

Technical Paper

Investigation on metadynamic recrystallization behavior in SA508-III steel during hot deformation

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ARTICLE INFO

Article history:

Received 14 December 2016

Received in revised form 8 July 2017

Accepted 10 July 2017

Keywords:

SA508-III steel

Metadynamic recrystallization

Kinetic equation

Microstructure

ABSTRACT

The metadynamic recrystallization (MDRX) behavior of SA508-III steel was investigated by isothermal double-hit hot compression tests at forming temperatures of 950–1250 °C, strain rates of 0.001–0.1 s⁻¹ and the inter-stage delay time of 1–300 s. Experimental results show that the effects of forming temperature and the strain rate are significant, while the pre-strain and initial grain size are less on metadynamic recrystallization behavior of SA508-III steel. Based on the experimental results, the kinetic equations and the grain size model for metadynamic recrystallization of SA508-III steel were established. Comparisons between the experimental and predicted results were carried out. The predicted results agree well with the experimental data, which indicates that the proposed kinetic equations can give a reasonable estimation of the softening behavior for this steel. Furthermore, by implementing the established kinetics and microstructural evolution equations of MDRX into commercial FE software, the hot forging process of SA508-III steel can be designed and optimized through numerical simulation.

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1. Introduction

SA508-III (ASME SA508 class III) steel has been extensively used as the shell of nuclear reactor pressure vessels and steam generators owing to its excellent toughness, high weldability and superior resistance to irradiation embrittlement. Nuclear power equipment is conventionally made of heavy forged parts [1,2]. The manufacturing process requires a relatively long period of time, in terms of multi-stage or multi-pass. During the interpass time, the materials often subject to complex strain, strain rate, and temperature histories. The metals and alloys always subject the dynamic recovery (DRV), dynamic recrystallization (DRX), static recrystallization (SRX), and metadynamic recrystallization (MDRX) in industrial forging processes. Meanwhile, microstructural changes of the materials during the hot forming process in turn affect the mechanical characteristics of the forging material. When strain in the first pass exceeds the critical strain of DRX and the metals and alloys after hot deformation are kept at high temperature, the MDRX takes place by continuous growth of the nuclei formed by DRX during deformation [3–12]. Therefore, the MDRX

behavior significant reduces stress in following pass and refines grain size during the hot forming process.

To date, the double-hit hot deformation test method has been widely used to investigate MDRX behavior of metals and alloys. Meanwhile there are many studies on mathematical modeling of MDRX softening and grain size evolution by using the hot torsion test [4,13–16]. Roucoules and Hodgson [4,13] investigated MDRX softening behavior of austenite for a Mo-Ti steel, and the importance of MDRX in hot rolling was assessed by carrying out simulations of a typical metadynamic recrystallization controlled rolling (MDRCR). Manshadi [7], Cho [14], Stewart [15] and Taylor [16] et al. investigated the MDRX behavior and established the models of MDRX kinetics and microstructure evolution for AISI 304 steel under different tests condition. Other researches, by using double-hit hot compression tests, Elwazri et al. [4,5], Lin et al. [8,9] for 42CrMo steel, Chen et al. [10,11] for 30Cr2Ni4MoV steel, Laasraoui et al. [17] for HSLA steel, Liu [18] for 300M steel and Peng [19] et al. for Q345 B steel investigated the effect of deformation parameters on softening and predicted the MDRX softening behavior under hot working conditions in multi-stage compression by the offset-stress method. All these models established based on the experimental results can be used to predict the softening fraction and grain size during multi-stage hot deformation.

In view of the wide application of SA508-III steel in the component manufacturing and servicing processes of nuclear reactor

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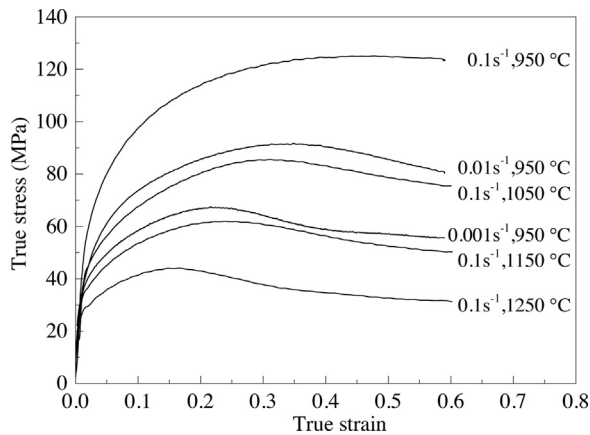


Fig. 1. Flow stress-strain curves of the SA508-III steel in different temperatures and strain rates for single hot compression tests.

pressure vessels and steam generators, there are many studies on the studied steel. Lee et al. [20] established the relationship between composition-structure-mechanical properties. Kim et al. [21] investigated the failure behavior of the weld heat-affected zones and strain aging and fatigue crack propagation under certain experimental conditions, and also developed new heat treatment processes to improve toughness for SA508-III steel. Sun et al. [1] and Dong et al. [2] established the DRX constitutive equations and formulated the microstructure evolution models under hot single compressive tests. However, there are few report on microstructure evolution and the kinetic modeling of MDRX behavior in the SA508-III steel during the hot forming process.

The objective of the present work is to investigate the MDRX behavior of SA508-III steel over a wide range of temperatures, strains and strain rates by double-hit hot compression tests. The effects of forming temperature, strain rate, pre-deformation degree, initial austenitic grain size and inter-stage delay time on the MDRX grain size and distribution were discussed in detail, and the kinetics and microstructural evolution equations were developed to predict the softening fractions and grain size, respectively. Comparisons between the experimental and predicted results were carried out.

2. Experimental material and procedures

2.1. Material and experimental equipment

Chemical composition (wt.%) of commercial SA508-III steel is as following: 0.18C-1.4Mn-0.79Ni-0.14Cr-0.51Mo-0.005V-0.22Si-0.024Al-0.0123N-0.005P-0.003S-0.04Cu-0.008Co-0.004As-0.0123N-(bal.)Fe. Cylindrical specimens were machined with a diameter of 10 mm and a height of 15 mm. In order to minimize the frictions between the specimens and die during hot deformation, thin graphite flakes were laid between the punch head and the specimen head. The specimens were resistance-heated by thermo coupled-feedback-controlled AC current. In order to study the progress of MDRX, double-hit compression tests were carried out on a servo-hydraulic Gleeble-1500D thermo-mechanical simulator.

2.2. Deformation schedules

In order to investigate the effects of strain on the softening behavior, three different deformation pre-strains (0.35, 0.45 and 0.55) were applied. As shown in Fig. 1, a series of typical true stress-true strain curves were obtained by single hot compression tests under different strain rates and temperatures in our previous work

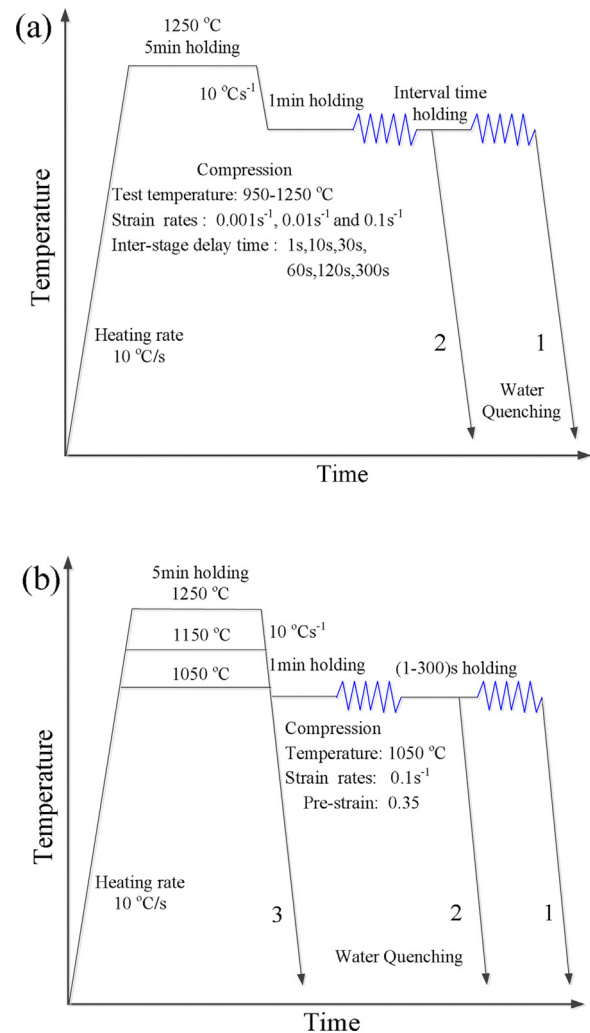


Fig. 2. Experimental procedure for double-hit hot compression tests. (a) considering the effects of deformation parameters on the softening and the austenite grain size, (b) considering the effects of initial austenite grain size.

published very recently [2]. The critical stresses (σ_p) were derived from the inflection points of the stress-strain curves, and the corresponding critical strains (ϵ_c) were obtained. The parameters for MDRX experiment can be deduced from single hot compression tests.

As shown in Fig. 2, two series of tests were performed. After the peak strain of DRX, the specimen was unloaded and held at the test temperature for time between 1–300 s to allow MDRX to occur. Then the specimen was reloaded to measure the level of MDRX softening. The second deformation procedure was the same as for the first pass. In the first series as shown in Fig. 2a-1, the specimens were heated to 1250 °C at a heating rate of 10 °C/s and held for 5 min. The specimens were cooled to the forming temperature at 10 °C/s and held for 1 min to eliminate thermal gradients. Four different temperatures (950 °C, 1050 °C, 1150 °C and 1250 °C) and three different strain rates (0.001 s⁻¹, 0.01 s⁻¹ and 0.1 s⁻¹) were used in double-hit hot compression tests. In the second series as shown in Fig. 2a-2, the same processes before the second load as described in the first series were conducted. The specimens were directly quenched into water for microstructural investigation.

In order to investigate the effects of initial austenite grain size on the microstructural evolution during MDRX, different heat treatment procedures were used before hot compression, as shown in Fig. 2b-1 and 2. The specimens were heated to 1050 °C, 1150 °C and

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