercial purity titanium (CP Ti) conforming to ASTM B381 Grade 2. The batches had different oxygen equivalent contents, 19% and 14% respectively. Uniaxial round bar tests included constant strain rate and constant stress rate tests, relaxation and sustained load tests. The experimental procedures for the tests are described elsewhere (4). At a strain rate of $10^{-4}s^{-1}$ the 0.2% proof stress of the two materials were 278MPa for 14% O_{eq} CP Ti and 390MPa for 19% CP Ti.

To describe the rate dependent material response the constitutive model used earlier by Smith and Jones (1) was used. This model is a single non-linear differential equation based on an overstress model, (2) where the total strain rate $\dot{\varepsilon}$ is given by

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

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

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

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

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

From the uniaxial tests the relaxation function $k[\Sigma]$ was determined. For the 14% O_{eq} CP Ti the relaxation function is

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

For the 19% O_{eq} CP Ti the relaxation function is

$$k[\Sigma] = \exp(18.37 - 0.11\Sigma) \tag{5}$$

Crack Growth Tests

Constant load tests on pre-cracked compact tension specimens (thickness 20mm, width 40mm and initial crack lengths of about 24mm) were also carried out on the two batches of CP Ti at room temperature. Test results for the 14% O_{eq} material have been reported earlier (3). Further experiments on the 19% O_{eq} CP Ti were carried out using the same techniques reported by Smith and Jones (3). For every test at constant load changes in crack length and load point displacement (δ) were measured as a function of time. The failure times for the tests on the two batches of CP Ti are shown in Figure 1.

FINITE ELEMENT ANALYSIS

Finite Element Model

The ABAQUS finite element code was used for the analysis. Due to symmetry a 2-D model of one half of a CT specimen was constructed. The experimental tests used side-grooved CT specimens, and consequently the FE model was given an effective thickness.

The rate dependent material model (Equation 1) was implemented using the UMAT routine in ABAQUS. The equations were formulated using equivalent values of stress (σ_{eq}), "equilibrium" stress (g_{eq}), total strain (ε_{eq}) and over stress (Σ_{eq}). Using this material model the FE analysis was able to provide simulations of the elastic-visco-plastic response of a component.

Sustained Load Cracking

The sustained load behaviour of the CT specimens was simulated by first applying a constant load rate up to the required load level and, then keeping this load constant over a period of time. Both plane strain and plane stress conditions were examined. The simulations were carried out at three load levels corresponding the experiments for each material, Figure 1.

Material fracture was not directly simulated in the FE analysis. Instead, crack growth was considered by post processing the simulations with the accumulation of displacement controlled by the crack growth rate. Separate FE simulations at constant load at different crack lengths were carried out. An example is shown in Figure 2 for plane stress conditions. Only very small amounts of creep displacement were obtained for plane strain conditions and further analyses for this stress state were not conducted. The experimental crack growth were used to determine the response in the simulation. For example, after a time interval Δt_1, it was known that the crack extended from "a" to "a+Δa". In the simulation it was assumed that at crack length "a" the accumulated displacement was δ_1 during Δt_1. After this time interval it was assumed that the crack length was "a+Δa", and the displacement at the new crack length matched that for the earlier crack length "a". For the new crack length $a+\Delta a$, and at the same matched initial displacement δ_1 the load point displacement continued for the next time increment Δt_2. The accumulated load point displacement (δ_2) corresponded to crack length $a+\Delta a$, and time increment Δt_2. This procedure was continued until final failure where failure corresponded to the onset of rapid accumulation of displacement. For n increments of crack growth the failure time was $\sum_{i=1}^{n} \Delta t_i$ and the accumulated load point displacement was $\sum_{i=1}^{n} \delta_i$. This procedure corresponds to using a strain hardening law in creep for variable stress.

The predicted displacements using this procedure are shown in Figure 3 for both batches of CP Ti. Also shown are the experimental results. The simulations for the 14% O_{eq} material are in good agreement with the experiments for the three loads used, Figure 3a. This is also reflected in the predicted failure times shown in Figure 1. The simulations for the 19% O_{eq} material overestimated the load point displacement, particularly for the higher loads of 16 and 17 kN, Figure 3b. Consequently the predicted failure times were shorter than the experiments.

CONCLUDING REMARKS

Although a direct method of introducing ductile damage accumulation was not introduced the FE simulations using a rate dependent constitutive model together with experimental crack growth show remarkable agreement with the experiments. The simulations reveal that the behaviour of the experiments is best described by plane stress conditions. Time dependent failure at room temperature can occur in CP Ti and it is shown that the failure time is a function of the equivalent oxygen content.

ACKNOWLEDGEMENTS

This work was supported by the Defence and Evaluation Research Agency, (DERA). We are grateful for their financial support and for supplying the experimental data for this work. In particular we are grateful to M Rahim and J Galsworthy for their support and co-operation.

REFERENCES

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

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

(3) Smith, D.J. and Jones, R.L., Fatigue Fract. Engng Mater. Struct. Vol. 14, No. 10, 1991, pp 979-989.

(4)Shatil, G and Smith, D J, Proc. ECF 10, 1994, pp 437-444.

(5) Shatil G, Phoplonker M, Smith D J and Galsworthy J, Proc. 8th World Titanium Conf, Vol 2, pp 1011-1018, 1995.

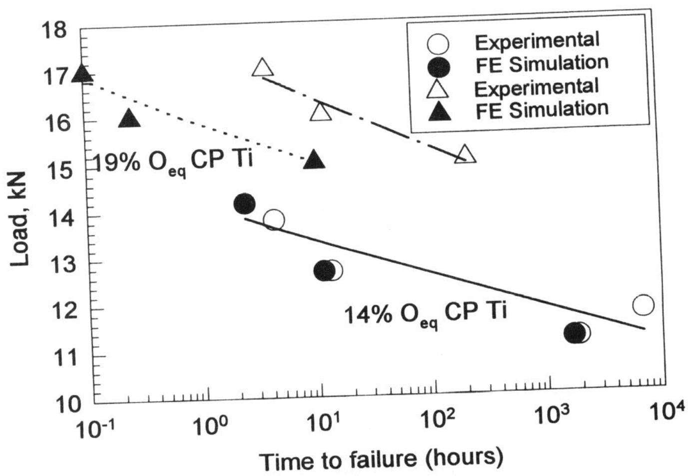

Figure 1 Experimental and simulated creep time to failure for CP Ti

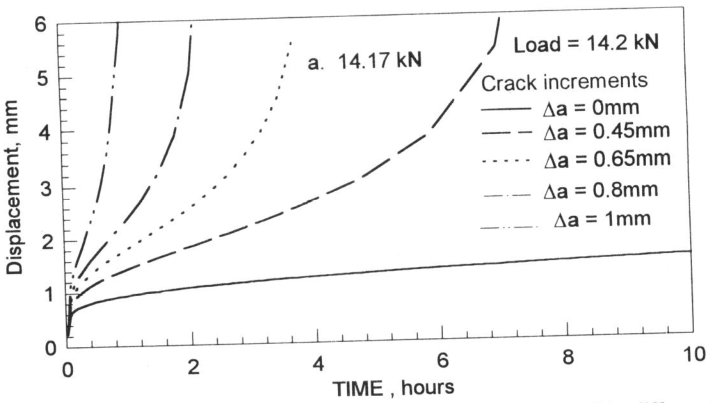

Figure 2 - Creep simulations of CT specimens with different crack increments for 14% O_{eq} CP Ti

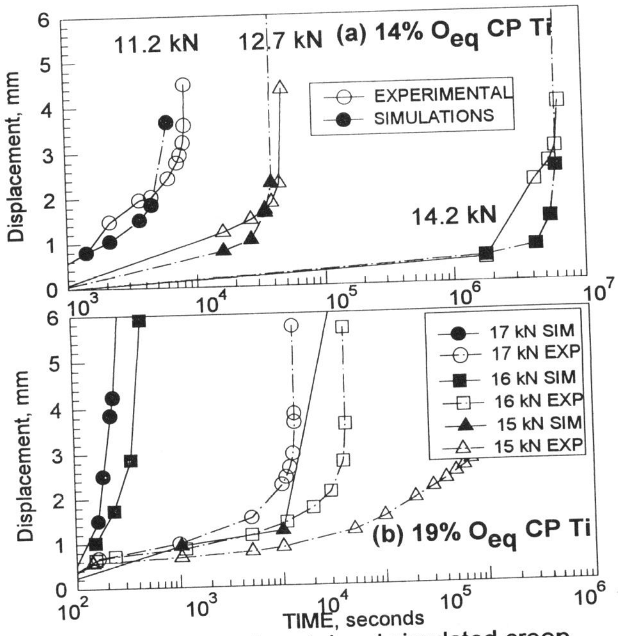

Figure 3 Experimental and simulated creep displacements