Characterising Creep Damage Directly from Digital Image Correlation Displacement Data

M. van Rooyen[1a] and T.H. Becker[1]

[1]Departement of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa

[a]melzvanrooyen@sun.ac.za

Abstract. An essential step in the lifetime prediction of critical power plant structures is the characterisation of creep damage. An experimental method is presented which employs Digital Image Correlation (DIC) to measure strain at multiple temperatures from a single specimen of the steel X20 CrMoV12-1 (X20) during accelerated (high-stress) creep tests conducted using a Gleeble thermomechanical simulator. Strain measurements are incorporated into a numerical damage-mechanics creep model in order to extract relative microstructurally-based damage parameters for X20 with varying levels of service history. Good correlation in damage categorisation is shown between this technique and the standard method of creep void counting.

Introduction

Critical power station components, such as steam pipelines, are subjected to high temperature and pressures for extended periods of time, necessitating regular assessment of their material integrity in terms of creep damage. Traditional techniques of characterising this damage involve counting voids (formed during diffusion creep) through replica metallography using high resolution microscopes. This technique, however, only focusses on the part surface, which is not fully representative of the damage throughout the material volume, and does not take the degradation of other microstructural features of higher Cr steels into consideration [1]. In the case where sections can be machined from the structure, a more holistic analysis can be performed through mechanical creep tests. Typically, these tests involve measuring creep strain at a single temperature and stress for long periods of time, requiring multiple samples. However, lengthy test durations required to match the long service life of material and heating costs coupled with the material requirements associated with conducting tests at several temperatures limits the ability to use conventional creep tests for damage characterisation of in-service material [2].

The presented technique takes advantage of the full-field strain mapping offered by Digital Image Correlation (DIC) by measuring creep strain curves at several temperatures from a single sample [1]. This is achieved by varying a thermal profile over the specimen length through resistive heating by a Gleeble thermomechanical simulator. High-stress creep tests are conducted in order to accelerate creep curve development to within ten hours of power plant steel X20 CrMoV12-1 (X20) samples with varying degrees of creep damage. The measured strains are subsequently applied to a damage mechanics-based creep model [3] in which two microstructural damage parameters are solved for through an optimisation routine, providing an indication of relative creep damage.

Experimental design and procedures

A Gleeble 3800 thermomechanical module is used to exert the thermal and loading profiles on specimens of X20 steel within a vacuum chamber. A longitudinal temperature gradient develops due to heat conduction to water-cooled grips that varies from 600 °C to about 500 °C over 7.5 mm. The full-field temperature distribution is measured using a Fluke Ti400 infrared (IR) imager on the back of the specimen surface (coated with matt black, heat resistant paint) viewed through an IR view port. A hydraulic ram applies a stress of 250 MPa on the specimen during a load-controlled tension test during which images are recorded of the heat-resistant speckle pattern through the Gleeble viewing window.

The stereo DIC setup consists of two LaVision Imager E-lite 5M cameras, 12-bit charge-couple device sensor chips as well as TECHSPEC 75 mm Double Gauss macro lenses, resulting in an effective resolution of about 1250 x 380 pixels and image scaling of 40 pixels/mm. Image calibration is achieved in-situ through a precision machined calibration plate. In order to suppress short wavelength light emitted from the heated surface, illumination is supplied by two white 20W LaVision LEDs and is filtered with Hoya B-440 colour filters. This configuration allows deformation measurements up to 900 °C before image saturation occurs.

Creep model

The creep model developed by Oruganti *et al.* [3] is used in this work to elucidate the relative damage from the creep curves. Eq. 1 gives the differential coupled equations for the creep strain rate and primary creep stress rate respectively at a particular stress σ and temperature T. This model also considers key

microstructural features which lead to the degradation of creep strength, namely precipitate coarsening D_p and subgrain growth D_s.

$$\dot{\varepsilon} = \dot{\varepsilon}_0' \exp\left(-\frac{Q_c}{RT}\right) \sinh\left[\frac{\sigma(1-H^*(1-D_S))}{\sigma_0(1-D_P)}\right], \qquad \dot{\sigma}_0 = K_1\left(1-\frac{\sigma_0}{K_2}\right)\dot{\varepsilon} \qquad (1)$$

Due to the relatively short duration of the creep tests, diffusion-based microstructural evolution does not occur and the damage parameters (D_p, D_s) are considered to remain constant for a particular material damage level. A MATLAB based optimisation routine determines these two parameters (which vary from 0 to 1) based on the best fit of the model to the measured strain data for several temperatures, whilst values for the activation energy Q_c, pre-exponent $\dot{\varepsilon}_0'$, stress redistribution parameter H^* and primary creep constants K_1 and K_2 are obtained from literature [3].

Results and discussion

Post-processing of the recorded images was performed using the LaVision DaVis software. Deformation was calculated using a subset size of 61 x 61 pixels with a 25 % overlap. Strains are calculated by differentiating linear plane fits to the displacement fields at several sampling locations, resulting in families of creep curves as seen in Fig. 1 for new and high damage X20. Shown in Fig. 2 are creep curves at 600 °C for new and low, medium and high damaged X20 at 250 MPa. For the same stress and temperatures, the curve development accelerates as the damage level increases. The calculated creep model damage parameters are given in Table 1 and compared to the void count damage characterisation of the X20 material. Generally, higher damage parameters are associated with materials with higher creep rates and correspondingly void densities. However, the void density criterion fails to correctly characterise the "low damage" material which is demonstrated to have a higher D_s value compared to "medium damage".
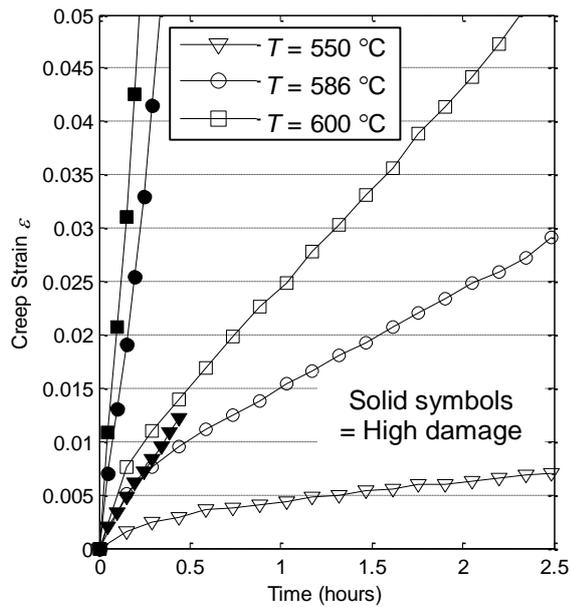

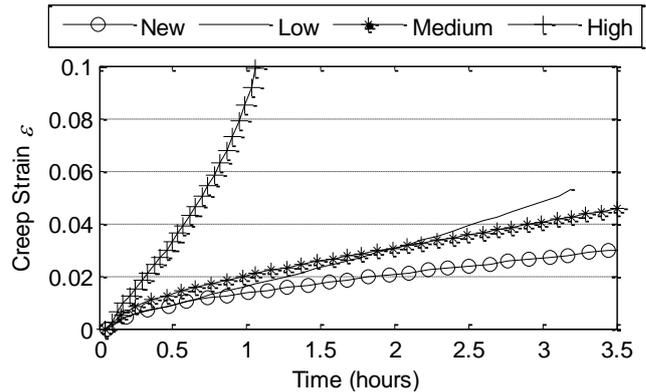**Figure 1: Creep curves of new and high damage X20 at various temperatures**

Figure 2: Creep curves at 600 °C and 250 MPa for various damage states of X20

Damage [voids/mm^2]	D_s	D_p
New	5 x 10^{-4}	0.222
Low (60-90)	0.0158	0.243
Medium (~200)	0.0120	0.243
High (220-690)	0.0445	0.302

Table 1: Damage parameters compared to void counting for X20

Conclusion

A technique for determining relative damage levels of ex-service X20 power plant steel from DIC-measured creep strain of a single sample is presented. The high density of DIC strain data allows damage parameters to be extracted from a comprehensive creep model at multiple temperatures in a single test run. This technique can supplement conventional techniques to confirm the remnant life estimations of critical power station components.

References

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