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Hot deformation behaviors and optimization of processing parameters for Alloy 602 CA

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A B S T R A C T

The hot deformation behavior of a new alloy, Alloy 602 CA is investigated by means of a series of compression tests. The stress-strain behavior, microstructure evolution and processing parameters optimization are studied carefully. Based on the measured stress-strain data, a two-stage method and a modified Arrhenius constitutive equation, which fit the experimental stress-strain curves well, are established for future numerical simulation. The final microstructure of the material after hot deformation shows a strong correlation with the processing parameters. During hot deformation, the main restoration mechanism for Alloy 602 CA is discontinuous dynamic recrystallization (DDRX) and dynamic recovery (DRV) accompanied by continuous dynamic recrystallization (CDRX). With temperature increasing and strain rate decreasing, the dynamic recrystallization (DRX) fraction increases. Grains begin to grow after DRX finishes at 1100 °C, 0.01 s^{-1}. A processing map based on dynamic materials model (DMM) is built and divided into four domains containing three feasible domains and an instable domain. The preferred domain to achieve uniform fine grains ranges from 1080 °C to 1100 °C, 0.01 s^{-1} to 0.1 s^{-1}.

1. Introduction

As a newly developed Nickel based alloy, Alloy 602 CA has become a promising material for high temperature components, due to its outstanding sustainability [1]. Generally, mechanical behaviors of materials mainly depend on their microstructures. In order to improve mechanical properties, the hot deformation process is usually adopted to achieve a desired microstructure for Alloy 602 CA [2]. As the hot deformation process proceeds under high temperature, the microstructure evolution is very sensitive to processing parameters (i.e. deformation strain, strain rate, temperature etc.) and hard to control. Thus, for the sake of improving the mechanical properties of materials, it is very significant to investigate stress-strain behaviors, find microstructure evolution mechanisms and optimize processing parameters for Alloy 602 CA.

In order to characterize the stress-strain behavior of materials during hot deformation process, constitutive equations are derived from the stress-strain data considering the effect of processing parameters [3]. In the past decades, many kinds of constitutive equations have been developed. Among these models, Johnson–Cook (J-C) model is the most widely used for its simplicity [4]. However, J-C model omits the coupling effects of strain, strain rate and temperature on stress-strain behavior during hot deformation process [5]. Artificial neural network model is a newly developed constitutive equations with high accuracy but fails to be widely used for the shortage of complexity [6,7]. To better represent the deformation mechanisms of metals, dislocation models are employed to describe the strain rate and temperature dependence of the strain hardening for mild steels and the Avrami relation is utilized to characterize the softening stage of hot deformation based on recrystallization kinetics [8,9]. For the sake of enhancing the precision while maintaining the efficiency of the algorithm, in

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recent years, a modified Arrhenius equation, which considers the effect of strain and endows strain rate and temperature with physical significances [10]. It is widely accepted to simulate the stress-strain behavior under hot deformation of stainless steels and magnesium alloys and shows good fit on patterns on stress-strain curves which indicating specific microstructure transformation in the material [11–14].

At high temperature, several types of metallurgical phenomena happen and result in complex microstructure evolution [15]. Dynamic recrystallization (DRX) usually happens as the major restoration mechanism to achieve uniform grains during hot deformation, due to the low stacking fault energy of nickel based alloys [16,17]. In recent years, dynamic recovery (DRV) is also found as softening mechanism during hot deformation of nickel based alloys, which provides a suitable condition for DRX occurring [18,19]. For Alloy 602 CA, creep behaviors and oxidation behaviors have been investigated in the past [20,21]. However, few experiments are done to investigate its microstructure changing at high temperatures with high strain rates. Thus, DRX and DRV properties of Alloy 602 CA should be investigated through hot deformation tests.

During hot deformation process, both stain rate and temperature have dominant influences on the final microstructure. Processing map, which is based on dynamic materials model (DMM), is a useful tool for quantifying the influence of processing parameters, controlling final microstructures and finally optimizing the processing parameters [22–24]. According to DMM, the work piece during hot deformation process is considered to be a dissipator of power and can be characterized by power dissipation efficiency. Domains with high power dissipation efficiency are treated as "safe" domains for hot deformation which usually relate to DRX [25]. Instable domains can be determined by the principle of the maximum rate of entropy of production. In instable domains, crack propagation, shear bands initiation or strain localization likely happens according to reference [26]. In this way, the processing map is able to identify temperature-strain rate windows for hot deformation.

Based on the urgent need of studying the hot deformation behavior of Alloy 602 CA and optimizing the processing parameters, hot deformation tests are carried out in this study. A two-stage model and a modified Arrhenius equation are built to describe the stress-strain behavior and the microstructure evolution is discussed in detail. Finally, a processing map based on DMM is developed to optimize processing parameters.

2. Materials and experiments

The chemical composition of Alloy 602 CA used in the investigation is given in Table 1. Alloy 602 CA is a nickel-based superalloy with Cr and Fe as the chief alloying elements. The material is provided by VDM Metals Company with a manufacturing procedure of hot rolled, annealed, water quenched and centerless ground. The dimensions of the specimen for deformation test are 13 cm in diameter and 20 cm in height. Before the isothermal hot deformation, the specimens are firstly heat treated at 1000 °C for 30 min and then water cooled to the room temperature.

The isothermal hot deformation tests are conducted on a computer-controlled servo-hydraulic MTS machine equipped with a radiant furnace. The MTS machine is programmed to operate at a constant true strain rate by incremental calculation of the current true strain. In order to minimize the effect of friction, Mo plates covered with boron nitride powder are used for lubrication. Specimens are firstly heated to the deformation temperature and held for 5 min prior to the hot deformation for the homogenization purposes. After that, they are compressed to a true strain of 0.7 at temperatures of 900 °C, 1000 °C, 1100 °C and strain rates of 0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1}, and finally water quenched to ambient temperature.

For the purpose of microstructure characterization, the specimens after hot deformation are sectioned along a length direction parallel to the compression axis. They are firstly grinded to 1200 grit and then polished using a 1 μm diamond suspension. After that, the specimens are etched polished and etched in a solution consisting of HCl (100 ml)+CH_3CH_2OH (100 ml)+$CuCl_2$ (5 g) at room temperature for 3–5 min. Optical microscopy (OM) tests and scanned electron microscopy (SEM) tests are conducted to reveal microstructures. In addition, the Electron Back-Scattered Diffraction (EBSD) test is carried out to characterize DRX features. The EBSD samples are electro-polished using a 10% Nital at −20 °C.

3. Results and discussion

3.1. Hot compressive deformation behaviors

The obtained stress-strain curves at various temperatures and stain rates are presented in Fig. 1. According to the shape of curves, it is convenient to divide each curve into two stages, a work hardening stage and a softening stage. At work hardening stage, the stress increases with strain. However, the work hardening rate is lower as the strain increases, which leads to the increasing rate of stress reducing. This phenomenon may be due to the dynamic recovery [27]. The softening stage begins at the end of work hardening stage, which leads to an obvious decrease in the flow stress. For nickel based superalloys, dynamic recrystallization is the main reason for the softening due to the formation of new grains and grain boundary migration which rearrange the dislocations [28,29]. The steady state is achieved when the dynamic equilibrium of hardening and softening reaches.

The flow stress is significantly affected by temperature and strain rate. A greater strain rate and a lower temperature lead to a higher flow stress. This is because both DRV and DRX are thermal activated. Dislocations are more easily to pile up at high strain rates and harder to diffuse at lower temperature. At 1100 °C with a strain rate of 0.001 s^{-1} and 0.01 s^{-1}, significant softening happens after the work hardening process, which is a strong indication of dynamic recrystallization. The detailed discussion of microstructure evolution will be illustrated in section 3.3.

3.2. Constitutive equation

3.2.1. A two-stage method

As has been discussed in section 3.1, flow curves experience work hardening and dynamic recovery at first and softening by dynamic recrystallization afterwards. The two-stage method describes the whole process by different models based on different stages [30]. To describe the first stage, Bergstrom and Estrin developed Eq (1) according to the dislocation density model [8,31].

$$\sigma = \left[\sigma_{sat}^2 - \left(\sigma_{sat}^2 - \sigma_0^2\right)\exp(-r\varepsilon)\right]^{0.5} \quad (\varepsilon < \varepsilon_c) \tag{1}$$

where σ_0 and σ_{sat} are the yield stress and saturated stress and ε_c is the critical strain for the occurrence of DRX. The parameter r represents the rate of DRV at a given deformation condition.

When the DRX happens, the softening of flow curves mainly depends on DRX kinetics X_d which can be characterized by the Avrami equation as follows [9]: