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Micromechanical model of the high temperature cyclic behavior of 9–12%Cr martensitic steels

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ABSTRACT

9–12%Cr quenched and tempered martensitic steels are known to soften under cyclic loadings at high temperature. The present article proposes a model based on physical mechanisms described at the scale of slip systems. This model describes explicitly the microstructural recovery (corresponding to a decrease of the dislocation density and subgrain coarsening) observed experimentally. The scale transition is carried out in the framework of self-consistent homogenization schemes. The model assumptions and its physical basis are explicitly discussed. The parameters are identified on a very limited amount of experimental data. The model turns out to give very good predictions and extrapolations for the cyclic softening effect observed in uniaxial tension–compression loadings for strain ranges larger than 0.3%. Stress–relaxation and creep behavior can also be simulated for high stresses. In addition the cyclic softening effect is reproduced for multiaxial tension–torsion loadings.

1. Introduction

The need for an increased thermal efficiency in advanced power generation systems led to the introduction of martensitic steels, and especially the 9–12%Cr family (Bloom et al., 2004; Swindeman et al., 2004). These materials have been optimized in terms of creep strength and are already widely used for energy production using fossil fuel. In the framework of Generation IV and Fusion nuclear reactors, these steels are candidate materials for several components (Klueh and Harries, 2001; Iracane et al., 2006). These components will be subjected to long term cyclic loadings like fatigue and creep-fatigue (the typical holding period is around one month) at temperatures close to 823 K. Laboratory creep-fatigue experiments cannot reach such long durations because of technical and cost issues.

Recent studies on commercial Grade 91 (which is a modified 9Cr–1Mo steel) showed that cyclic loadings coupled to high-temperature creep loadings lead to a fast and strong cyclic softening effect, which deteriorates the mechanical properties such as the creep strength (Dubey et al., 2005; Chilukuru et al., 2009; Fournier et al., 2009a,b). The study of the hysteresis loops of pure fatigue and creep-fatigue tests (Fournier et al., 2006a,b) has shown that this cyclic softening effect is mainly due to a decrease of the kinematic component of the stress X also called the backstress. Transmission Electronic Microscopy (TEM) observations have shown that the cyclic softening effect was correlated to a coarsening of the initial martensitic laths and subgrains (Kim and Weertman, 1988; Kostka et al., 2007; Dubey et al., 2005; Kimura et al., 2006; Vasina et al., 1995; Fournier et al., 2009b) and to a decrease of the dislocation density (Armas et al., 2004). No significant modifications of the precipitates was noticed at 823 K (Fournier et al., 2006a) due to a higher tempering temperature. These microstructural modifications were shown to be heterogeneous and influenced by crystallographic orientation and grain neighborhood (Fournier, 2007, 2009b).

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Constitutive modeling of the cyclic behavior of martensitic steels have already been proposed (Aktaa and Schmitt, 2006). These models are able to reproduce most of the phenomena observed under cyclic loadings but limitations (Aktaa and Petersen, 2009) linked to thermo-mechanical and multiaxial loadings are encountered. Generally speaking the parameters and equations of this type of models do not explicitly take into account the microstructural features (Lemaitre and Chaboche, 1987; Koo and Lee, 2007; Chaboche, 2008; Sai, 2011). Attempts can be made to interprete them in terms of physical phenomena, but extrapolations and predictions out of the range of identification remain hazardous. Physically-based models, taking into account the microstructural modifications (subgrain and lath coarsening, dislocations annihilation,...) were expressed analytically (Sauzay et al., 2005, 2008; Fournier et al., 2005) and also applied to creep (Sauzay, 2009). These models give correct tendencies for both the cyclic softening and the microstructural modifications. In addition, as they are based on the physical mechanisms responsible for the cyclic softening effect at the scale of dislocations, they may be more relevantly extrapolated beyond the experimental database, which is necessary for the above mentioned long term applications. However, up to now, the scale transition between the microscopic phenomena and the macroscopic mechanical behavior was carried out using analytical boundary formulations like those of Sachs (1928) and Taylor (1938). These formulations enable to bound the actual mechanical behavior, but can account neither for the strain range effect nor for the effect of crystallographic orientation or grain neighborhood.

The present article proposes a first pragmatic implementation of this physically-based model within a self-consistent homogenization scheme (Bornert et al., 2000). Its main objective is to reproduce the cyclic softening effect observed under pure fatigue and under creep-fatigue conditions. First the material microstructure and the physical basis of the model are described (Section 2). Then the equations are detailed and the parameters identified (Section 3). Finally, the simulation results are presented and discussed (Sections 4 and 5).

2. Material and physical mechanisms modeled

2.1. Material

The material under study is a Grade 91 steel produced by Usinor. The chemical composition is given in Table 1. The steel plate was austenitized at 1050 °C for 30 min, quenched and tempered at 780 °C for 1 h. The as-received very fine tempered martensitic microstructure is presented in Fig. 1. Several microstructural scales are observed in these materials. The largest one (15–60 μm) is the prior austenitic grain (PAG) which is divided into martensitic packets, themselves made of block of laths. Within blocks, the laths are divided into subgrains. Two main types of precipitates are observed. On the one hand, large (100–300 nm) $M_{23}C_6$ type particles are mainly located along large angle boundaries and on the other hand smaller (30–50 nm) MX type precipitates are distributed rather homogeneously inside the material.

If the crystallographic texture of the as-received material is approximately isotropic, the martensitic transformation leads to the existence of specific misorientations between block of laths (Kurdjumov and Sachs, 1930; Nishiyama, 1971; Gourgues et al., 2000; Morito et al., 2003). Recent studies have shown that the minimum angle between two blocks of laths is around 5° (Barcelo et al., 2009, 2010). Within blocks, between laths and subgrains, the mean misorientation is much lower and boundaries are considered to be low-angle boundaries (LABs). The mean block size is around 2.3 μm whereas the mean subgrain size is around 0.38 μm (Fournier et al., 2009b). The as-received dislocation density was measured to be around $1.8 \times 10^{14}\ \mathrm{m}^{-2}$ (Fournier et al., 2009b).

As a first approximation the crystallographic orientations of the simulated phases will be randomly taken from an isotropic distribution which is consistent with EBSD and XRD texture measurements (Fournier et al., 2009b).

After fatigue and creep-fatigue loadings at 823 K, previous studies have shown no significant modification of the precipitation state (in terms of both density and size). However, the subgrain size increases and tends to the mean block size and the dislocation density falls down to $2.8 \times 10^{13}\ \mathrm{m}^{-2}$. These studies (Fournier et al., 2006a,b, 2009b) also showed that this recovery of the microstructure (the increase in subgrain sizes and the decrease in the dislocations density) was responsible for the cyclic softening effect and directly correlated to the cumulated viscoplastic deformation. In addition to the cumulated viscoplastic deformation, the amount of viscoplastic deformation applied at each cycle $\Delta\epsilon_{vp}$ also influences this microstructural phenomenon: for high values of $\Delta\epsilon_{vp}$, the recovery is homogeneous, whereas for low $\Delta\epsilon_{vp}$ (almost purely elastic loading), the recovery appears only inside a few blocks of laths (Fournier et al., 2009b).

These mechanical and microstructural results are the basis of the proposed model.

2.2. Physical basis of the model

Considering the results of the microstructural observations summarized above, a mechanism of annihilation of the LABs was proposed and detailed in Sauzay et al. (2005). Let us consider that LABs are made of an arrangement of dislocations as

Table 1
Chemical composition of the P91 steel under study.

Element	C	N	Cr	Mo	Mn	Si	Nb	V
Wt (%)	0.088	0.043	8.776	0.915	0.354	0.329	0.078	0.191