Strain rate sensitivity of Zircaloy-4

Yang Liu[a], Paul Wan and Fionn Dunne

Department of Materials, Imperial College London

[a]yang.liu@imperial.ac.uk

Abstract. Zircaloy-4 is widely used in nuclear engineering. This paper addresses strain rate sensitivity of Zircaloy-4 during stress holds relevant to cladding tube. Creep testing has been conducted on a notched large-grained ‘blocky alpha’ sample for an hour and strains measured using digital image correlation (DIC). “Butterfly”-shaped strain patterns within the highly textured blocky alpha material are observed and the spatial distributions of intra-granular creep straining captured and compared with crystal plasticity finite element method (CPFEM) modelling [1]. Strain rate sensitivity of Zircaloy is found to be significant at 20°C reflecting the creep occurring, which is likely to be important in the understanding of delayed hydride cracking, which is a major failure mechanism which takes place during the long dwell periods in service performance of cladding tube [3].

Introduction

Zircaloy 4 is a zirconium alloy widely used in the nuclear industry providing the structural support for fuel rods, employed because of its low neutron absorption, excellent corrosion and mechanical properties. Its strain rate sensitivity is crucial for understanding its mechanical response during stress holds of cladding tubes.

Experimental setup

Local strain measurement in the region of interest (ROI) was carried out by in-situ optical microscopy-based Digital Image Correlation (DIC) using a Questar Microscope Lens (QM-100), QIclick versatile scientific CCD camera, a three-point bend testing rig and a three-axis sliding supporting stage. Speckled surfaces using homogeneously distributed 1 μm silica particles were used to capture the creep strain fields shown in Figure 1 (a). The three-point bend testing was setup on a Shimadzu universal testing machine.

Crystal plasticity modelling

A gradient-enhanced dislocation based HCP crystal plasticity model has been utilised to capture the strain rate sensitivity, stress redistribution and creep during load holds under a range of temperature conditions. The dislocation slip process along the $\boldsymbol{s}^{\text{th}}$ slip direction is based on a resolved shear stress exceeding the local slip system strength and the thermally activated escape of pinned dislocations from obstacles.

The crystal plasticity slip rule accounts for both forward and backward dislocation slip, and a slip system shear strain rate develops when the resolved shear stress τ^s exceeds its critical value τ_c^s [1],

$$\dot{\gamma}^s = \rho_m \nu (b^s)^2 \exp\left(-\frac{\Delta F}{kT}\right) \sinh\left(\frac{\Delta V}{kT}(\tau^s - \tau_c^s)\right) \tag{1}$$

where b^s is the Burgers vector magnitude of this slip system, ρ_m the mobile dislocation density, and ν is the frequency of dislocation jump attempts. The activation energy ΔF and activation volume ΔV are the two crucial parameters controlling the dislocation slip rate sensitivity with respect to the applied load. k is the Boltzmann constant. The critical resolved shear stresses for the prism, basal and pyramidal slip systems are given by $\tau_c^{basal} = 1.33\tau_c^{prism}$; $\tau_c^{pyramidal} = 3.48\tau_c^{prism}$.

Figure 1 shows the strain component ε_{11} distributions from both experimental DIC measurements and crystal plasticity modeling at different holding times and at the unloaded state. At the beginning of the load hold, the strain concentrates near the notch tip due to the stress concentration and results from the elastic and time-independent plastic strain evolution during the load-up. As the holding time increases from 30s to 20min, the strain field quickly develops into the specimen and forms the characteristic butterfly shape. Some local heterogeneity develops resulting from the crystal plastic anisotropy of slip and the interactions with the grain boundaries because of local constraint. The strain fields are reasonably well captured by the crystal plasticity model, which facilitates the determination of the key slip system properties for zircaloy-4 ΔF and ΔV which control the material’s strain rate sensitivity.

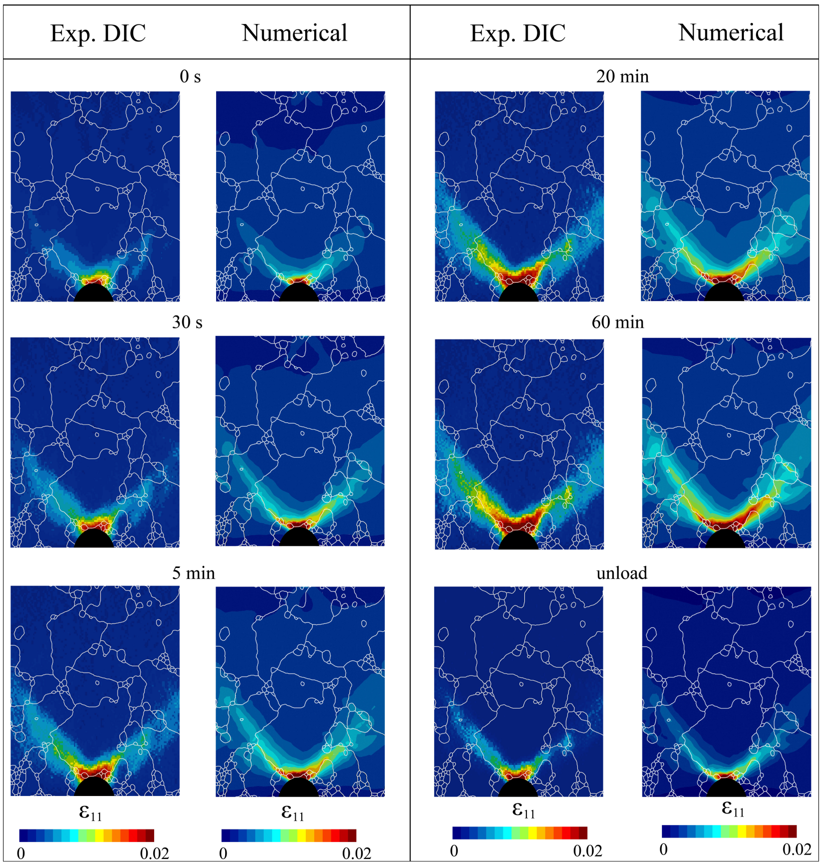

Fig. 1. Strain ε_{11} fields evolving at the times shown the during stress hold. Experimental DIC and of CPFEM results are shown. The white lines indicate grain boundaries.

Conclusion

Zircaloy-4 creeps at 20°C, and its strain rate sensitivity has been quantified. In this way, the creep response of a notched sample under bending has been measured using DIC techniques near a notch and is captured by crystal plasticity modelling theory. Creep sensitivity is well described by the slip rule. The microstructural stress relaxation and redistribution which occurs as a result of its strain rate sensitivity could be crucial for its in-service performance, particularly relating to hydrogen concentration (which is stress dependent) and the consequent formation of hydrides. The latter are the primary drivers of delayed hydride cracking in service.

References

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