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Creep modelling of P91 steel employing a microstructural based hybrid concept

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ABSTRACT

In 9–12% Cr steels, tertiary creep stage is led by the synergistic effect of precipitate coarsening, substructure recovery and cavitation, therefore difficult to address it physically. Overcoming this problem to a certain extent, in present research work creep curves of P91 steel are modelled up to the onset of tertiary regime, based on a hybrid concept that couples a physical model to continuum damage mechanics (CDM) approach. The physical approach describes the microstructure evolution, CDM approach addresses the damage evolution and this combination enables to model up to the onset of tertiary creep stage. The aforementioned hybrid approach considers three types of dislocation densities explicitly, i.e., mobile, boundary and dipoles. Furthermore, the number density and size of precipitates in as-received condition is obtained from MatCalc software and incorporated in the model. The modelled creep curves are in good agreement with the experimental creep curves up to the onset of tertiary creep stage. The evolution of different dislocation densities, subgrain size and damage parameters are discussed thoroughly. The evolution of glide and climb velocities are also compared for the first time. From the investigated conditions, it is deduced that glide velocity dominates over climb and hence accommodating the creep strain. It must be further emphasized that the model predicts higher dislocation densities and smaller subgrain size at higher stresses, in accordance with empirical relationships.

1. Introduction

The Fe-Cr-Mo/Wo ferritic-martensitic steels, with 9–12% Cr, have been the workhorse materials for the several components (e.g., superheater coils, headers and steam piping) of energy generating systems (nuclear and non-nuclear) [1–9]. These steels are being used at high temperatures up to 625 °C. P91 steel belongs to this category and high temperature strength of this material depends on the precipitation state, substructure and solid solution hardening. The role of the precipitates is to hinder the dislocation movement as well as to retard the growth of the subgrains. These precipitates can coarsen or transform to new phases under the creep loading conditions [5]. On the other hand, creep conditions result in climb and glide recovery due to the annihilation of dislocations. The rearrangement of dislocations structure via thermally activated dislocation motion transform the martensitic laths into more polygonized subgrains [9]. The synergistic effect of these changes in microstructure drives the material towards softening and eventually failure [2,3,10].

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Microstructural modelling gives a better understanding of materials response under the creep loading conditions. The models based on physical parameters such as dislocation density and precipitate evolution provide an in-depth insight about the material response during creep [11–19]. The time span of steady state creep can be predicted when the modelling is coupled with experimental results, thereby enabling extrapolation to predict safe life with more precision [20]. The martensitic steels have a complex substructure, which can be described by different types of dislocations (mobile, dipole and boundary dislocations). A simple approach assuming one type of dislocation density cannot represent the complex dislocation configurations within the tempered martensitic structure [11,18,19].

In the recent past, different modelling approaches have been evolved to describe the creep behavior in martensitic-ferritic steels. Physics based approach were used by Ghoniem et al. [11], Magnusson et al. [16], Murchú et al. [17] and Barkar et al. [20] while CDM based models were used by McLean et al. [21], Yin et al. [22] and Semba et al. [23] to model the creep behavior. Furthermore, physical approach and CDM approach have been coupled together to describe the creep curves [18,19]. It is important to mention that the aforementioned approaches have enriched the knowledge in the field of creep modelling, however with a limited consideration on the use of internal variables in the model [18,19]. In particular, the comparison between glide velocity and climb velocity of dislocations is not reported yet in this material.

In the present work, creep curve of P91 steel were modelled using a hybrid concept [18,19] that considers the dislocation density, subgrain size and damage evolution during creep exposure. Three categories of dislocations, i.e., mobile, dipole and boundary as well as subgrains size were used as microstructural input parameters. The initial precipitation state was simulated through software MatCalc and incorporated in the model. Finally, the model was validated with the in-house experimental creep curve, data from literature, as well as by microstructural characterization. A comparison between glide and climb velocity of dislocations is also discussed for the first time.

2. Material and methods

The chemical composition (in wt.%) of the P91 steel is 0.12C, 0.3Si, 0.45Mn, 0.013P, 0.003S, 8.23Cr, 0.98Mo, 0.13Ni, 0.014Al, 0.06Nb, 0.22V, 0.041N and balance Fe. The material was normalized at 1060 °C for 30 min and air cooled. Subsequently, it was tempered at 770 °C for 60 min and air cooled. The creep specimen was fabricated with an aspect ratio of five according to drawing shown in Appendix A. The specimen was loaded for 9000 h at 650 °C with an initial tensile stress of 60 MPa and creep strain was measured using the interrupted strain measurement technique according to the EN ISO 204:2009 standard [2]. Transmission electron microscopy (TEM) was used for the characterisation of the microstructure. Scanning transmission electron microscopy (STEM) with high-angle annular dark-field (HAADF) contrast was used to characterize the subgrains and elemental mapping was used to identify the precipitates. Other than own creep curve, two creep curves from literature, one at 80 MPa/600 °C and another at 120 MPa/600 °C were used to validate the model [5,24]. The precipitation state of as-received material was simulated with the help of software MatCalc [25–27], that works on CALPHAD and the solid-state transformation approach. The precipitation kinetics of as-received material was simulated considering the input parameters given in Appendix B.

3. Creep model

In normalized and tempered condition (i.e., as-received condition) when P91 steel is subjected to creep loading, the microstructural evolution can be described by the dislocations motion considering interactions such as multiplication of dislocations, annihilation of dislocations, immobilization and subgrain growth. In the light of these interactions, an advanced creep model based on models of Ghoniem et al. [11], Yadav et al. [18] and Basirat et al. [19], is used for the creep strain modelling in the present study. This advanced model considers a more general model for the climb velocity [28–30] different from previous approaches [11,18].

In as-received condition, the total dislocation density of P91 steel can be divided into three categories: mobile ρ_m, dipole ρ_{dip} and boundary ρ_b dislocations [9,11,18]. Under creep condition the rate of change of the mobile dislocation density is expressed as a function of dislocation generation and dislocation annihilation, wherein the generation considers multiplication of dislocations while annihilation takes into account the dipole formation, climb and glide recoveries.

$$\frac{d\rho_m}{dt} = \left[\frac{v_g}{h_m}\cdot\rho_m\right] - \left[\frac{v_g}{2R_{sbs}}\cdot\rho_m\right] - [8\rho_m^{3/2}v_c] - [d_{anh}\cdot(\rho_m + \rho_{dip})\cdot\rho_m\cdot v_g] \tag{1}$$

In the above equation v_g is the glide velocity, $h_m = 1/\rho_m{}^{0.5}$ is the dislocation spacing of mobile dislocations, R_{sbg} is the subgrain radius, v_c is the climb velocity and d_{anh} is the length parameter for spontaneous annihilation [11,18]. In above Eq. (1), the glide velocity follows the expression [11,18],

$$v_g = a_1.\ \exp\left(\frac{-Q}{kT}\right)\left[\frac{\Omega}{kT}\right]\sigma_{eff}, \tag{2}$$

where Q is the activation energy for dislocation glide, Ω is the atomic volume, k is the Boltzmann constant, T is the temperature, σ_{eff} is the effective stress and a_1 an adjustable parameter. The effective stress is the resultant of applied stress σ_{app} and internal stress σ_i and is given as [11,18,19],

$$\sigma_{eff} = \sigma_{app} - \sigma_i, \tag{3}$$

When materials are loaded at high temperature, the microstructure provides resistance to the deformation in terms of a reacting