Journal of Materials Processing Technology 239 (2017) 359–369

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Prediction of microstructure and ductile damage of a high-speed railway axle steel during cross wedge rolling

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ARTICLE INFO

Article history:
Received 28 March 2016
Received in revised form 14 August 2016
Accepted 3 September 2016
Available online 5 September 2016

Keywords:
Unified constitutive modeling
Microstructure evolution
Ductile damage
Cross wedge rolling
High-speed railway axle steel
Experimental validation

ABSTRACT

Microstructure and ductile damage have a significant influence on the deformation behavior of high-speed railway axles during hot cross wedge rolling (CWR) and its final performance. In this study, based on the continuum damage mechanics, a multiaxial constitutive model coupling microstructure and ductile damage was established to predict the evolution of microstructure and ductile damage of 25CrMo4 during hot CWR processes. Material constants within the multiaxial constitutive model were determined by Genetic Algorithm (GA) optimization techniques from thermo-mechanical test data. The derived multiaxial constitutive model was embedded into the DEFORM-3D software through a user subroutine. FE simulation of CWR was performed to predict the microstructure evolution and ductile damage. CWR experiments were also carried out to validate the proposed model. The predicted grain size and ductile damage agree well with the experimental results. Good agreements indicate that the derived multiaxial constitutive model is reliable and can be used to predict the evolution of microstructure and ductile damage during CWR process.

1. Introduction

CWR has been used to produce a wide range of stepped axisymmetric components (Ji et al., 2015). High-speed railway axle is one kind of stepped symmetry shaft parts which usually are made of 25CrMo4 (EA4T) due to its good comprehensive performance (Xu et al., 2012). Hot forging processes are usually used to produce high-speed railway axles (Li, 2007). During hot forging, a fine microstructure can be guaranteed under conditions of enough deformation (Baiwei, 2006). Compared with the hot forging, the CWR process is characterized by many advantages, such as lower material and energy consumption but high-quality products (Li et al., 2002). Hu et al. (2006) firstly produced the high-speed railway axles of high precision using CWR technology. Therefore, CWR has been paid more attention as an advanced forming technology to produce high-speed railway axles for those advantages.

Railway axle is one of the critical components in a high-speed train, which works under cyclic rotating and bending conditions (Mancini and Cera, 2008). It is important to obtain high performance such as high fatigue resistance and static/dynamic loading strength for high-speed railway axles. It is shown that coarsening grain and micro-damage have an impact on the high performance of railway axles (Zerbst et al., 2013). The prediction of microstructure and ductile damage evolution can contribute to grain refinement and avoid the appearance of micro-damage by optimizing the process parameters of CWR. It is vital to establish the microstructure evolution and ductile damage model to predict the distribution of grain size and micro-damage in the workpiece during CWR.

Many studies on modeling of microstructure evolution during CWR have been carried out. Wang et al. (2005) established a microstructure evolution model of AISI 5140 for predicting the distribution of grain size in the workpiece during CWR. Zhang et al. (2012) implemented the microstructure model of GH4169 alloy into DEFORM-3D using user defined subroutine for FE simulation of CWR. Zhao et al. (2008) viewed the dynamic recovery as the main softening mechanism and established the dynamic recovery model of 6061 aluminum alloy during CWR. However, little work has been

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http://dx.doi.org/10.1016/j.jmatprotec.2016.09.001
0924-0136/

conducted on developing a unified multiscale constitutive model to describe the interrelationship between different physical variables and predict the distribution of grain size and ductile damage during CWR.

Many ductile damage models also have been developed by extensive researchers. Three types of ductile damage model can be summarized: namely failure criteria (FC), micromechanics-based damage (MBD) model and continuum damage mechanics (CDM) model (Cao, 2015). Teng et al. (2005) assigned a fracture criterion to predict crack formation in the projectile. Bai and Wierzbicki (2008) proposed a new FC model considering both the hydrostatic pressure and Lode dependence. Lou et al. (2014) proposed a ductile damage model to describe the effect of microstructures, Lode parameter, temperature, and strain rate on the ductility of metals. FC model has fewer parameters to determine, and can be applied easily to FE software. However, the application of FC model is limited with regard to the large plastic deformation and complex loading paths (Cao et al., 2013).

Many researchers proposed typical volume cell models using MBD method to account for the effect of ductile damage on material stress softening. Min et al. (2011) applied the modified Gurson-Tvergaard-Needleman (GTN) model to predict the forming limit diagram (FLD) of aluminum alloy 5052-O1 sheet. Malcher et al. (2014) provided an extended GTN model incorporating Lode angle and stress triaxiality upon the prediction of damage location under a low-stress triaxiality. Cao et al. (2015) proposed a Gurson-like nonlinear homogenization-based model considering void shape change and void rotation to predict the distribution of ductile fracture. At a high-stress triaxiality, it is successful to use the MBD method model to predict ductile damage. However, at a low-stress triaxiality, the prediction ability of ductile damage is limited for Gurson-like model (Cao, 2015).

Compared with FC and MBD method, CDM method has advantages of coupling the stress-strain relationship with physical variables of microstructure and damage (Huo et al., 2015). Multiaxial and multiscale constitutive equations coupling microstructure and ductile damage can be established using CDM method. Kachanov (2013) systematically elaborated the basic theory of CDM and its applications in predicting damage of metal forming. Ambroziak (2007) proposed an improved Chaboche elasto-viscoplastic constitutive model coupling the Lemaitre isotropic damage model using CDM method. Lin and Balint (2009) investigated the damage nucleation and growth for a free-cutting steel and developed a ductile damage evolution model using CDM method to predict the damage distribution during hot rolling. Cao et al. (2014) introduced a Lode-dependent enhanced Lemaitre damage model to predict ductile fracture at a low-stress triaxiality.

The aim of presented paper is to predict the distribution of grain size and micro-damage during CWR for 25CrMo4 high-speed railway axle steel. Firstly, a multiaxial and multiscale constitutive model coupling microstructure and ductile damage was established using CDM method. Secondly, the material constants within the model were determined using GA optimization techniques. Thirdly, the derived multiaxial model was implemented into commercial software Deform-3D for FE simulation of CWR. The distribution characteristics of microstructure and ductile damage can be predicted. Finally, hot CWR experiments were carried out to validate the FE simulation results.

2. Development of multiaxial constitutive model

During CWR process a given material passes through different stress-strain 3D states. Multiaxial constitutive equations are developed on the assumption of Von-Mises criteria and isotropic hardening. An energy dissipation rate potential is defined as follows (Lin et al., 2005):

$$\psi = (\frac{A_1}{A_2})\cosh[A_2(\frac{\sigma_e}{1-D} - R - k)] \tag{1}$$

where $\sigma_e = \sqrt{\frac{3S_{ij}^2}{2}}$ represents the effective stress. $S_{ij} = \sigma_{ij} - \delta_{ij}\sigma_{ij}/3$ represents the stress deviators. A_1 and A_2 are material parameters. D represents the amount of ductile damage, varying from 0 (i.e. undamaged material) to 0.7 (i.e. total failure of the material) (Mohamed et al., 2012). R is the isotropic hardening parameter, which is related to dislocation density. k represents initial yield stress, which is a temperature dependent parameter.

Chaboche (2008) proposed the expression of plastic strain rate tensor according to visco-plasticity constitutive theories:

$$\dot{\varepsilon}_{ij}^p = \dot{\lambda}(\partial\psi/\partial\sigma_{ij}) = [3S_{ij}/(2\sigma_e)]\dot{\varepsilon}_e^p \tag{2}$$

where $\dot{\lambda}$ is the plastic multiplier. $\dot{\varepsilon}_e^p$ is the effective plastic strain rate.

Considering the interrelationship between microstructure and ductile damage as well as their influence on the material deformation behaviors, the unified multiaxial constitutive equations for 25CrMo4 using CDM method are established as (Lin et al., 2007a):

$$\dot{\varepsilon}_{ij}^p = [3S_{ij}/(2\sigma_e)]\dot{\varepsilon}_e^p \tag{3}$$

$$\dot{\varepsilon}_e^p = A_1 \sinh[A_2(\frac{\sigma_e}{1-D} - R - k)](\frac{d_0}{d})^{\gamma_1} \tag{4}$$

$$\dot{X} = Q_0[x\bar{\rho} - \bar{\rho}_c(1-X)](1-X)^{\lambda_1} \tag{5}$$

$$\dot{x} = H_1(1-x)\bar{\rho} \tag{6}$$

$$\dot{\bar{\rho}} = A_4(d/d_0)^{\delta_1}(1-\bar{\rho})|\dot{\varepsilon}_e^p|^{\delta_2} - C_r\bar{\rho}^{\delta_3} - [(A_3\bar{\rho})/(1-X)^{\delta_4}]\dot{X} \tag{7}$$

$$\dot{R} = 0.5B_1\bar{\rho}^{-0.5}\dot{\bar{\rho}} \tag{8}$$

$$\dot{d} = G_1(d_1/d)^{\psi_1} - G_2\dot{X}(d/d_0)^{\psi_2} \tag{9}$$

$$\dot{\sigma}_{ij} = E(1-D)(\dot{\varepsilon}_{ij}^T - \dot{\varepsilon}_{ij}^p) \tag{10}$$

$$\dot{D} = \begin{cases} \pi_1(1-D)\dot{\bar{\rho}} + \pi_2\dfrac{D}{(1-D)^{n_1}}(d/d_0)^{n_2}|\dot{\varepsilon}_e^p|^{n_3} & if \eta > -\dfrac{1}{3} \\ 0 & otherwise \end{cases} \tag{11}$$

where superscript "." of individual variables in Eqs. (2)–(11) represents differential with time. Eq. (4) is a function to depict the viscoplastic flow behavior of the material. $(\frac{d_0}{d})^{\gamma_1}$ in Eq. (4) describes the effect of grain size evolution on the visco-plastic flow of material. d_0 represents initial grain size, which can be determined together with A_1 A_2 and γ_1 as a material parameter. Eq. (5) describes the evolution of recrystallization fraction, which is related to the normalized dislocation density $\bar{\rho}$. The normalized dislocation density $\bar{\rho}$ is defined as: $\bar{\rho} = 1 - \rho_i/\rho$, where ρ_i and ρ respectively represents initial dislocation density and real dislocation density during material deformation. $\bar{\rho}_c$ in Eq. (5) represents the critical dislocation density, which is a temperature dependent parameter. When the dislocation density reaches the critical value $\bar{\rho}_c$, given enough incubation time, recrystallization would begin. Q_0 and λ_1 in Eq. (5) are material parameters. Eq. (6) describes the incubation fraction evolution, which controls the recrystallization incubation time. H_1 is a temperature dependent parameter. Eq. (7) is the differential equation of normalized dislocation density $\bar{\rho}$. Eq. (7) is composed of three portions. The first term represents the dislocation multiplication and dynamic recovery. The second term represents the dislocation annihilation due to static recovery. The last term reflects the dislocation density decreases with the increases of recrystallization fraction. δ_1, δ_2, δ_3, δ_4, A_3 and A_4 in Eq. (7) are material parameters. C_r is a temperature dependent parameter. Eq. (8) describes the variation of isotropic hardening, R, with