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Creep Modelling of P91 Steel for High Temperature Power Plant Applications

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Abstract

There has been considerable interest in the development of continuum damage (CDM) mechanism based model for creep life predictions of 9CrMoNbV steel. It is reported that the steel has high dislocation density in normalized and tempered condition whereas with creep exposure it goes down significantly. The paper examines one of the recent models and attempts to incorporate this as an additional damage parameter. This has resulted in much better prediction of creep stain time plots for this steel.

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Keywords: Creep; damage mechanics; dislocation density; constitutive equation

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Nomenclature

$\dot{\varepsilon}_0$	A characteristic strain rate that depends on precipitate volume fraction and mobile dislocation density.
Q_d	Activation energy associated with diffusion of vacancies and formation of jogs
σ	Applied stress
σ_0	is a normalising stress that is related to the dislocation-particle interactions (see subsequent equation 6&7)
h'	Effective modulus
H	*Limiting value of H. Occurs on completion of stress transfer. Its initial value is zero.
D	$_p$Coarsening damage defined $\left(1-\frac{\lambda_i}{\lambda}\right)$ as where λ_i is the initial inter-particle spacing and λ is the inter-particle spacing at any given time.
D_d	Dislocation damage defined as $\left(\frac{\rho}{\rho_i}\right)$ where ρ_i is the initial dislocation density and ρ is the dislocation density at any given time.
D_n	Damage due to evolution cavities and necking.
K_p	Rate constant for particle coarsening at a temperature T
K_{p0}	Absolute rate constant for particle coarsening

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Q_p	Activation energy for particle coarsening
Ts	Solvus temperature
ΔH_s	Thermodynamic parameter controlling dissolution of precipitate
σ_{0m}	Friction stress of matrix in absence of precipitates
C	Model parameter governing the evolution of cavities & necking
B	Model parameter describing change dislocation density
N	Stress exponent for power law creep equation
ε_f	Rupture strain
ε_s	Strain at which steady state is attained

1. Introduction

Although 9CrMo steel has been in existence since long; it has not been as popular as 2.25CrMo steel for high temperature applications in power plants because of its inferior creep resistance. Addition of strong carbide formers to this grade to retain Mo in solid solution has been one of the most significant innovations to improve its creep resistance. This has lead to the development P91 grade steel which is now one of the most preferred materials for high temperature parts of modern power plants [1]. This being a relatively new material it does not have enough long term creep term data in open literature. Predictive power of empirical models based on short term data is limited. Therefore there have been considerable efforts in the development of constitutive models based on underlying principles of evolution of structural changes in the material [24,8]. The one by Hore et al [7] has used a set of equation suggested by Dyson et al [5,6] to estimate the material parameters for 2.25CrMo steel for which long term creep strain time data are available in open literature. They have shown that by changing only a few of the parameters based on the logic that particle coarsening in P91 steel is much slower it is possible to predict creep behaviour of this relatively new grade of steel. However predictions in this case were not as good as those in the case of 2.25CrMo steel. One of reasons could be the major difference in their initial microstructures. P91 steel has tempered lath Martensite whereas 2.25CrMo steel has tempered Bainite. Therefore there is likely to be a large difference in their initial dislocation density. As a result of creep exposure dislocation density in P91 steel decreases significantly. This is possibly the reason why unlike 2.25CrMo steel it shows significant primary creep behaviour. This paper suggests a method of incorporating this in the model used by Hore et al as an additional damage parameter. The predicted creep strain time plots have been compared with experimental data.

2. Model Description

Hore et al in their model describing evolution of creep strain considered the effects of particle coarsening (D_p), stress transfer from the matrix to precipitates (H), dislocation softening (D_d) and increase in stress due to reduction in load bearing cross section. Unlike superalloy dislocation density in P91 steel decreases with time. The contribution of dislocation damage on initial creep rate is maximum at time t = 0. With time this keeps decreasing resulting in strengthening and a corresponding decrease in creep rate. This is why D_d has been defined as follows:

$$\dot{D_d} = -\frac{\dot{\rho}}{\rho_\iota}; At\ t = 0;\ \rho = \rho_i\ \therefore D_d = 1\ \&\ as\ t \to \infty\ \rho \ll \rho_i\ \therefore D_d \to 0$$

In the above expression ρ_i denotes initial dislocation density. It is expected to decrease with time as follows

$$\dot{D_d} = -\frac{\dot{\rho}}{\rho_\iota} \tag{1}$$

It can be shown using the Orowan equation $\dot{\varepsilon} = \rho b v$ relating mobile dislocation density (ρ), Burger's vector (b) and velocity of dislocations (v) to strain rate ($\dot{\varepsilon}$) that

$$\epsilon = k\sqrt{\rho} \;\&\; \dot{\epsilon} = k\frac{\dot{\rho}}{2\sqrt{\rho}} \tag{2}$$

In the above expression *k* is a constant. On substituting equation 2 in 1 one gets

$$\dot{D}_d = -B\varepsilon\dot{\varepsilon} \quad where\, B = 2/k^2 \tag{3}$$

It is possible to arrive at a rough estimate of the magnitude of the constant *B* by integrating equation 3 and substituting the condition that at $t = 0$ $D_d = 1$ & $\varepsilon = 0$ whereas at large t; $D_d = 1$ & $\varepsilon = \varepsilon_s$. Thus:

$$B = \frac{2}{\varepsilon_s^2} \tag{4}$$

The magnitude of ε_s which is a measure of strain after which there is little change in dislocation density. If this is taken as 0.02 to 0.05 then B is of the order of 800-5000. In other words the effect of dislocation density lasts over a relatively short time. However it is likely to affect creep strain rate significantly during the initial part of the strain time plot.

The equation set used to model creep of this steel has thus been modified. The notations used are exactly same as those used by Hore et al. The nomenclature for ready reference has been included as a list of symbol.

$$\begin{aligned}
\dot{\varepsilon} &= 0.5\dot{\varepsilon}_0\left(1 + D_d\right)\exp\left[-\frac{Q_d}{RT}\right]Sinh\left[\frac{\sigma(1-H)}{\sigma_0(1-D_p)\left(1-D_n\right)}\right]\\
\dot{H} &= \frac{h'}{\sigma}\left(1-\frac{H}{H^*}\right)\dot{\varepsilon}\\
\dot{D}_d &= -B\varepsilon\dot{\varepsilon}\\
\dot{D}_n &= \frac{n}{\varepsilon_f}\dot{\varepsilon} = C\dot{\varepsilon}\\
\dot{D}_p &= \frac{K_p}{3}(1-D_p)^4\\
\dot{\sigma} &= \sigma\dot{\varepsilon}
\end{aligned} \tag{5}$$

Incorporation of a multiplying factor 0.5 in the expression for creep rate becomes necessary to satisfy the initial condition. Both necking and cavitation lead to a reduction in effective load bearing area of the specimen. Following Dyson et al this has been incorporated as (D_n) where n is stress exponent. There is a considerable similarity between the expression for dislocation damage term used by Hore et al and the expression for (D_n) . Since stress exponent *n* for P91 steel is around 10 and the strain to rupture ε_f is approximately equal to 0.35 the constant C is likely to be around 30. No wonder Hore et al reported this to be 27.

In addition to the equation set 5 we need to define temperature dependence of the term K_p, which denotes kinetic rate constant for the dissolution of load bearing precipitates and the friction stress σ_0. Following Hore et al these have been represented as follows:

$$K_p = K_{p0}\exp\left(-\frac{Q_p}{RT}\right) \tag{6}$$

$$\sigma_0 = \sigma_{0m}\left[1-\exp\left(-\frac{\Delta H_s}{RT_s}\left(\frac{T_s}{T}-1\right)\right)\right] \tag{7}$$

Therefore in order to represent the creep behaviour of this steel we need only one additional parameter apart from those used by Hore et al. Table 1 gives the parameter set used in the present work.

Table 1: Material Parameters for P91 Steels [7].

Alloy	$\dot{\varepsilon}_0$	Q_d	σ_{om}	ΔH_s	T_s	h’	H*	Q_p	K_{po}	C
	s^{-1}	$KJmol^{-1}$	MPa	$KJmol^{-1}$	K	MPa		KJmol-1	s^{-1}	
P91	3.0E08	300	30	140	950	1.03E04	0.3	210	2.2E05	27

3. Results and discussions

Figures 1-2 give present a comparison of predicted creep strain time plots with experimental data under two test conditions. Prediction appears to be much better than those reported by Hore et al. This is primarily because of the incorporation of an additional equation representing decrease in dislocation density during the initial stages of creep in this steel.

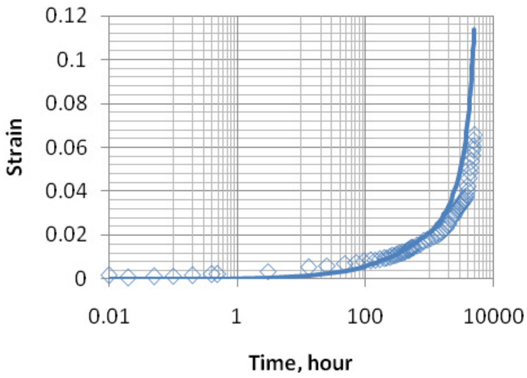

Fig. 1. A comparison of predicted and experimental creep strain time plot at 240MPa 540C. The line denotes predicted plot whereas the points are experimental data.

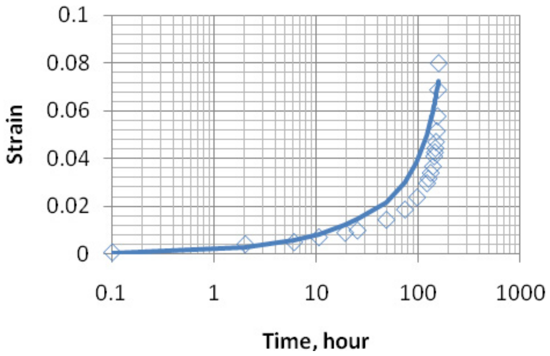

Fig. 2. A comparison of predicted and experimental creep strain time plot at 140MPa 625C. The line denotes predicted plot whereas the points are experimental data.

Figure 3 presents predicted time to reach 1% strain over wide range of test conditions. The line denotes predicted results whereas the points are experimental data. Keeping in view the scatter shown by experimental creep data the predictions are fairly close to the experimental results.

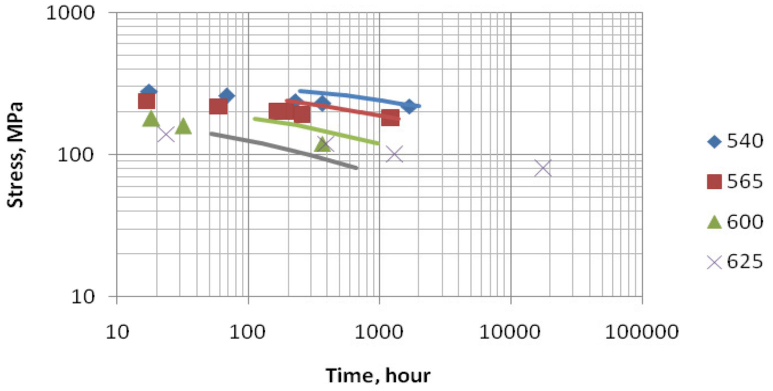

Fig. 3. A comparison of life time plots for P91 steel under different test conditions. Points denote experimental results and the lines predictions

4. Conclusions

A constitutive equation for considering the effect of decreasing dislocation density on the evolution of creep strain has been developed and it has been incorporated in the equation used by Hore et al to simulate creep behaviour of CrMo steel. The predictions of creep life appear to be consistent with the experimental data.

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