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Constitutive modelling of stress-relaxation behaviour of tempered martensitic P91 steel using sine hyperbolic rate law

J. Christopher*, B.K. Choudhary

Deformation and Damage Modelling Section, Materials Development and Technology Division, Indira Gandhi Centre for Atomic Research, HBNI, Kalpakkam, 603102, Tamil Nadu, India

HIGHLIGHTS

- A constitutive model has been developed to describe stress-relaxation behaviour.
- Interrelationship between internal stress and relaxation stress has been derived.
- Model accurately described the relaxation stress vs. hold time data of P91 steel at 873 K.
- Model can predict the variations in activation volume and inter-barrier spacing with hold time.

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ABSTRACT

A constitutive model describing stress-relaxation behaviour of P91 steel at 873 K has been presented. In the model, the equations defining the evolution of internal stress and relaxation stress with time have been coupled with the sine hyperbolic rate law to predict the relaxation stress as a function of hold time as well as the stress dependence of inelastic strain rate. The evolution of internal stress with time has been derived from the power law dependence of internal stress on relaxation stress. The predicted evolution of internal and effective stresses with time exhibited an initial rapid decrease followed by stress plateaus at longer durations. The applicability of the model has been demonstrated for two different strain holds of 1.3 and 2.5% in P91 steel. It has been shown that the present model can be used to predict the evolution of inter-barrier spacing and activation volume with time for both the strain holds at 873 K. Further, the observed increase in activation volume and inter-barrier spacing with hold time in P91 steel has been presented.

1. Introduction

Stress-relaxation technique offers considerable advantages for material testing in terms of economical evaluation of mechanical properties and kinetics of deformation useful to derive the constitutive laws in metals and alloys [1]. It has been demonstrated that the short-time stress-relaxation data can be conveniently employed for the evaluation of creep strength, life prediction and remnant life assessment of engineering materials [2,3]. Further, stress-relaxation behaviour also finds application towards alloy design, development and optimisation of new alloys [2,4,5]. During stress-relaxation, the external constraint i.e., the total applied strain is kept constant. In this imposed condition, the increase in inelastic strain is compensated by the decrease in elastic strain by an equal amount, which in turn leads to stress reduction governed by stress-strain proportionality or the modulus of elasticity. In stress-relaxation test, the decrease in stress i.e., the relaxation stress (σ_r) is monitored as a function of elapsed time (t). It is well known that the kinetics of stress reduction is either governed by dislocation processes more importantly the dislocation-local obstacle interaction [6–8] or diffusional creep mechanisms [9,10]. It was reported that diffusional creep mechanisms can play an important role at low stresses [9,10], potentially at later stages of stress-relaxation. Though empirical [11] or polynomial relationships [3,12] were employed to describe the stress-relaxation data, investigations related to development of kinetic theory of relaxation and its applicability towards the description of relaxation behaviour of tempered martensitic steels have not been established. In view of this, an attempt has been made to propose a new

* Corresponding author.
E-mail address: jchris@igcar.gov.in (J. Christopher).

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model based on kinetics of dislocation processes for accurate description of stress-relaxation behaviour of P91 tempered martensitic steel. In this modelling framework, the internal stress has been taken as an internal state variable and the capability of this state variable based model for simulating the inelastic behaviour during stress-relaxation has been presented. It is important to mention that state variable based models provide adequate description to both inelastic deformations during stress-relaxation and long-term creep behaviour of engineering materials [13].

Modified 9Cr-1Mo (commonly known as P91) tempered martensitic steel is a favoured structural material for high temperature steam generator (SG) applications in thermal and nuclear power generating industries [14]. The microstructures of 9% Cr steels consists of high initial dislocation density inside lath, hierarchical boundaries in terms of prior austenite grain boundaries (PAGs) and martensite packets, blocks, sub-blocks and laths with fine distribution of precipitates [15]. Based on experimental observations in P91 steel, it has been shown that the subgrain coarsening remains dominant during deformation under stress-relaxation conditions at high temperatures [16,17]. The variation in subgrain size with time during stress-relaxation in turn is related to the variations in obstacle spacing (λ) with time. These observations clearly indicate that the activation volume and internal stress vary with time or relaxation stress in P91 steel. In view of this, a model accounting for the variations in activation volume and internal stress with time has been developed which consist of differential equations defining the sine hyperbolic kinetic law and the rate of evolution of internal stress and relaxation stress. The applicability of the model has been demonstrated for two different strain holds of 1.3 and 2.5% in P91 steel at 873 K.

2. Modelling framework for stress-relaxation

2.1. Generalised condition for stress-relaxation models

During stress-relaxation, the external constraint i.e., the total applied strain (ε_t), made up of elastic (ε_e) and inelastic (ε_{in}) strain components is kept constant. Hence, the total strain rate is given as

$$\dot{\varepsilon}_t = \dot{\varepsilon}_e + \dot{\varepsilon}_{in} = 0. \tag{1}$$

The elastic strain rate ($\dot{\varepsilon}_e$) term in Eq. (1) can be expressed as

$$\dot{\varepsilon}_e = \frac{\dot{\sigma}_r}{C} \tag{2}$$

where C is the effective modulus of the sample-machine system and $\dot{\sigma}_r$ is the stress-relaxation rate. The relation between stress-relaxation rate and inelastic strain rate can be derived from Eq. (1) and Eq. (2) as

$$\dot{\varepsilon}_{in} = -\dot{\varepsilon}_e = -\frac{\dot{\sigma}_r}{C}. \tag{3}$$

Equation (3) implies that the decrease in elastic strain is exactly balanced by an increase in inelastic strain during relaxation. This results in decrease in stress values with hold time. All theoretical approaches [6–8] to the relaxation process are based on Eq. (3) and therefore, Eq. (3) represents a general differential equation describing stress-relaxation behaviour. In general, relaxation models [6–8] mainly focus on the development of interrelationship between inelastic strain rate and relaxation stress. Among the existing models [6], the model proposed by Feltham [7] is widely used to describe the stress-relaxation behaviour of different metals and alloys [18–20].

2.2. Feltham relationship for stress-relaxation

Based on dislocation-local obstacle interaction theory, Feltham [7] proposed the inelastic strain rate relationship to describe the stress-relaxation behaviour as

$$\dot{\varepsilon}_{in} = \dot{\varepsilon}_0 \rho_m \exp\left(\frac{-(Q - (\sigma_r - \sigma_i)\Delta V)}{kT}\right), \tag{4}$$

where σ_i is the relaxation stress and $\sigma_r - \sigma_i$ is equal to the effective stress (σ_e). $\dot{\varepsilon}_0$ is a constant that includes a frequency factor, the area swept out by an activated dislocation and the Burgers vector (b). ρ_m is the mobile dislocation density, Q is the activation energy, ΔV is the activation volume, k is the Boltzmann's constant and T is the absolute temperature. According to Feltham [7], the values of $\dot{\varepsilon}_0$, ρ_m and ΔV are unchanged during stress-relaxation and the internal stress σ_i is assumed as a constant. Equation (4) is substituted in Eq. (3) followed by the integration of Eq. (3) with appropriate boundary conditions is represented as

$$\int_{\sigma_{r0}}^{\sigma_r} \exp\left(\frac{(Q - (\sigma_r - \sigma_i)\Delta V)}{kT}\right) d\sigma_r = \int_0^t -C\dot{\varepsilon}_0 \rho_m dt, \tag{5}$$

where σ_{r0} is the relaxation stress at t = 0. Equation (5) yields

$$\sigma_r = \sigma_r - \frac{kT}{\Delta V} \ln\left(1 + \frac{t}{t_0}\right), \tag{6}$$

where $\frac{1}{t_0} = \frac{C\,\dot{\varepsilon}_0\,\rho_m\,\Delta V}{kT} \exp\left(\frac{-(Q - (\sigma_{r0} - \sigma_i)\Delta V)}{kT}\right)$ with t_0 is treated as a constant. Equation (6) is employed for the description of relaxation behaviour of different materials. Further, Feltham relation [7] combined with Ramberg-Osgood [21] stress-strain formulation was used to describe the cyclic stress-strain and cyclic stress-relaxation behaviour of 1CrMoV rotor steel [22]. Based on kinetic rate theory, DiMelfi [8] derived a similar relation applicable to stress-relaxation behaviour of engineering materials. However, predicted relaxation stress vs. hold time data derived by DiMelfi model [8] exhibited significant deviations from the experimental relaxation stress vs. hold time data at longer durations. In addition to this, the assumptions related to constancy in activation volume and internal stress in stress-relaxation model directly implies constancy in the obstacle or inter-barrier spacing in the formulations [7,8]. The reported increase in lath width or subgrain size accompanied with decrease in dislocation density for P91 steel [16,17] suggested that the substructural variations alters inter-barrier spacing which resulted in the variations in internal stress (σ_i) and activation volume (ΔV) during stress-relaxation. From the microstructural aspects, it is evident that Feltham relation [7] involving constancy in internal stress and activation volume is not applicable for describing the stress-relaxation behaviour of P91 steel. An alternate to Feltham relationship [7], state variable based model has been developed in the present study.

2.3. State variable based model for stress-relaxation

In the present formulation, sine hyperbolic rate relation proposed by Christopher and Choudhary [23] has been used to describe the inelastic strain rate during stress-relaxation. The model has been originated from the Orowan equation [24]. Based on Orowan equation, the shear strain rate ($\dot{\gamma}$) is given as

$$\dot{\gamma} = \rho_m b v, \tag{7}$$