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A study of the creep behavior of modified 9Cr–1Mo steel using continuum-damage modeling

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ABSTRACT

A micromechanical model is developed for the evaluation of creep deformation and rupture times of modified 9Cr–1Mo steel specimens. Creep deformation in metals is generally induced by the dislocation generation, motion, and annihilation. To evaluate the creep behavior of the modified 9Cr–1Mo steel the Orowan's equation was employed, which is valid for both glide and climb-controlled dislocation movement. The evolution of the dislocation density was modeled by considering the generation and annihilation of single and dipole dislocations. In addition to dislocation motion as a basis for creep deformation, there are several other factors which determine the creep resistance of this steel. Among these, the most significant are precipitate coarsening, solid solutions depletion, and void/crack nucleation and growth. The evolution of these mechanisms during creep deformation was accounted for by introducing specific continuum damage terms. Creep tests were also performed at several stress and temperature levels. The comparison of the numerical model results with the experimental data showed satisfactory agreement.

1. Introduction

It is estimated that in the next 20 years the world demand for power supplies will increase by up to 50%. Thus, developing advanced energy resources becomes essential. The developed energy sources must be sustainable, environmental friendly and cost effective. Nuclear power meets these requirements for large scale power generation. The development of advanced nuclear power plants is followed under the Next Generation Nuclear Plant (NGNP) program. The NGNP program focuses on the development of the Very-High-Temperature Reactor (VHTR), which represents the next generation of the high temperature gas-cooled reactors. The VHTR is a helium-cooled, graphite-moderated reactor with a once-through uranium fuel cycle. The VHTR design specifications, include higher operating temperatures, longer design life, and higher working pressures compared with previous reactor types, which makes it necessary to consider new metallic alloys with improved creep properties for reactor pressure vessels and reactor internals. One such candidate material is modified 9Cr–1Mo steel.

Recently, several research studies have been performed to elucidate and model the creep behavior in metals. Preußner et al. (2009) developed a dislocation density-based creep model, and the creep behavior of single fcc, bcc, and hcp crystals was studied using this model. Venkataramani et al. (2008) developed a finite element crystal plasticity creep model and performed a parametric study to identify the primary microstructural parameters causing early crack initiation by load shedding in Ti-6242 during creep. They used the Schmid factor and the grain size and shape as the most critical parameters to prevent stress concentration and crack initiation.

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Fischer and Svoboda (2011) extended the Nabarro creep model to the general dislocation microstructure. At low stress levels the creep is controlled by the generation/annihilation of vacancies at dislocations jogs. They developed a model based on vacancy activity, dislocation microstructure and applied stress state, and simulation results were compared to experimental measurements of creep rates in P91 steel at low stresses and high temperatures. Oberson and Ankem (2009) studied the creep deformation behavior of α-Ti-1.6 wt.% V. The formation of twinning at high strains was explained by dislocation pileups. Morra et al. (2009) studied the precipitate coarsening in tempered SAE 52100 steel. It has been shown that the growth of carbide precipitates is in correlation with the plastic strain evolution. Creep strength of as-cast and annealed Fe–Ni–Al alloy has been investigated by Muñoz-Morris et al. (2009). It has been shown that in the annealed alloy with less volume fraction of precipitates the creep strength decreases significantly while the ductility increases. Horstemeyer and Bammann (2010) performed a review on the development and the use of internal state variable theory based on the Coleman and Gurtin thermodynamics formulations for dislocations, creep, and continuum damage mechanics.

The material of interest in this study is modified 9Cr–1Mo steel, and was developed in late 1970s for use in fossil fuel power plants, according to Swindeman et al. (2004). The main advantages of modified 9Cr–1Mo steel which make it a suitable candidate for VHTR structures are limited radiation hardening at higher temperature, lower shift in the Ductile-to-Brittle Transition Temperature (DBTT), low thermal expansion coefficient, and better void swelling resistance than austenitic steels. Furthermore, modified 9Cr–1Mo steel is a precipitate-hardened alloy with a stable microstructure. The mechanical behavior and chemical composition of the modified 9Cr–1Mo steel have been optimized in the recent years. This steel contains alloying elements such as Nb and V, which form fine and stable particles, and help to improve its creep strength.

The creep behavior of the 9Cr–1Mo steel has been studied by several researchers during the past years. (Sklenička et al., 1994, 2003) suggested that the role of dislocation substructure is dominant for the creep behavior of 9Cr–1Mo steels. According to their study, carbide particles merely stabilize the substructure, while the dislocation structure and/or substructure development determine the creep behavior of the steel. Spigarelli et al. (1997) concluded that the high values of the activation energy and the creep stress exponent indicate that in the high stress regime creep strain is controlled by dislocation movement and particle-dislocation interaction (Orowan by-pass and/or climb). Böck and Kager (2005) have performed an extensive research on the finite element modeling of the creep behavior of modified 9Cr–1Mo steel. Instead of using standard evolution laws for predicting long term creep, they proposed to utilize models which were based on microstructural variables. Arzt and Wilkinson (1986) proposed a dislocation based model for creep. The model is valid for local and general climb of dislocations regardless of the climb mechanisms. In this model the threshold stress is defined as the dislocation-particle attractive interaction. Creep models based on microstructure have also been proposed by several other authors (Ghoniem et al., 1990; Blum et al., 2002; Raj et al., 1995, and Raj, 2002). The common theme of these models is that they employ multiple microstructural variables based on averaged microstructural quantities, such as the mobile dislocation density, static dislocation density, boundary dislocation density, subgrain radius, precipitate radius, precipitate concentration and glide energy.

Fujimitsu (2006) studied the material degradation in modified 9Cr–1Mo steel welds during creep deformations. He proposed a new approach for the evaluation of creep degradation and life assessment in modified 9Cr–1Mo steel welds by the hardness measurement method. The uniaxial high-temperature creep behavior of the base metal and weldment of 9Cr1MoNbV steel was studied by Gaffard et al. (2005). They also investigated the type IV failure in the heat affected zone. Furthermore, a one-dimensional model based on a power law and the Monkman–Grant models were proposed for life time assessment of the weldment. Besson et al. (2009) proposed a model which integrated the power-law creep, diffusional creep and a simple damage term for simulating the creep-failure behavior of the inter-critical heat affected zone. Fournier et al. (2011) introduced a micromechanically based model considering the dislocation density and subgrain coarsening in order to predict the cyclic softening in the 9–12%Cr martensitic steels. The model shows a good consistency with the experiments for strain over 0.3%. Sauzay (2009) studied the effect of annihilation of low angle boundaries and the micro-grain coarsening during creep deformation of tempered martensite steel, and developed physically-based computations following the Read and Shockley model.

Several studies have been performed to evaluate the effect of precipitates on the creep behavior of 9Cr–1Mo steel. The type, size and volume fraction of precipitates in the modified 9Cr–1Mo steel were investigated by Chilukuru et al. (2009). They showed that *V* forms fine particles of M_2X, which may provide short term high creep strength, but the rapid coarsening of M_2X at the subgrain boundaries and *Z*-phase precipitation decrease the overall creep resistance. Kabadwal et al. (2010) found that the primary creep stage of a specimen tempered at 500 °C was controlled by the mobile dislocation density reduction and is a recovery process, while for the specimens tempered at 800 °C, the primary creep is controlled by the increase in creep resistance due to the fine precipitation of VX. Also, it has been mentioned that the growth of $M_{23}C_6$ in the tertiary creep stage relates to the creep rate increase.

In addition to temperature and applied stress, there are several microstructural parameters which influence the creep behavior of materials. Continuum damage models have been widely used to simulate the material degradation due to microstructural evolution. During the past decades numerous continuum damage mechanics models coupling with plasticity, viscoplasticity, creep, and fatigue have been developed. (e.g., Voyiadjis and Kattan, 1992; Murakami et al., 1998; Abu Al-Rub and darabi, 2012; Bieler et al., 2009; Brünig et al., 2008; Egner and Skoczeń, 2010; Marotti de Sciarra, 2012; Kang et al., 2009). The tertiary creep stage of the modified 9Cr–1Mo steel is governed by several the microstructural processes which degrade the material. Ashby and Dyson explained the creep damage by the loss of internal and external sections, microstructure degradation, and gaseous environmental attack. Each category was found to contain several micro-mechanisms