Fusion Engineering and Design 118 (2017) 129–134

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Viscoplastic equations incorporated into a finite element model to predict deformation behavior of irradiated reduced activation ferritic/martensitic steel

Yuanyuan Wang[a,*], Jijun Zhao[a,*], Chi Zhang[b]

[a] Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), Dalian University of Technology, Dalian 116024, China
[b] Key Laboratory of Advanced Materials of Ministry of Education, School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- The initial internal variable in the Anand model is modified by considering both temperature and irradiation dose.
- The tensile stress-strain response is examined and analyzed under different temperatures and irradiation doses.
- Yield strengths are predicted as functions of strain rate, temperature and irradiation dose.

ARTICLE INFO

Article history:
Received 19 July 2016
Received in revised form 24 March 2017
Accepted 24 March 2017

Keywords:
Modified Anand model
Irradiation hardening
Finite element method
Mod 9Cr-1Mo steel

ABSTRACT

The viscoplastic equations with a modified initial internal variable are implemented into the finite element code to investigate stress-strain response and irradiation hardening of the materials under increased temperature and at different levels of irradiated dose. We applied this model to Mod 9Cr-1Mo steel. The predicted results are validated by the experimentally measured data. Furthermore, they show good agreement with the previous data from a constitutive crystal plasticity model in account of dislocation and interstitial loops. Three previous hardening models for predicting the yield strength of the material are discussed and compared with our simulation results.

1. Introduction

Reduced activation ferritic/martensitic (RAFM) steel has been developed as a candidate structural material for DEMO reactor and possibly for fusion power reactors. The dominant influence of neutron irradiation on RAFM steel is a significant increment of strength and a reduction of ductility, which is related to irradiation-induced microstructure evolution [1]. In general, an increase in yield strength is accompanied by elongation reduction under irradiation, which is caused by the interaction among irradiation-induced dislocation and defect clusters. For instance, Fujii and Fukuya [2] observed small stable defect clusters (i.e., dislocation loops) in ion-irradiated A533B steel under thermal annealing at 673 K. Irradiation-induced dislocation loops was found with a high number density at 573 K in F82H steel, which is responsible for the irradiation hardening [3]. Little [4] also pointed out that the major mechanism of irradiation hardening in irons and steels involves the defect obstacles to dislocation motion.

Numerous theoretical simulations on structural materials have been carried out to investigate their mechanical properties and thermal stabilities under irradiation. Xiao et al. [5] developed a size-dependent tensorial elastic-viscoplastic self-consistent model to capture the stress-strain response of copper and the relevant irradiation damage effect. Based on a coupled viscoplastic deformation damage model, Aktaa and Petersen [6] considered irradiation-induced hardening and its recovery to predict the constitutive behavior of Euro97 and F82H after irradiation. A simple physical model by coupling mobile dislocation density and irradiation loops was proposed by Pokor et al. [7] to examine the effect of irradiation defects on the work hardening behavior of stainless steels. The slip resistance by considering the interaction between dislocations and defects, both partially originated from irradiation, was summarized and used in the framework of continuum dislocation dynamics (CDD) to predict the strength and deformation behavior of single crystal α-Fe [8]. Deo et al. [9] implemented the dispersed barrier hardening law into the viscoplastic self-consistent (VPSC) code to predict the yield strength of ferritic steels under different irradiation doses. Patra and McDowell [10] formulated a mechanism-based internal state variable (ISV) continuum crystal plasticity model by considering dislocation motion and defect evo-

* Corresponding authors.
E-mail addresses: 630wyy@163.com (Y. Wang), zhaojj@dlut.edu.cn (J. Zhao).

http://dx.doi.org/10.1016/j.fusengdes.2017.03.145
0920-3796/

lution during irradiation to simulate the tensile and creep behavior of the structural materials. Irradiation creep is usually referred to dislocation climb-enhanced glide mechanisms that are caused by absorbing or emitting irradiation-induced vacancy or interstitial defects. The bias driven by interstitials and the stress-induced preferred absorption of defect models involving dislocation climb are used to understand the irradiation creep of various steels (i.e., ferritic, martensitic and austenitic steels) as well as zircaloy [11].

Among various constitutive models, the well-established viscoplastic model for steels and alloys proposed by Anand [12] and Brown [13] has the following two basic features. First, no explicit yield condition and no loading/unloading criterion are required in this model. The plastic strain is assumed to take place at all nonzero stress values, although the rate of plastic flow at low stresses may be immeasurably small. Second, this model employs only one internal variable to represent the isotropic deformation resistance to the macroscopic plastic flow offered by the internal state of the material. Hence, it can simply and efficiently capture deformation features. For example, the comparison of stress-strain curves between the Anand viscoplastic model and the experimental data of steel at high temperatures and various strain rates shows reasonable agreement [14].

Recently, Marsh and co-workers [15] innovatively implemented viscoplastic equations into the finite element model to simulate the plastic deformation of irradiated tungsten at high temperatures and irradiation doses. Such constitutive model for predicting deformation behavior of the irradiated materials is feasible and effective. However, it is a considerable challenge to use a single set of parameters in the Anand viscoplastic model to predict mechanical properties of both unirradiated and irradiated materials simultaneously instead of using separate sets of parameters, as was done by Marsh et al. [15]. Therefore, we further modify one of key parameters in the Anand model by considering both temperature and irradiation dose. This allows us to use one set of parameters to predict mechanical deformation of the structural materials before and after irradiation at various levels of temperature, dose and strain rate.

Mod 9Cr-1Mo steel (9Cr-1Mo also known as T91) as a kind of RAFM steels has been developed for the first wall and blanket components of nuclear fusion reactors owing to its excellent irradiation resistance [16] and good high-temperature strength [17]. In the present work, finite element simulation in conjunction with the modified Anand model is performed to study the temperature, irradiation dose and strain rate dependence of stress-strain response and irradiation hardening of Mod 9Cr-1Mo steel.

2. Simulation methods

2.1. Anand viscoplastic model

A set of constitutive formulas, namely the Anand equations, has been proposed by Anand and Brown [12,13] to describe large, isotropic and viscoplastic deformation behaviors as well as small elastic deformation. In order to investigate the inelastic deformation of a material using the Anand model, the physical conditions (e.g., strain rate and temperature) should be considered. In the Anand model, the isotropic deformation resistance to the macro plastic flow is represented by a single scalar internal variable s. This internal variable is used to reflect the effects of dislocation density, solid solution strengthening, grain size, and so on. The deformation resistance is proportional to the equivalent stress σ. The relationship between σ and s is expressed as

$$\sigma = cs, c < 1 \tag{1}$$

where c is a material parameter as a function of strain rate and temperature. Thus

$$c = \frac{1}{\xi}\sinh^{-1}\left[\left(\frac{\dot{\varepsilon}^p}{A}\exp(\frac{Q}{RT})\right)^m\right] \tag{2}$$

where $\dot{\varepsilon}^p$ is the inelastic strain rate, ξ is the material constant for the multiplier of stress, A is the pre-exponential factor, Q is the activation energy, R is the universal gas constant, T is the absolute temperature, and m is the strain sensitivity.

Combining Eqs. (1) and (2) gives the inelastic strain rate in the following form

$$\dot{\varepsilon}^p = A\exp\left(-\frac{Q}{RT}\right)\left[\sinh\left(\xi\frac{\bar{\sigma}}{s}\right)\right]^{\frac{1}{m}} \tag{3}$$

The internal variable s is assumed to be defined as follows

$$\dot{s} = h(\sigma, s, T)\dot{\varepsilon}^p \tag{4}$$

with

$$h = h_0|1 - \frac{s}{s^*}|^a \mathrm{sign}\left(1 - \frac{s}{s^*}\right), a \geq 1 \tag{5}$$

and

$$s^* = \hat{s}\left[\frac{\dot{\varepsilon}^p}{A}\exp\left(\frac{Q}{RT}\right)\right]^n \tag{6}$$

where $h(\sigma, s, T)$ is a hardening function considering dynamic strain hardening and recovery, h_0 is the hardening/softening constant, a is the strain rate sensitivity of hardening/softening, s^* is the saturation value of s for a given temperature and strain rate, and $\hat{s}$ is a coefficient. Hence, the evolution equation for the internal variable can be written as

$$\dot{s} = \left[h_0|1 - \frac{s}{s^*}|^a \mathrm{sign}\left(1 - \frac{s}{s^*}\right)\right]\dot{\varepsilon}^p, a \geq 1 \tag{7}$$

Eqs. (3)–(7) are the basic equations in the Anand model to describe the influence of temperature, strain rate and strain hardening on the material deformation. At a given temperature and loading strain rate, material deformation shows the steady plastic flow. The stress σ corresponds to the saturated stress σ^* when the plastic deformation rate is proportional to the loading strain rate. To extend the expression of saturated stress σ^* ($\sigma^* = cs^*$), Eqs. (1), (2) and (6), associated with the saturation stress, temperature and strain rate, are employed. The final formula for σ^* becomes

$$\sigma^* = \frac{\hat{s}}{\xi}\left[\frac{\dot{\varepsilon}^p}{A}\exp\left(\frac{Q}{RT}\right)\right]^n \sinh^{-1}\left[\frac{\dot{\varepsilon}^p}{A}\exp\left(\frac{Q}{RT}\right)\right]^m \tag{8}$$

Under isothermal condition and $s^* > s$, $\frac{d\sigma}{d\varepsilon^p}$ can be derived from Eqs. (1) and (7) as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon^p} = ch_0|1 - \frac{\sigma}{\sigma^*}|\mathrm{sign}\left(1 - \frac{\sigma}{\sigma^*}\right) \tag{9}$$

Finally, integration of Eq. (9) leads to

$$\sigma = \sigma^* - \left[(\sigma^* - cs_0)^{1-a} + (1-a)\left(ch_0(\sigma^*)^{-a}\right)\varepsilon^p\right]^{\frac{1}{1-a}} \tag{10}$$

2.2. Determination of model parameters

In the present model, nine parameters of unirradiated Mod 9Cr-1Mo steel for the Anand model are fitted and determined from the uniaxial tensile experimental data [18]. This determination procedure is presented in detail as follows [19],

a) The values of A, Q/R, m, n and $\hat{s}/\xi$ are determined from the constant strain rate and temperature by means of a nonlinear least square fit using Eq. (8).
b) The constants determined in step (a) with constant strain rate and variable temperature can be used to evaluate a series of σ^*