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Recrystallization of 30Cr2Ni4MoV ultra-super-critical rotor steel during hot deformation. Part Ш: Metadynamic recrystallization

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ABSTRACT

The metadynamic recrystallization (MDRX) behavior of 30Cr2Ni4MoV ultra-super-critical (USC) rotor steel during hot deformation was investigated based on the first part of this study, in which the evolution of the dynamically recrystallized structure was studied in detail. Compression tests were performed using double hit schedules at temperatures of 970–1250 °C, strain rates of 0.001–0.1 s^{-1} and inter-pass time of 1–100 s. Based on the experimental results, the kinetic equations and grain size model were established. Results show that the effects of deformation parameters, including forming temperature and strain rate, on MDRX softening fractions and austenite grain size in the two-pass hot deformed 30Cr2Ni4MoV steel are significant. Results also reveal that the pre-strain (beyond the peak strain) has little influence on the MDRX behaviors in 30Cr2Ni4MoV steel. Comparisons between the experimental and the predicted results were carried out. A good agreement between the experimental and the predicted results was obtained, which verified the developed models.

1. Introduction

World energy demand is projected to increase at about 1.8% per year between 2000 and 2030 [1]. According to the resource quantity and energy density, atomic power, thermal power, and hydraulic power generation technologies will still be used as main power generation methods in the next 20–30 years. Especially, considering that thermal power generation is safe and its utility value is high as a power generation method with a high capacity to respond to load change, thermal power generation is expected to play an important role in the power generation field. However, there is a requirement for reduction of harmful emission from coal fired units and also an increasing demand for limiting greenhouse gas (CO_2) emission. From the viewpoint of the increasing demand of energy and environmental requirements, the ultra-super-critical (USC) power plants, with reliability, the priority of the high power generation efficiency and low pollutants emission, have got rapid development in China [2]. Low pressure (LP) turbine rotor is one of the key components for the USC power plants. Based on manufacturing technology and equipment, the LP turbine rotor can be divided into three basic categories: assembled rotor, welded rotor and integral forged rotor. Compared with other two categories, integral forged rotor is widely recognized as the most reliable rotor characterized by both high strength at elevated temperatures and high toughness. The degree of difficulty in designing and manufacturing of integral forged rotor is highly dependent on forging process and mechanical property performance of forging material. Thus, many researches focus on understanding of microstructure changes and softening mechanisms taking place during the complex forging processes [3–10].

Owing to its good balance of strength, toughness and wear resistance, 30Cr2Ni4MoV (American grade: 3.5 Ni–Cr–Mo–V) USC rotor steel is widely used as turbine rotor and disk material of the USC power plants. LP of 1000 MW USC steam turbine rotor is conventionally made from large forged parts whose manufacture requires a relatively long period of time, during which dynamic recrystallization (DRX) [3–5], static recyrstallization (SRX) [6,7] and metadynamic recrystallization (MDRX) [8–11] are key microstructural evolution mechanisms. Meanwhile, the forging material often subjects to complex time, strain, strain rate, and temperature histories in industrial forging processes. Therefore, it deserves further investigation on metal and alloys behavior at hot deformation condition. In this study, MDRX behavior in hot deformed 30Cr2Ni4MoV steel was investigated by hot compression tests. The effects of forming temperature, strain rate, pre-strain, initial austenitic grain size and inter-pass time on the austenite grain size were discussed, and the kinetic equations were also developed to predict the softening fractions induced by MDRX. Comparisons between the experimental and the predicted results were carried out.

2. Experimental material and procedures

Chemical composition of 30Cr2Ni4MoV steel employed in this investigation was 0.28C–1.85Cr–3.35Ni–0.42Mo–0.089V–0.22Mn

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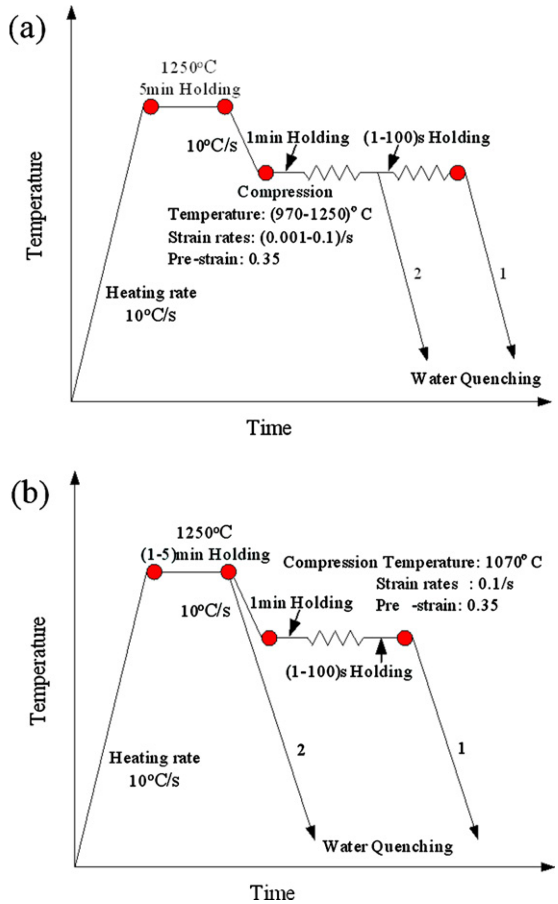

Fig. 1. Schematic illustration of experimental procedure for hot compression tests. (a) Considering the effects of deformation parameters on the softening and the austenite grain size and (b) considering the effects of initial austenite grain size.

–0.006Si–0.004P–0.002S–0.007Al–0.06Cu–0.004Sn–0.004As (bal.) Fe, all values given in wt.%. 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. To study the progress of MDRX, double hit tests were performed. The uniaxial hot compression tests were conducted using a computer-controlled servo-hydraulic Gleeble-1500D thermo-mechanical simulator. As shown in Fig. 1(a), two series of tests were performed. In the first series (Fig. 1(a-1)), the specimens were heated to 1250 °C at a heating rate of 10 °C/s and held for 5 min. Then, the specimens were cooled to the forming temperature at 10 °C/s and held for 1 min to eliminate thermal gradients. Four different temperatures (970 °C, 1070 °C, 1170 °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 hot compression tests. The pre-strain is greatly above the critical strain for DRX, as determined by the previous single hit tests [4]. The specimens were then unloaded and held at the forming temperatures for different inter-pass times to allow MDRX to occur. In this study, pre-strain refers to the strain of the first pass, and inter-pass time refers to the delay time between two deformation passes. Then, the specimens were deformed to a small strain of 0.2%, to measure the level of metadynamic softening that had occurred, and the specimens were then rapidly quenched with water. The fraction softening (F_s) is determined by the offset method:

$$F_s = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1} \quad (1)$$

where σ_m is the flow stress at the first interruption, σ_1 and σ_2 are the offset stresses (0.2%) at the first deformation and the second deformation, respectively, and the recrystallized fraction, X_{mdrx}, can be determined from the softening data using the following equation, $X_{mdrx} = (F_s - 0.2)/0.8$ [12]. In the second series (Fig. 1(a-2)), the same processes before the second load as described in the first series were conducted, and then the specimens were directly quenched with water for microstructural investigation. Additionally, 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. 1(b-1). In order to obtain the different initial austenite grain size, some specimens were heated to 1250 °C at a heating rate of 10 °C/s and held for 1 min, 3 min and 5 min, and then the specimens were directly quenched with water without deformation (Fig. 1(b-2)). Finally, the quenched specimens were sliced along the axial section. The sections were polished and etched with saturation picric and optical micrographs were recorded.

3. Results

3.1. Double hit flow curves

Examples of true stress–strain curves obtained from the double-hit hot compression tests of 30Cr2Ni4MoV steel are depicted in Fig. 2. It can be observed that the yield stress of the second deformation generally decreases with the increasing in the inter-pass time under the same heat treatment history and deformation schedule. In other words, the MDRX phenomenon becomes more and more obvious as the inter-pass time increases. Because the pre-strain under this deformation condition exceeds the critical strain (ε_c), DRX occurs. During DRX occurring in the first pass of the deformation, there are always nuclei present in the material and some grain boundaries are migrating. When the deformation is interrupted, these boundaries continue to migrate and nuclei continue to grow without the need for an incubation period. This form of recrystallization therefore proceeds very rapidly after deformation, but the rate of recrystallization falls with time as the grains grow progressively into less dislocated material in the heterogeneous structure produced by the repeated cycles of DRX [13]. This will greatly reduce the peak stress and strain after MDRX.

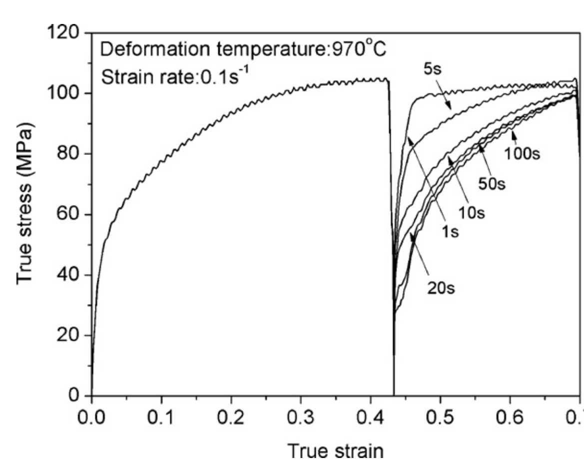

Fig. 2. Typical true stress–strain curves showing the softening taking place for different inter-pass time at deformation temperature of 970 °C and strain rate of 0.1 s^{-1}.