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Analysis of dynamic recrystallization behaviors in resistance heating compressions of heat-resistant alloy by multi-field and multi-scale coupling method

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ABSTRACT

The deep understanding of the dynamic recrystallization (DRX) behaviors by grain morphology analysis in an electrical–thermal–mechanical coupling process for a heat-resistant alloy involves a multi-field and multi-scale dynamic coupling issue. As for SNCrW austenitic heat-resistant alloy, based on the true stress–strain data the DRX volume fraction evolution kinetics including a modified Avrami type equation, and a modified version of *meso*-scale cellular automaton (CA) method with Laasraoui-Jonas hardening and recovery models were solved. The multi-field and multi-scale coupling finite element (FE) model was developed by implanting the solved DRX kinetics model and CA model into the electrical–thermal–mechanical multi-field coupling method. Following which, a series of simulations corresponding to different strain rates and temperatures were implemented. The simulated results show that the mean grain size and DRX volume fraction increase with the increase of temperature, and decrease with the increase of strain rate. The microstructural evolution during the whole forming process were illustrated and described numerically. Finally, the simulated grain morphology was validated by metallography observations. The average relative deviation of grain size between experiment and simulation results is limited in 7.47%.

1. Introduction

SNCrW, a typical austenitic heat-resistant alloy, possesses superior elevated temperature performance such as strength, creep strength, and intergranular corrosion resistance [1,2]. It is widely applied in most of diesel engine components, especially in exhaust valves which are always prepared by an electric upsetting process. As for this alloy, Quan et al. [1] constitutively modeled the evolution of dynamic recrystallization (DRX) volume fraction by a modified Avrami type equation based on the true stress-strain data acquired from a series of resistance heating isothermal compressions. Quan et al. [3] also constructed a series of processing maps at different true strains by superimposition of power dissipation maps and instability maps, and then DRX-predominant parameter windows with higher power dissipation efficiency were identified. The previous work of Quan et al. [1,3] focused on the flow behaviors, and hot intrinsic workability of SNCrW alloy. By now, it is commonly believed that the grain refinement induced by DRX contributes to the mechanical property enhancement of an alloy, and the analysis of the grain morphology evolution corresponding to different deformation conditions contributes to the mechanical performance adjustment [4]. Nevertheless, it is extremely difficult to dynamically observe the grain morphology evolution process in a physical experiment, while the numerical analysis based on finite element (FE) method provides an efficient solution.

In the 80s of last century, Packard et al. [5] firstly introduced a meso-scale cellular automaton (CA) method into material science field. By now, CA method has been extensively developed to simulate the grain morphology evolution process involving different mechanisms such as DRX, dynamic recovery (DRV), grain growth, grain deformation, etc. [6–8]. Goetz et al. [9] was the first to simulate the grain morphology evolution during the DRX process by CA method in 1998. Liu et al. [10] established a CA model to simulate the DRX process in a Ni-based superalloy, and described the relationships between the average size of dynamically recrystallized grains and the steady-state flow stress. Chen et al. [11] aimed to develop a CA model with a topology deformation technique for simulating the grain variations of 30Cr2Ni4MoV rotor steel during the austenitizing and hot compression processes. Ding et al. [12] developed a CA model on the basis of fundamental metallurgical principles, by which the grain morphology evolution in plastic flow was simulated for an oxygen free high

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conductivity (OFHC) copper. In summary, all the reported investigations focus on the meso-scale analysis in a thermal-mechanical coupling issue, while few attention was paid to the meso-scale analysis in an electrical-thermal-mechanical coupling problem due to the difficulty in establishing a multi-field and multi-scale dynamic coupling FE model. In a resistance heating isothermal compression, a specimen was heated up to a certain temperature by self-resistance and a passing current flux, and then it was compressed by a hydraulic pressure [13]. The analysis of DRX behaviors in a resistance heating isothermal compression is obviously a typical electrical-thermal-mechanical multi-field and multi-scale coupling problem [14]. Consequently, solving the modeling issue is significant to analyze, control and adjust the grain morphology in any resistance heating forming process.

This work solved the modeling issue in a resistance heating isothermal compression process. In its modeling process of multi-scale coupling issue, a modified version of CA model with Laasraoui-Jonas hardening and recovery models, was implanted into the multi-field coupling method. The developed multi-field and multi-scale coupling FE model was applied to simulate the grain morphology evolution in a series of resistance heating isothermal compression processes. Moreover, the FE analysis was validated by the microstructure observations. The comparisons between experimental statistics and simulation results indicated that the average deviation was limited in 7.47%. The essential stress-strain data for modeling come from a series of such compression tests conducted in a temperature range of 930–1130 °C and a strain rate range of 0.01–10 s^{-1}, on Gleeble-1500 thermo-mechanical simulator.

2. Experimental procedures

The material selected in this work is as-extruded SNCrW austenitic heat-resistant alloy, whose compositions are (wt.%) as follows: C 0.25, Si 1, Cr 20, Ni 10, M 1, W 2, Fe (balance). Twenty-one specimens with a diameter of 8 mm and a height of 12 mm were separated from an as-extruded bar by wire-electrode cutting. As shown in Fig. 1, the experimental procedures correspond to a homogenization cycle and an isothermal hot compression cycle (heating, temperature-holding and isothermal compression periods) in twenty specimens. All specimens were homogenized in a furnace by keeping at the temperature of 1100 °C for 12 h. In all resistance heating isothermal compression tests, a thermo-mechanical simulator, Gleeble-1500, with a high speed heating system, a servo hydraulic system, a digital control system and a data acquisition system, was used. Before a compression, two thermocouple wires were welded on the middle surface of a specimen to collect timely temperature signal feedback and bridge a current-adjusting loop. When a specimen was placed on the holding device, two tantalum foils with a diameter of 20 mm were put between the cylindrical specimen and anvils to reduce friction in material flow. In the following, twenty specimens were respectively resistance heated to a specified temperature at a heating rate of 10 °C/s and held at this temperature for 180 s to eliminate internal temperature gradient. Subsequently, each specimen was compressed with a fixed height reduction of 60% under different temperatures (930 °C, 980 °C, 1030 °C, 1080 °C and 1130 °C) and strain rates (0.01 s^{-1}, 0.1 s^{-1}, 1 s^{-1} and 10 s^{-1}). After each compression, the deformed specimen was quickly quenched by water to retain the deformed grain morphology at an elevated temperature. It is worth noting that one specimen without isothermal compression was considered as the as-received specimen for original grain morphology observation. Then, all the deformed specimens and the non-deformation one were sectioned by wire-electrode cutting along their cylinder axes, following which, the cutting surfaces went through standard polishing, etching and corroding. The etchant was as follows: 10% HF, 30% HNO3 and 60% H2O. Eventually, the grain morphology at the billet center was detected by the metallurgical microscope.

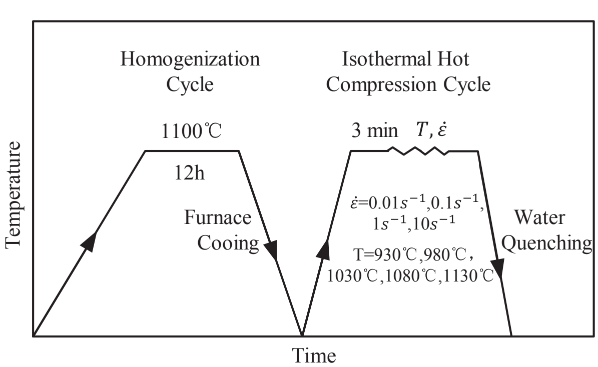

Fig. 1. Experimental procedures of compression tests.

During the resistance heating isothermal compressions, the variations of stress and strain data were monitored in real time. The transferring from the collected nominal stress-strain into true stress-strain is kept in line with the following formula: $\sigma_T = \sigma_N(1-\varepsilon_N)$, $\varepsilon_T = \ln(1-\varepsilon_N)$, where σ_T is the true stress, σ_N the nominal stress, ε_T the true strain and ε_N the nominal strain.

3. Modeling on DRX behaviors

3.1. Modeling on evolution behaviors of DRX volume fraction by stress-strain curves

3.1.1. Characteristics of true stress-strain curves

Three metallurgical phenomena including work hardening (WH), DRV and DRX, exist during a plastic deformation process, and they are indicated by stress-strain curves in Fig. 2. As for a WH-type stress-strain curve, stress increases rapidly and continuously to a limit value due to the predominant effect of WH. As for a DRV-type stress-strain curve, stress speedily increases to a saturated value at the initial stage of deformation, then the saturated value is maintained till end of deformation indicating a balance WH and DRV. As for a DRX-type stress-strain curve, stress increases rapidly to a peak value, following which it decreases gradually to a statured value since reaching the balance between DRX and DRV. The true stress-strain curves of SNCRW alloy under different temperatures (930–1130 °C) and strain rates (0.01–10 s^{-1}) are shown in Fig. 3 [1]. It is obvious that both deformation temperature and strain rate have noticeable influence on the flow stress of SNCRW heat-resistant alloy. The true stress-strain curves of 930–1030 °C exhibit a single peak followed by a distinct downtrend of true stress, which implies the occurrence of DRX. While in the curves of 1080–1130 °C, the single peak is followed by a steady stage. The characteristics of true stress-strain curves support that the curves of 930–1030 °C are considered as DRX-type, and the curves of 1080–1130 °C are considered as DRV-type. Therefore, in this work, the

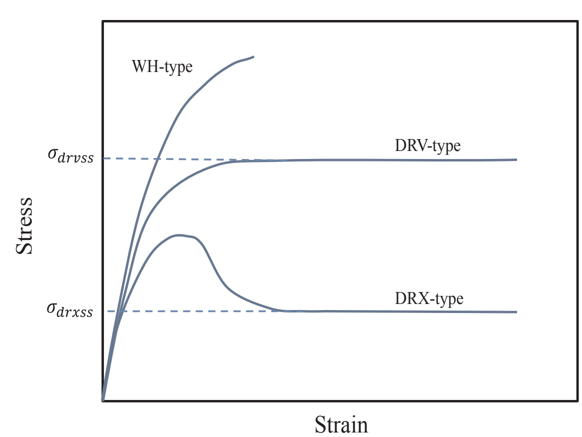

Fig. 2. Typical stress-strain curves corresponding to three metallurgical phenomena.