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A physically based constitutive model of As-forged 34CrNiMo6 steel and processing maps for hot working

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ABSTRACT

In this paper, isothermal compression tests of as-forged 34CrNiMo6 steel were carried out using a Gleeble–1500D testing machine for the deformation temperatures ranging from 1173 K to 1473 K and strain rates ranging from 0.005 s^{-1} to 1 s^{-1}. Flow stress curves were obtained under the given conditions. Using regression analysis, the hyperbolic sine law Zener–Hollomon equation was established, and the hot deformation activation energy was obtained as 376.5 kJ mol^{-1}. To predict the flow stress for hot working, a constitutive model including work hardening-dynamic recovery modeling and the corresponding Avrami–type dynamic recrystallization equation was established. The work hardening-dynamic recovery model was derived based on the evolution equation of the dislocation density and the work hardening rate. All parameters in this model can be expressed in terms of the Zener–Hollomon parameter. Our results indicated that the proposed constitutive model had high prediction accurately for hot working of as-forged 34CrNiMo6 steel. Furthermore, the optimized processing parameters for the as-forged 34CrNiMo6 alloy steel were determined based on the processing maps and microstructure.

1. Introduction

34CrNiMo6 steel is a typical medium-carbon low-alloy steel with high strength, which is widely used for manufacturing of automobile connecting rods, large-scale crankshafts and forged rotors. Hot plastic forming is usually chosen for these products due to the lower plasticity of 34CrNiMo6 steel at room temperature. Moreover, microstructural evolution strongly affects the mechanical properties of the product during the hot deformation process. To obtain the thermomechanical processing parameters and optimize the hot working process for 34CrNiMo6 steel alloys, it is necessary to study their constitutive models and processing maps.

Generally, various constitutive models including the phenomenological and physically based models and artificial neural networks (ANN) have been established based on different deformation parameters (strain, strain rate and deformation temperature) [1]. In previous investigations, the use of phenomenological constitutive equation has been the common modeling approach for predicting the flow stress at elevated temperatures in which Sellars-Tegart constitutive equations, Johnson-Cook model and compensated Arrhenius model are used to represent the system [2–5]. These models contain only a few material constants, which could be determined from the uniaxial hot compression tests. However, these models ignore the influence of the dislocation density on the flow stress. Since the dislocation density is an important parameter in thermomechanical processing, these constitutive models do not relate the strain, strain rate and deformation temperature. Hence, a physically based constitutive model has been developed in recent years, correlating work hardening, dynamic recovery and dynamic recrystallization [6–10]. The predictions obtained in these studies are essentially in agreement with the experimental results, revealing that these constitutive models can accurately describe the flow stress at hot deformation conditions.

The processing map based on dynamic material model (DMM) has been generalized to optimize the working parameters of metallic materials and to control the microstructure during hot deformation [11–13]. Shi et al. [14] studied the hot deformation behavior of GH4945 superalloy and the optimum hot deformation parameters were obtained based on the processing maps. Chen et al. [15] determined the optimal processing parameters for the PM 8009Al/Al2O3 alloy based on the processing maps and the microstructure. Zhou et al. [16] divided the processing maps of the 25CrMo4 alloy into three domains and optimized the parameters for the forging process. These studies have revealed that a processing map is an effective technique for the optimization of the hot working parameters and for the analysis of microstructural evolution mechanisms during hot deformation.

Prior research on 34CrNiMo6 steel has been focused on the heat

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treatment process, processing properties, and fatigue [17–20]. Maniee et al. [21] reported on a comparative study of tribological and corrosion behavior of plasma nitrided 34CrNiMo6 low-alloy steel in different conditions. Hu et al. [22] proposed that the processing properties of 34CrNiMo6 steel were the same as those of 18Cr2Ni4WA and suggested that 34CrNiMo6 steel could be substituted for the 18Cr2Ni4WA used for manufacturing of crankshafts. Xu et al. [23] investigated the brittle and plastic fracture behaviors of the 34CrNiMo6 alloy and reported that the ductile-brittle transition temperature of the 34CrNiMo6 alloy was between −50 °C and −70 °C, and the fracture form gradually transformed into brittle fracture below −70 °C and to ductile fracture above −50 °C. Branco et al. [24] investigated low-cycle fatigue behavior of 34CrNiMo6 steel and found microstructural defects with relatively large size of 2–30 μm at the surface or in the interior of the specimens. Cochet et al. [25] investigated the heat treatment of the 34CrNiMo6 steel used for mooring shackles and constructed a model that yielded a very good representation of the material properties. These achievements made a significant technical contribution to the production and manufacture of 34CrNiMo6 products in the heavy forging industry. However, to date, few investigators have focused on the development of a constitutive model and the optimization of the hot working process of the 34CrNiMo6 steel.

In this study, as-forged 34CrNiMo6 steel was investigated by isothermal hot compression tests at various temperatures and strain rates. A physically based flow stress constitutive model was established, and its predictions were compared to the experimental data. Moreover, the hot processing maps at different strains were established based on the dynamic materials model. The optimal hot forming parameters of the as-forged 34CrNiMo6 were obtained based on the processing maps and microstructure observation. It is desired that the conclusions will provide some guidance for the hot working process of as-forged 34CrNiMo6 steel.

2. Experimental procedure

The chemical composition of the as-forged 34CrNiMo6 steel investigated in this work is given in Table 1, and the initial microstructure is shown in Fig. 1. The average grain size is approximately 180 μm. Experimental samples with the diameter of 8 mm and height of 12 mm were cut from the as-forged 34CrNiMo6 alloy bar after a homogenizing treatment as shown in Fig. 2. To study the dynamic recrystallization behavior of 34CrNiMo6 steel, the uniaxial hot compression experiments were conducted on a Gleeble-1500D thermal simulator according to the schematic representation of hot compression shown in Fig. 3. Considering the effect of the friction between the specimen and the dies, graphite spacers were placed on both ends of the sample to reduce the friction between the indenter and the sample. Initially, the specimens were heated to 1473 K at the rate of 10 Ks^{-1} and were kept at that temperature for 2 min. In the second stage, the specimens were cooled to the deformation temperature at the rate of 5 Ks^{-1} and were kept at that temperature for 1 min to eliminate the temperature gradient. Next, the tests were performed to the true strain of 0.8. The temperature range was 1173–1473 K, and the temperature interval was 50 K. The strain rates were 0.005, 0.01, 0.1 and 1 s^{-1}. Furthermore, the deformed specimens were cut along the axial direction by using low-speed one-way walk wire cut electrical discharge machining (LS-WEDM). Finally, the samples were prepared and chemically etched with a saturated aqueous picric acid solution to observe the morphology of austenite using an optical microscope.

Table 1
Chemical composition of as-forged 34CrNiMo6 steel (wt.%).

C	Si	Mn	Cr	Ni	Mo	P	S	Fe
0.34	0.28	0.58	1.53	1.51	0.23	0.008	0.004	Bal

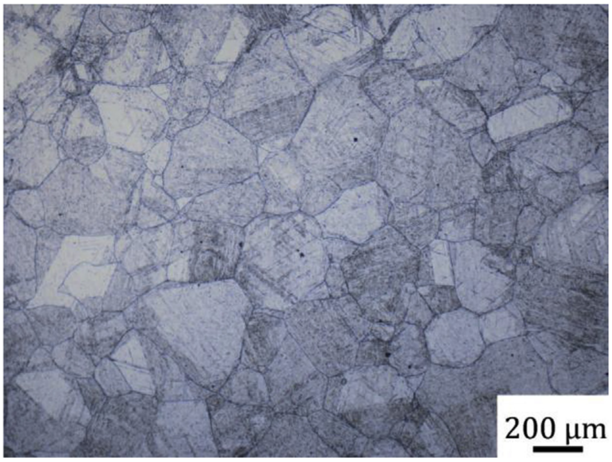

Fig. 1. Initial microstructure.

3. Results and discussion

3.1. Flow behavior

It is well-known that the interfacial friction between the specimen and dies can affect the experimental result. The schematic plot of a sample before and after the compression is shown as Fig. 4. Generally, before correcting the flow curves, the friction effect should be evaluated by a barreling coefficient as reported by Roebuck [26].

$$B = hR_M^2/h_0R_0^2 \tag{1}$$

where B is the barreling coefficient, h is the height of deformed specimens, R_M is the maximum radius of deformed specimens, and h_0 and R_0 are the initial heights and radius, respectively. When $1 < B \le 1.1$, the measured flow stress curves could be considered as true stress-true strain curves and may not be correct; when $B > 1.1$, the measured flow stress curves must be corrected.

Based on the above theory, the dimensions of the specimens before and after the deformation are measured at the various deformation conditions, and the B values are calculated, as shown in Table 2.

It can be observed from the data presented in Table 1 that because all B values are smaller than 1.1, the measured flow stress under all the deformation conditions could not be corrected.

The typical flow stress curves of as-forged 34CrNiMo6 steel under the temperatures in the 1173–1473 K range with the strain rates ranging from 0.005 to 1 s^{-1} are shown in Fig. 5. It can be seen from Fig. 5 that most of the flow stress curves show typical complete dynamic recrystallization (DRX) behavior. Normally, a typical DRX behavior exhibits three distinct stages with increasing strain at elevated temperature as shown in Fig. 6. In the initial stage, work-hardening (WH) dominates, and the flow stress increases sharply to the stress value corresponding to the critical strain of dynamic recrystallization. In the second stage, the softening mechanism gradually becomes dominant. The flow stress curve reaches the maximum value and then decreases until stabilizing because dynamic recovery (DRV) and dynamic recrystallization (DRX) play a noticeable role in softening behavior in this stage. In the final stage, most of the curves tend to retain a dynamic balance among the HW, DRX and DRV. Similarly, the characteristics of these flow stress curves can also be observed in the case of other alloys [4,27,28]. These curves correspondingly can be explained by considering the microscopic mechanism. In the initial stage, the HW and DRV have the same effect on the dislocation density [29]. Considering that the 34CrNiMo6 steel is an alloy with a low stacking fault energy, the DRV is weaker than the work hardening, resulting in the dislocation multiplication rate being higher than the dislocation annihilation rate. Therefore, the flow stress increases intensely with increasing strain for