Materials and Design 67 (2015) 165–172

Contents lists available at ScienceDirect

Materials and Design

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

Study on hot workability and optimization of process parameters of a modified 310 austenitic stainless steel using processing maps

Hongying Sun [a,c], Yongduo Sun [b], Ruiqian Zhang [b], Man Wang [a], Rui Tang [b], Zhangjian Zhou [a,*]

[a] School of Materials Science and Engineering, University of Science and Technology Beijing, Xueyuan Road 30, Haidian District, Beijing 100083, China
[b] Science and Technology on Reactor Fuel and Materials Laboratory, Nuclear Power Institute of China, P.O. Box 436, Chengdu, Sichuan 610041, China
[c] School of Mechanical Engineering, Anyang Institute of Technology, West of Huanghe Road, Wenfeng District, Anyang, Henan Province 455002, China

ARTICLE INFO

Article history:
Received 6 September 2014
Accepted 25 November 2014
Available online 3 December 2014

Keywords:
Austenitic stainless steel
Hot workability
Processing map
Microstructure
Hardness

ABSTRACT

To investigate the optimized hot deformation parameters of a modified 310 austenitic stainless steel, the hot compression tests were performed using a Gleeble 3500 thermal simulator. The hot deformation behavior and hot workability characteristics were investigated in a temperature range of 800–1100 °C and a strain rate range of 0.1–10 s^{-1}. The hot processing maps of the tested steel were developed based on the dynamic material model (DMM), from which the safe deformation regions and instable deformation regions were determined. The corresponding microstructural and hardness evolutions during deformation were analyzed in detail. It was found that the deformation in the safe regions was beneficial to dynamic recovery (DRY) and dynamic recrystallization (DRX), while the deformation in unstable region would lead to flow instability, kink boundaries and grain growth. Near 950 °C, the energy dissipation rates were unusually lower, and the hardness of the deformed sample exhibited a significant increase, as a result of strain-induced precipitation. Coupled with the microstructure analysis and processing map technology, the workability map was schematically plotted and the optimal working conditions were determined. Such conditions were: temperatures in the range of 1075–1100 °C and strain rates in the range of 0.5–1.7 s^{-1}. These conditions are critical to attain an excellent homogeneous microstructure with fine grains after deformation for the modified 310 austenitic stainless steel.

1. Introduction

Austenitic stainless steels have excellent oxidation resistance and superior high temperature creep properties as compared to ferrite stainless steels. For these reasons, austenitic stainless steels have been selected as one of important structural materials for applications in extreme environments, such as advanced nuclear industries [1] and power plants [2]. Austenitic stainless steels with well-developed microstructures and desired properties are usually formed by reasonable processing. However, several unfavorable defects may be caused inevitably by some improper forming processes [3,4]. Therefore, the selection of reasonable hot working parameters plays an important role in the manufacturing process. During the past few decades, many scholars have attempted to optimize the processing parameters of alloys through experiments and theoretical modeling [5,6]. Their studies have contributed to the understanding of the mechanisms of hot deformation. But it was still difficult for researchers to achieve their optimization aims until the concept of the dynamic materials model (DMM) was first proposed by Prasad in 1984 [7]. Processing maps are usually constructed based on the DMM. Processing maps can be used to control microstructures, determine optimal deformation parameters [8] and explain different deformation mechanisms [9]. At present, processing maps based on the DMM have been widely used because of its characteristics of convenience, accuracy and quickness, such as for non-ferrous alloys [10] and several stainless steels [11].

Considerable attention has been focused on the constitutive flow behaviors and workability of 304L, AISI 304 and 316L using processing maps established by the corresponding contour maps. To obtain the desired microstructure and satisfied properties, different deformation mechanisms have been conducted in a temperature range of 600–1200 °C and a strain rate range of 0.001–100 s^{-1}. AISI304L steel experienced dynamic recrystallization (DRX) at temperature of 1150 °C and strain rate of 0.1 s^{-1} [12], while AISI 304 steel underwent DRX at 1100 °C and 0.1 s^{-1} [13], and 316L stainless steel occurred DRX at 1250 °C and 0.05 s^{-1}. In addition, the dynamic recovery (DRY) region of 316L steel was at 900 °C and 0.001 s^{-1} [14]. Consequently, Venugopal research group

---

* Corresponding author. Tel./fax: +86 10 62334951.
E-mail address: zhouzhj@mater.ustb.edu.cn (Z. Zhou).

http://dx.doi.org/10.1016/j.matdes.2014.11.041
0261-3069/© 2014 Elsevier Ltd. All rights reserved.

carried out industrial validations of processing maps by press forging, hammer forging, rolling and extrusion of AISI 304, 316L and 304L austenitic stainless steels [15,16]. The results showed that the hot workability of austenitic stainless steels highly depended on their chemical compositions and initial microstructure. Besides the DRX and DRY domains, processing maps also exhibit several unavoidable instability regions, such as flow localization, dynamic strain aging (DSA), adiabatic shear bands, kink bands and intense deformation bands. These regions are related to the low efficiency of energy dissipation at high strain rates [17], and provide the guidance for avoidance of the deformation defects. Tan's work [18] on the processing maps and hot workability of super 304H demonstrated that the large energy dissipation efficiency contributed to the occurrence of DRX, and the optimal deformation parameters of super 304H were at 1100 °C and the strain rate was more than 0.5 s^{-1}. These researches validate that processing maps are significant and necessary to predict the optimal deformation parameters and guide the subsequent plastic forming in industry.

Among all of the existing austenitic stainless steels, AISI 310 steel is an advanced austenitic stainless steel with improved oxidation and corrosion resistance properties. At present, although considerable effort has been expended in the research of constitutive flow behavior and workability of common austenitic stainless steels, little attention has been focused on the effects of precipitation process during hot deformation. Moreover, few studies have investigated the processing maps and the workability characteristics of advanced 310 austenitic steel. In particular, these available studies lack an examination of the effects about dynamic precipitation on the processing maps and workability.

In our previous work, hot behaviors and microstructures of a modified 310 austenitic stainless steel have been researched in order to determine the optimum deformation parameters [19]. However, it is difficult to obtain required information due to the complicated influences of second phases and precipitates that exist prior to or during the deformation. In the present study, we establish the processing maps of the tested steel based on the DMM, and further describe the workability maps by microstructural analysis. Then we determine the reasonable working perimeters of the modified 310 steel based on the microstructural analysis and workability maps.

2. Experimental procedures

The investigated material was a modified 310 austenitic stainless steel which was fabricated by vacuum induction melting. The chemical composition of this tested steel was designed as: 25Cr, 20Ni, 0.1C, 0.65Si, 0.2Ti, 0.2Zr, 0.15W, 0.15V, and balance Fe (wt.%). Cylindrical hot compression specimens with a size of Φ 8 mm × 15 mm were cut from the forged plate. The initial microstructure of the specimen showed a single-phase of austenite with a small quantity of twins.

All high-temperature compression tests were conducted by using a Gleeble-3500 thermal mechanical simulator. To minimize the friction during deformation, a layer of high-temperature lubricant composed of MoS_2 was daubed on the sample surfaces. Before testing, specimens were heated to 1200 °C at the rate of 10 °C s^{-1} and held for 10 min. The specimens were then cooled to different test temperatures at the rate of 5 °C s^{-1}, and these specimens were held for 5 min. The deformation temperatures were 800, 900, 950, 1000 and 1100 °C, and their strain rates were 0.1, 1 and 10 s^{-1}, respectively. Most of the samples deformed at a constant strain rate to the true strain of 0.68, while two additional samples were respectively compressed to the strains of 0.34 and 1.2 at 1100 °C and 1 s^{-1}. After deformation, the samples were instantly quenched into water.

The samples were sectioned from the center for the microstructural analysis. The sectioned samples were then progressively ground to 2000 grids with SiC sand papers, and then they underwent electrolytic polishing. And specimens were etched for 10–30 s using 0.5g $FeCl_3$ + 6 mL HCl + 10 mL H_2O as a solution to reveal the microstructures. Microstructural observations were performed using an optical microscope (OM, ZEISS Observer. A1m) and a scanning electron microscopy (SEM, FEI Quata 200) equipped with electron back-scatter diffraction (EBSD) detector and an energy dispersive spectrometer (EDS). Rockwell hardness and Vickers hardness were measured by different sclerometers (TIME TH320 and Leica VMHT 30 M, respectively). Every sample was measured more than three times, and the result was their average value.

3. Results and discussion

3.1. Stress strain curves

Fig. 1 shows the true stress-strain curves at various strain rates and temperatures. Almost all of the flow curves reveal peak flow stresses and flow softening. But when the strain reaches 1.2 at the strain rate of 1 s^{-1} and temperature of 1100 °C, the curve shows a steady state. In the initial stage of compressive deformation, the hardening plays a significant role and the stress greatly increases with the strain. When the strain goes critical value, DRX is activated. The stress continues to increase until it reaches a peak value, at the same time the stored energy come to the highest value. It is known that the driving force for DRX is the stored energy, thus DRX become more dominant with the increase of the stored energy. On the other hand, the stored energy is consumed as DRX occurred, resulting in the activation of flow softening, and the stress decreases abruptly. Along with the consumption of stored energy, the rate of DRX gradually decreases until full DRX is achieved (see Fig. 1(d), $\varepsilon = 1.2$). This dynamic equilibrium between the softening and hardening in the matrix is very difficult to be obtained, because DRX occurs in this low stacking fault energy steel by an important reversion mechanism [20,21]. Thus, the characteristics of recrystallization (steady state) in curves are not observed till the strain reaches 1.2. The shapes of the stress-strain curves, work hardening, flow softening, steady state and oscillation behaviors are related to the specific hot working process and inherent deformation mechanisms [22]. Understanding of the mechanisms of strain hardening and softening mechanisms during hot working is important for the investigation of the hot working process. Therefore, further additional studies about the deformation mechanisms were performed, which will be discussed in the following sections.

3.2. Hot processing maps

The constitutive behaviors of materials are usually studied through the investigation of processing maps based on DMM, which has been described in detail by Prasad and Sasidhara [23]. The energy dissipation during hot deformation consists of two portions: one is used for plastic deformation, and the other is consumed by structural changes. The ratio (η) of the energy dissipation that is consumed by structural changes to the total energy is plotted with a contour line as a function of strain rate and temperature. Thus, an energy dissipation map is developed.

The efficient energy dissipation ratio η during hot working is [24]:

$$\eta = 2m/(m+1) \tag{1}$$

In Eq. (1), m is the strain rate sensitivity, which can be denoted as [25]: