Materials and Design 66 (2015) 309–320

Contents lists available at ScienceDirect

Materials and Design

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

Experimental study and numerical simulation of dynamic recrystallization behavior of a micro-alloyed plastic mold steel

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ARTICLE INFO

Article history:
Received 22 June 2014
Accepted 25 October 2014
Available online 4 November 2014

Keywords:
Dynamic recrystallization
Material genome data
Hot compression
Finite element method
Plastic mold steel

ABSTRACT

To research the dynamic recrystallization (DRX) characteristics of a micro-alloyed plastic mold steel (MnCrNb, SDP1®), a series of hot compression tests using Gleeble-3500 thermo-mechanical physical simulator are implemented under different temperatures and strain rates. In addition, the microstructure of specimens after hot compression tests are also observed by optical microscope. Combined Estrin and Mecking mathematic model (EM) with Avrami equation, the important material genome data of SDP1, such as DRX kinetic model, dynamic recovery (DRV) kinetic model and grain size evolution model, is established by the inverse analysis of flow stress curves to estimate the microstructure evolution during hot deformation. Furthermore, combined with the obtained material kinetic model, an elastic–plastic finite element (FE) model is built to simulate the microstructure evolution of SDP1 during the single-pass hot compression and compare with the experimental results. The results indicate that the simulation results agree well with the experimental ones, which verifies the availability of obtained material genome data. The finite element method (FEM) is an effective approach to analyze the hot compression process, which can provide a theoretical guidance and optimization scheme for making the more reasonable hot working procedure.

1. Introduction

During the fabrication process of large plastic mold steel blooms, the low impact toughness of production is one of the major quality issues. By analyzing the microstructure of production, the main causes for this phenomenon can be attributed to the coarse grain and nonuniform grain size. As the most important manufacturing process of plastic mold steel, microstructure control in free forging process determines product quality directly. The discontinuous dynamic recrystallization (DRX) occurred during hot deformation process is one of the most important microstructure evolution behaviors. Because the DRX behavior occurred in forging process can refine the grain size, enhance the structural homogeneity and improve the mechanical property of production, it has attracted widespread attention. Recently, there are a large number of literatures on the establishment of DRX kinetics model and the computer simulation of microstructure evolution [1–8]. McQueen and Ryan [9] introduced Zener–Hollomon parameter to establish the creep equation to describe the influence of deformation condition on DRX behavior. Since then, this method is widely used to establish DRX kinetic model. Based on this method, Reyes-Calderón et al. [10] employed the metallographic analysis and the numerical regression method to research the microstructure evolution of different micro-alloyed TWIP steels. In addition, Reyes-Calderón et al. [11] also used EBSD system to analyze the microstructure evolution under different deformation conditions and suggest that Ti is the most efficient micro-alloyed element to refine grain size. Soltanpour and Yanagimoto [12] established a series of hot working kinetic models of a Cr–Mo–V steel, such as DRX and static recrystallization (SRX). These kinetic models were also defined as the material genome data to describe the hot deformation behavior and microstructure evolution. Combining the material genome data with finite element method (FEM), Cho et al. [13] predicted microstructure evolution of hot die steel during the high-temperature deformation process. Bennett et al. [14] carried out a coupled thermo-mechanical finite element analysis of isothermal axisymmetric compression and to compare the levels of relative stress error during each hot compression test. In addition, Bennett [15] also compared different material models using an FE model of the spike-forging process and made recommendations. Evans et al. [16,17] determined of the hot working properties of alloys and estimated the structural changes during hot working by FEM. Furthermore, with the improvement of computer technology, many numerical techniques, such as Monte Carlo method and cellular

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http://dx.doi.org/10.1016/j.matdes.2014.10.076
0261-3069/

automata method, are also widely used to simulate the hot deformation. For example, Hesselbarth and Göbel [18] introduced a cellular automata model to simulate the recrystallization behavior and discussed the influence of model parameters on the nucleation kinetics. Ding and Guo [19] used a new approach of combining the cellular automata method with theoretical principles of DRX to simulate the microstructural evolution of DRX during thermo-mechanical processing. Zheng et al. [20] developed a modified CA model to predict the post-dynamic austenite-to-ferrite transformation and reverse transformation in a low-carbon steel. Recently, the multiscale coupling simulation as a novel numerical algorithm [21,22] is adopted to predict the topological and morphological evolution of microstructure during the hot deformation process. Das et al. [21] presented a modeling strategy that combines neuro-fuzzy methods to define the material model with cellular automata representations of the microstructure, it can deal with the large deformations of metal processing. Takaki et al. [22] developed a novel multiscale hot-working model by coupling the multi-phase-field DRX model and large deformation elastic–plastic FEM to evaluate the microstructure evolution and macroscopic mechanical behavior. However, it must be point out that an accurate acquisition of material genome data is the basic and essential requirements for any numerical simulation.

Based on the above motivation, the plastic mold steel SDP1 is employed to study the DRX characteristic during a isothermal hot deformation process. For this purpose, the hot compression tests are performed on a Gleeble-3500 thermo-mechanical physical simulator under different temperatures and strain rates. The DRX kinetic models of SDP1 regarded as the important material genome data are established by the regression analysis of flow stress curves obtained from the hot compression tests. In addition, the microstructure of specimens after hot compression tests are also be observed by optical microscope. Combined with the material genome data of SDP1, an elastic–plastic FEM model of hot compression test is built to evaluate the microstructure evolution and the macroscopic mechanical behavior, to verify the validity of the obtained material genome data and then to provide a theoretical guidance for making the more reasonable hot working procedure.

2. Experimental procedure

2.1. Experimental material and hot compression procedure

The material used in the present investigation is as-forged micro-alloyed plastic mold steel (MnCrNb, SDP1®) and its normal chemical composition is given in Table 1. To research its dynamic recrystallization (DRX) characteristics, a series of isothermal uniaxial hot compression tests are performed using Gleeble-3500 thermal simulator under different temperatures and strain rates. Initially, the test material is preheated to 1100 °C and held 2 h to obtain a homogeneous equiaxial grain structure and then cut into a cylindrical rod 12 mm long and having a diameter of 8 mm. Fig. 1 gives the schematic diagram illustrating the hot compression procedure, which consists of the following steps:

- *Heating:* specimen is heated to 1200 °C with a heating rate of 5 °C/s and then held 120 s to ensure uniform temperature throughout the specimen.

Table 1
Normal chemical composition of SDP1 plastic mold steel (wt.%).

Element	C	Cr	Mn	Mo	Si	N	Nb	Fe
wt.%	0.30	1.4	1.9–2.5	0.2–0.35	0.2	0.008	0.035	Bal.

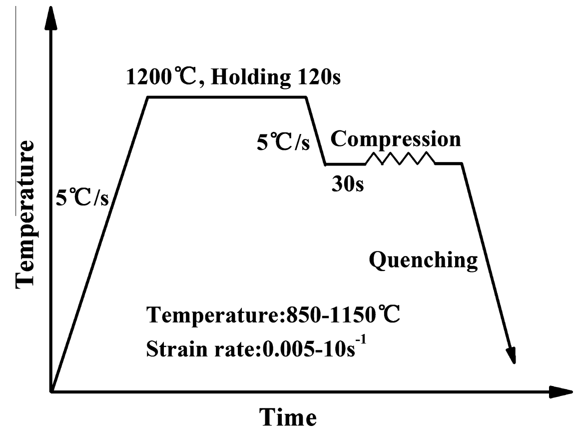

Fig. 1. Schematic diagram of SDP1 hot compression test.

- *Compression:* different hot deformation condition is adopted with the range of deformation temperature from 850 °C to 1150 °C and the strain rate from 0.005 s^{-1} to 10 s^{-1}.
- *Quenching:* specimen experiences a rapid cooling to keep the morphology of high temperature austenite microstructure after compression.

The surface of hot compression specimen used for metallographic observation is perpendicular to the compressed side. The austenite grain boundary is etched by the over saturated solution of trinitrophenol. The average grain size of specimen under different hot deformation conditions is calculated by a volume average of the grain using the line intercept method.

2.2. Experimental results of hot compression

Fig. 2 gives the flow stress curves of SDP1 under different hot deformation conditions. It could be seen that, under the conditions of high temperature and low strain rate, the flow stress increases rapidly with increasing strain before reaching the peak value (namely, peak stress) and subsequent decreases until a steady state. While, under the condition of low temperature and high strain rate, the peak stress is inconspicuous because DRX has not been completed yet. The flow stress curve of SDP1 exhibits the typical characters of DRX and dynamic recovery (DRV).

3. Establishment of material model

3.1. Zener–Hollomon parameter

To reveal the underlying relationship among the hot compression conditions, McQueen [23–25] introduced the Zener–Hollomon parameter to study the influence of deformation conditions (i.e. strain, strain rate and temperature) on DRX behavior. It can be described by the following equation [26–28]

$$Z = A[\sinh(\alpha\sigma_p)]^n = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \quad (1)$$

where Z is the Zener–Hollomon parameter. A, α and n are material constants. R, Q, $\dot{\varepsilon}$ and σ_p are gas constant, hot deformation activation energy, strain rate and peak stress, respectively. As claimed in many pioneering works focused on the DRX behavior [9,10,23], all material constants in Eq. (1) can be verified by regression analysis on the flow stress curves of SDP1 (see Fig. 2). Fig. 3 demonstrates the relationship among the strain rate $\dot{\varepsilon}$, peak stress σ_p and temperature T under different hot compression conditions,