Creep strain prediction of 2 ¼ Cr 1Mo steel— A model based approach

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Abstract. The paper examines the potential of a model based approach for predicting creep behaviour of 2 ¼ Cr 1Mo steel. Effects of prior strain and thermal aging on the shape of the creep curve have been experimentally established. Particle coarsening has been identified as the dominant mechanism of creep. Creep curves theoretically simulated using particle coarsening model have been compared with those obtained for a variety of initial microstructural conditions.

Keywords. Deformation mechanism; strain softening; particle coarsening; time softening; tertiary creep; damage mechanism.

1. Introduction

2 ¼ Cr 1Mo steel is extensively used in high temperature components primarily because of its excellent creep resistance. Although simple uniaxial stress rupture test data on such steel over a range of stresses and temperatures may be enough to satisfy the current needs of the designer, with growing use of computer based design technique, there is now considerable interest in characterizing the shape of the complete creep strain time plots of such materials. Unlike pure metal or single phase alloys they rarely exhibit a well established steady state creep regime, rather after a small primary strain the creep rate progressively increases from a minimum value ($\dot{\epsilon}_i$) until fracture. The level of sophistication of analytical design using finite element method depends on the ability to accurately represent the full shape of creep curve under various stresses and temperatures. Broadly two types of approaches are being explored. Empirical approach uses specific expressions to describe evolution of creep strain as function of time. Notable amongst these is the θ projection popularized by Evans and Wilshire (1985). They prefer to describe the creep curves as:

$$\epsilon = \theta_1 [1 - \exp(-\theta_2 t)] + \theta_3 [\exp(\theta_4 t) - 1], \quad (1)$$

where ϵ is the creep strain, t the time and θ_i ($i = 1, 2, 3, 4$) represents four parameters used to describe the creep curve. Computer programs are available to extract these from experimental $\epsilon-t$ plots. In order to allow interpolation or extrapolation of data over different stresses and temperatures it is necessary to describe the parameter θ_i as function of stress (σ) and temperature (T). The form commonly used is given by:

$$\log \theta_i = a_i + b_i T + c_i \sigma + d_i \sigma T, \quad (2)$$

where a_i, b_i, c_i, d_i ($i = 1, 2, 3, 4$) are constants.

Clearly a set of 16 constants are required to characterize the creep curve of any engineering material. The main problem of this approach is its limited power of extrapolation beyond the domain of available test data and the requirement of a large volume of test data to obtain 16 material constants.

The mechanism based approach however does not suffer from such limitation. The one developed by the high temperature materials group at the National Physical Laboratory, Teddington and Cambridge University deserves special attention (Ashby and Dyson 1984; Barbosa *et al* 1988). Dyson and McLean (1990) have recently reviewed the current status of this approach. Based on the shape of the creep curves more emphasis has been placed on the contribution of tertiary creep. Following Ashby and Dyson (1984), damages responsible for tertiary creep can be classified into three categories: (i) Microstructural changes (e.g. dislocation density, precipitate size etc.) that reduce the strength of material (ω_1), (ii) loss of external section size due to geometrical changes that leads to a change in stress in constant loading condition (ω_2) and (iii) loss of internal load bearing section due to cavitation or cracking which commonly occurs at grain boundaries (ω_3).

The damage parameter ω_i ($i = 1, 2, 3$) can be defined in several ways. Explicit forms of equations relating creep strain and damages have been suggested on the basis of the current understanding of deformation mechanisms in engineering material. For example materials exhibiting strain softening the creep strain accumulation has been represented as:

$$\begin{aligned}\dot{\epsilon} &= \dot{\epsilon}_i \exp(\omega_1 + \omega_2 + \omega_3), \\ \dot{\omega}_1 &= C_1 \dot{\epsilon}, \\ \dot{\omega}_2 &= C_2 \dot{\epsilon}, \\ \dot{\omega}_3 &= C_3 \dot{\epsilon},\end{aligned}\tag{3}$$

where $\dot{\epsilon}_i$, C_1 , C_2 , C_3 are the model parameters for a given stress and temperature (Barbosa *et al* 1988; Dyson 1988; Dyson and Gibbons 1987). Following Dyson and McLean (1983), appropriate model for materials susceptible to time softening relating $\dot{\epsilon}$ with ω_i has been represented as:

$$\begin{aligned}\dot{\epsilon} &= \dot{\epsilon}_i (1 + \omega_1)^n \exp(\omega_2 + \omega_3), \\ \dot{\omega}_1 &= a(1 - b\omega_1)^4, \\ \dot{\omega}_2 &= C_2 \dot{\epsilon} \\ \dot{\omega}_3 &= C_3 \dot{\epsilon}\end{aligned}\tag{4}$$

where a and b are the parameters representing the kinetics of particle coarsening (Barbosa *et al* 1988) and n is the stress exponent for $\dot{\epsilon}_i$. The main advantage of representing the creep behaviour by a set of coupled differential equations is that based on our knowledge of dominant mechanism of deformation the number of parameters required to describe the process can be significantly reduced. For example in the case of single crystal material, since there is no grain boundary, the effect of cavitation could be ignored ($\omega_3 = 0$). Similarly if one were to look at constant

stress creep data where the effect of decreasing cross sectional area is compensated by proportionate load reduction it is not necessary to consider the influence of ω_2 . Consequently the tertiary creep behaviour of single crystal superalloys exhibiting strain softening could be considered by a set of two equations only viz (Ghosh *et al* 1990):

$$\begin{aligned}\dot{\epsilon} &= \dot{\epsilon}_i \exp(\omega_1), \\ \dot{\omega}_1 &= C_1 \dot{\epsilon}.\end{aligned}\quad (5)$$

The present work examines the creep behaviour of 2 1/4Cr 1Mo steel to identify the dominant mechanism of deformation so that a simple model based approach for creep strain prediction could be developed.

2. Mechanism of creep deformation

Creep strain-time plots of 2 1/4Cr 1Mo steel given in figure 1 under three different microstructural conditions clearly reveal the dominant influence of tertiary creep. Typical microstructures of this steel before and after creep exposure given in figure 2 show significant coarsening of carbide. Softening due to precipitate growth may therefore appear to be the obvious mechanism for the continuously increasing creep rate. However in the case of superalloys in spite of particle coarsening being quite evident from microstructural examinations, strain softening due to increased mobile dislocation density was identified as the dominant mechanism of tertiary creep

Figure 1. Creep strain time plots of 2 1/4Cr 1Mo steel at 550°C, 150 MPa under three different microstructural conditions.

Figure 2. Microstructures of 2 1/4Cr 1Mo steel (a) before creep test and (b) after creep test showing significant coarsening of carbides.

(Dyson and McLean 1983; Barbosa *et al* 1988). This was established on the basis of the effect of prior cold work and thermal aging. Therefore creep tests were conducted on thermally aged as well as cold worked test specimens of Cr Mo steel. Figure 3 shows their effect. Whilst prior aging significantly increases the tendency to soften the effect of prior cold work resulted in a marginal strengthening. Chaudhuri (1993) examined the effect of aging and cold work on 2 1/4Cr 1Mo steel over a range of stresses and temperatures. Irrespective of the microstructure the results exhibit similar trend. Therefore in the case of Cr-Mo steel a model based on particle coarsening such as the one represented by (4) is more appropriate. Besides the microstructural examination did not show any sign of creep cavitation. High rupture ductility observed in this steel is also indicative of absence of cavitation. Therefore the contribution of cavitation towards creep strain accumulation

Figure 3. Effect of thermal aging and prior cold work on creep strain time plot of 2 1/4Cr 1Mo steel at 550°C, 150 MPa.

can be neglected (i.e. $\omega_3 = 0$). Assuming that the minimum creep rate follows a power law kind of stress dependence with n as the stress exponent, the contribution of the change in cross sectional size under constant load creep test can be estimated. It has been shown that under such cases $C_2 = n$ (Dyson 1988). Therefore constant load creep strain time plots of 2 1/4Cr 1Mo steel could be represented as:

$$\begin{aligned}\dot{\epsilon} &= \dot{\epsilon}_i (1 + \omega)^n \exp(n\epsilon), \\ \dot{\omega} &= a(1 - b\omega)^4,\end{aligned}\quad (6)$$

where ω_1 has been redesignated as ω . Thus only four parameters viz., $\dot{\epsilon}_i$, n , a and b are required to describe the creep behaviour of CrMo steel using a mechanism based model. Chaudhuri *et al* (1993) suggested a method of extracting the parameters a and b from creep strain time plot. $\dot{\epsilon}_i$ can be estimated at various stresses and temperatures using the conventional numerical method and its temperature and stress dependence could be established. This gives the magnitude of n as well. Chaudhuri *et al* (1993) looked at constant load creep curves of 2 1/4Cr 1Mo steel over a wide range of temperatures and stresses. The exact functional forms to represent the above parameters have been determined. Using these and the numerical scheme put in the form of a computer programme, creep curves of 2 1/4Cr 1Mo steel could be stimulated under any arbitrary test conditions. Validity of such predictions have been analyzed in the subsequent part of the paper.

3. Results and discussion

Figure 4 presents a comparison of the calculated creep curve at 550°C, 108 MPa

with an experimental creep curve reported by Maruyama *et al* (1990). The creep curves used to estimate the material constants even though they were for the same grade of steel were from a totally different source (Wolf 1990). In the light of this fact the matching between the experimental and the predicted curves is indeed excellent. Since these steels are susceptible to time softening as a result of thermal exposure, the difference in the shape of predicted and experimental creep curves will depend on whether the initial microstructures were similar. Constant load creep tests were carried out in our laboratory on 2 ¼Cr 1Mo steel having three different initial microstructures, viz. 100% bainite, ferrite + bainite and ferrite + carbide. Figures 1 and 5 show the influence of initial microstructure on the nature of creep strain

Figure 4. Comparison of theoretically predicted creep curve for 2 ¼Cr 1Mo steel with experimental data reported by Maruyama *et al* (1990).

Figure 5. Comparison of predicted creep curve at 600°C, 100 MPa with those for the different initial microstructural conditions.

Figure 6. Comparison of predicted and experimental time to reach 5% strain for three different microstructural conditions.

time plots. Clearly the structure having ferrite and globular carbide shows the least creep resistance. Theoretically calculated creep curve using the material data obtained from an analysis of creep curves used by Wolf (1990) has also been superimposed on figure 5. The fact that this does not match with any of the experimental plots obtained in this work is not surprising. This is primarily because the initial microstructure (particle size) in these cases is different. Figure 6 presents a comparison of the calculated and predicted time to reach a specific strain level (5%). This shows predictions in general are closer to experimental data for ferrite carbide structure indicating that the microstructures of the steel investigated by Wolf (1990) and Maruyama (1990) consisted of ferrite carbide aggregate. The results presented indicate that there is a need to generate and classify the creep data on Cr Mo steel in terms of its initial microstructure. Work in this direction is currently in progress in our laboratory.

4. Conclusions

- (i) Particle coarsening is the dominant mechanism controlling the shape of the creep curves of 2 1/4Cr 1Mo steel.
- (ii) Model based prediction could be fairly accurate if the material constants are evaluated from steels having similar microstructure.
- (iii) Creep behaviour of 2 1/4Cr 1Mo steel is highly sensitive to its initial microstructure and heat treatment.

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