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A new application of unified constitutive equations for cross wedge rolling of a high-speed railway axle steel

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ABSTRACT

The mechanical properties of 25CrMo4 steel for high-speed railway axles depend on its microstructural evolution during hot cross wedge rolling (CWR). In this paper a set of mechanism-based unified constitutive equations has been determined for the prediction of elastic-viscoplastic material behaviour and microstructural evolution of the 25CrMo4 steel during hot CWR processes. Hot compression tests were conducted using a Gleeble thermo-mechanical simulator at temperatures in a range of 1223–1433 K and at strain rates in a range of 1.0–10.0/s. A set of equations was determined from experimental data of static grain growth, grain refinement and viscoplastic flow using a genetic algorithm (GA) method. Good agreements between the experimental and predicted data were obtained. The determined constitutive equations were implemented into the commercial FE code, DEFORM-3D, via a user defined subroutine and CWR processes were modelled. CWR tests were also carried out and microstructure examinations were conducted. FE simulation results, such as grain size, were compared with those of CWRed parts. Good agreements have been obtained, which shows that the determined constitutive model enables microstructure evolution in CWR processes to be well predicted.

1. Introduction

Cross Wedge Rolling (CWR) has been used to produce a wide range of stepped axisymmetric components (Dong et al., 2000a,b). In CWR the work piece revolves and is deformed in a gap between two contra-rotating rolls, the peripheries of which are wedge-shaped dies. High speed railway shafts are normally made of 25CrMo4 steel due to its good mechanical properties in extreme conditions (Xu et al., 2012). Railway shafts are traditionally formed by hot forging (Cornell, 1950). Given sufficient deformation, grain structure can be refined throughout the whole axle (Cui, 2006) providing high strength and toughness and good ductility. However hot forging of 25CrMo4 steel axles requires multi-step processes, which results in low tool life and high cost (Pater et al., 2006; Li et al., 2002; Dong et al., 1998). Compared with the traditional forging, the benefits of cross wedge rolling are significant: It produces components with higher performance, in shorter time, with less raw material, and at a lower cost. Therefore the CWR technique was firstly used for the production of railway axles in 2006 (Li et al., 2006).

The fatigue resistance (Meng, 2009; Zhang et al., 2012, 2013) and the crack growth resistance (Klinger and Bettge, 2013; Zerbst et al., 2013) of high speed train axles is directly related to grain size of the processed parts. Therefore, it is vital to use the physically-based finite element simulation to predict and control the grain size of CWRed shafts. Much work on finite element modelling of CWR has been reported. Dong et al. (2000a,b) used a three-dimensional FE model to characterize the stress and deformation behaviour with reference to internal defects. Pater (2006) developed a three-dimensional mechanical FE model to simulate the distributions of strain, strain rate, mean stress and rolling load components. However, little work has involved microstructural evolution prediction in FE simulation of CWR processes.

Numerous researchers have focused on the thermal-mechanical properties and material characteristics of 25CrMo4 during hot forming. Xu et al. (2012) investigated the hot deformation behaviour of axial steel deforming at a temperature range of 950 to 1150 °C and strain rates from 0.1 to 20.0/s using a Gleeble thermo-mechanical simulator. Li (2007) obtained a constitutive relationship of 25CrMo4 steel by thermal-mechanical testing for radial forging processes, and optimized the preform based on finite

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element simulation. Little research work was conducted on unified constitutive equations to predict the coupling of viscoplastic deformation and microstructure evolution of the material.

Approaches to modelling microstructure may be classified into four types (Grong and Shercliff, 2002). They are: empirical (Sellars and Whiteman, 1979; Sellars, 1990), advanced statistical (Ai et al., 2003), direct simulation of microstructural evolution (Haghighat and Taheri, 2008; Qian and Guo, 2004) and physically-based internal state variables. The internal state variable method provides a microstructural evolution modelling framework based on the significance of physical parameters of materials, and it can reflect the knowledge of the physical phenomena arising in thermal-mechanical deformation processes (Grong and Shercliff, 2002). It is capable of describing simultaneously correlation between physical variables at different scales and their evolution with time and/or strain. The microstructural parameters, such as grain size, recrystallization fraction and dislocation density, may be selected as individual internal variables. Horstemeyer and Bammann (2010) reviewed the development and usage of internal state variables (ISV) and stated that the ISV equations can be implemented into common CAE codes and thus materials processes can be modelled and optimized. Toloui and Serajzadeh (2009) employed the ISV method and developed a set of microstructural evolution constitutive equations for predicting static recrystallization fraction change after hot strip rolling. Although it is difficult to determine the constants arising in the model due to the complication of the equations, the power of the material model has been demonstrated for real applications. Many researchers (Cao and Lin, 2008; Cao et al., 2008; Lin and Yang, 1999) have provided techniques for solving this problem. Cao and Lin (2008) proposed a novel multi-objective function to eliminate scale differences within the equations and enhanced the efficiency of calculation. This has promoted the use of the ISV method in materials processing applications. More attention has been paid to the use of the ISV method in materials processing applications.

The aim of this paper is to apply the physically-based internal state variable method to 25CrMo4 constitutive modelling, so that microstructural evolution in hot CWR of high-speed railway shafts can be predicted. In this paper, hot compression tests of 25CrMo4 were carried out on a Gleeble thermal-mechanical simulator. A set of unified viscoplastic constitutive equations was calibrated from experimental data of hot compression tests. The determined unified constitutive equations were implemented in the commercial FE code, DEFORM-3D, and microstructural evolution in CWR of a high speed railway axle was predicted. The simulation results of grain size evolution were further validated through CWR tests and conclusions are given at the end of the paper.

2. Experimental procedures

Hot uniaxial compression tests using a thermo-mechanical simulator Gleeble-1500 have been conducted to characterize the viscoplastic flow and microstructural evolution of high-speed railway axle steel 25CrMo4 at high temperatures. The chemical composition of the steel is shown in Table 1. Cylindrical compression specimens of 8 mm in diameter and 15 mm in length were machined from the original ingot, as shown in Fig. 1.

Table 1
Chemical composition of 25CrMo4 (% in weight).

C	Mn	Si	P	S	Cr	Ni
0.28	0.77	0.34	0.01	0.004	1.16	0.07
Mo	V	Cu	O	H	Fe	
0.23	0.02	0.12	0.0014	0.00016	Balance	

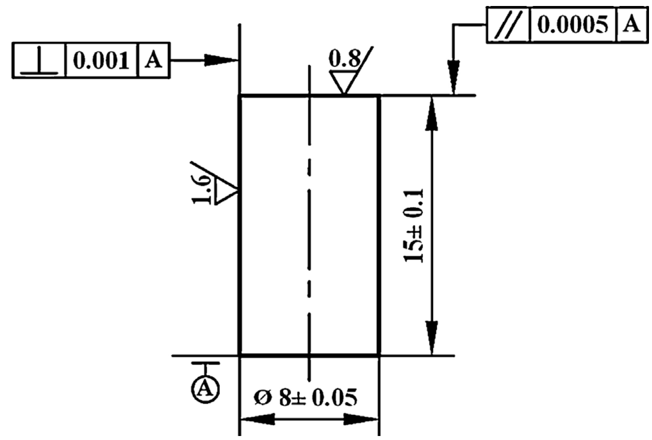

Fig. 1. Dimensions of specimens (unit: mm).

Two types of tests, i.e. static grain growth tests and grain refinement tests were carried out under isothermal conditions. Static grain growth tests were used to measure austenitic grain growth after deformation, and grain refinement tests were used to study the effects of strain and strain rate on material recrystallization and grain size evolution. Strain–stress curves of the material at different temperatures and strain rates were also obtained from these experiments.

2.1. Static grain growth tests

An experimental programme for static grain growth tests is shown in Fig. 2. Each specimen was heated to 1253 K at a heating rate of 20 K/s and then heated to 1273 K at a heating rate of 2 K/s to prevent overshooting. The specimen was soaked at 1273 K for 3 min to obtain complete austenitization. Subsequently, a specimen was either heated or cooled to one of the following deformation temperatures T_1: 1223 K, 1273 K, 1323 K or 1373 K. Then the specimen was compressed to a predefined axial engineering strain of 0.6 (corresponding to 60% reduction in height) at a strain rate of 1.0/s at the deformation temperature T_1, which ensured the occurrence of recrystallization and thus refinement of the initial austenitic grain size. During the deformation, the real strain was measured using a C-Gauge (measuring specimen diameter changes) at the central section of the testpiece. Due to the buckling and other effects, the measured local strain is normally higher than the average axial

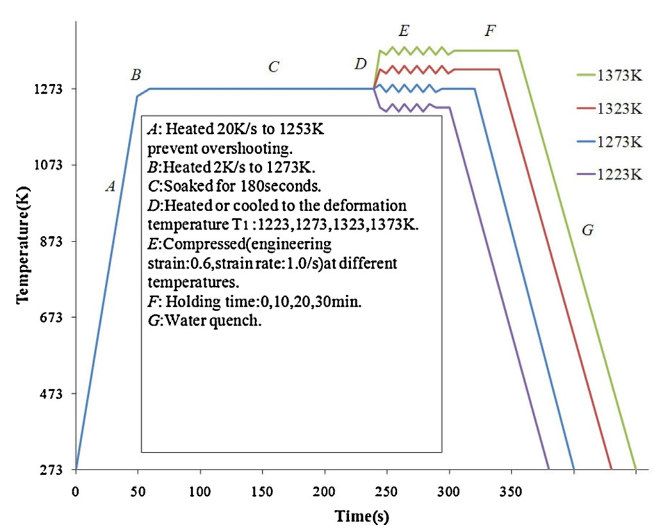

Fig. 2. Temperature profiles for static grain growth tests.