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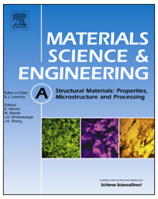

Flow softening of 253 MA austenitic stainless steel during hot compression at higher strain rates

Jingqi Zhang, Hongshuang Di*, Xiaoyu Wang

State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, PR China

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ABSTRACT

The flow softening of 253 MA austenitic stainless steel was investigated by means of hot compression tests performed over the temperature range of 900–1150 °C. Constant true strain rates of 0.01 s^{-1}, 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1} and 20 s^{-1} were used. The effect of deformation temperature and strain rate on the flow softening and the flow softening mechanisms in the high strain-rate regime (1–20 s^{-1}) was examined. The flow curves at higher strain rates, i.e. 10 s^{-1} and 20 s^{-1}, were characterized by a single peak followed by continuous stress softening at higher strain levels. The degree of flow softening increased with increasing strain rate and increasing temperature. The flow softening was attributed to thermal softening due to deformation heating, microstructural softening by dynamic recrystallization (DRX) and flow instability. Deformation heating produced by plastic work resulted in significant temperature rise in the steel. The thermal softening due to deformation heating was more pronounced at higher strain rates and lower temperatures. DRX was found to take place at higher deformation temperatures and higher strain rates; this was confirmed by the double-differentiation method proposed by Poliak and Jonas. Flow instability in the form of localized deformation bands occurred at the temperatures of 900 °C and 950 °C. The processing map developed as per Murty–Rao's instability criterion was found to yield an overestimate of the unstable flow region. Based on the flow behavior and microstructure analysis, it is concluded that this steel is suitable to be hot worked at higher strain rates and higher temperatures in order to reduce the flow stress and to refine grain size.

1. Introduction

The hot deformation behavior of metals reflects the dynamic equilibrium between work hardening and flow softening at elevated temperatures. On the one hand, plastic deformation results in stored energy within the material in the form of dislocations, thus causing work hardening. On the other hand, the annihilation of dislocations takes place either by dynamic recovery (DRV) or by dynamic recrystallization (DRX). In metals with low to medium stacking fault energy (SFE) such as austenitic stainless steels, DRV, which involves the processes of dislocation climb and cross-slip, is limited and DRX may occur when a critical deformation condition is achieved [1]. DRX causes a reduction in the dislocation density and therefore leads to flow softening in the true stress–true strain (σ–ε) curve; this softening is considered to be microstructural softening [2]. Besides, DRX can result in significant grain refinement and thereby is recognized as an important tool for controlling the microstructure and properties of metallic materials [3].

Microstructural evolution by DRX is dependent upon deformation temperature (T) and strain rate ($\dot{\varepsilon}$) in addition to strain (ε). Since DRX is thermally activated in nature, a higher deformation temperature usually leads to a higher degree of DRX for a given strain rate. However, the influence of strain rate on DRX is complex, especially at higher strain rates [5,6]. Firstly, increasing strain rate indicates a shorter time of deformation, which is probably not sufficient for the initiation of DRX in some steels and alloys. Secondly, during high strain-rate deformation the heat generated by plastic work is essentially retained, causing a significant temperature rise in the material. Such temperature rise due to deformation heating may be beneficial to accelerating DRX [6,7].

Similar to DRX, deformation heating can also result in a pronounced drop in flow stress, which is considered to be thermal softening. The degree of thermal softening increases with increasing strain rate [8]. If the strain rate is sufficiently high, then the strength loss due to thermal softening outweighs the strength increase due to work hardening. Hence, plastic deformation will become unstable and give rise to localized band-like microstructure such as flow localization or adiabatic shear band. It is also well documented that flow instability leads to significant

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* Corresponding author. Fax: +86 24 23906472.
E-mail address: hongshuang.di@gmail.com (H. Di).

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stress softening [9,10].

In metal forming processes such as forging and rolling, large reduction over a short time is always desired to maximize productivity as well as to minimize processing costs [4], it is therefore important to understand the hot deformation behavior of material in the high strain-rate regime. In particular, knowledge of the flow softening and the underlying mechanisms is needed in order to determine the hot working loads and, more importantly, to control the microstructure. The flow softening that occurs simultaneously with deformation at higher strain rates may be attributed to the contributions of the above-mentioned three mechanisms, i.e. DRX, deformation heating and flow instability. Normally, it is very difficult to isolate the contribution of each mechanism. However, it is possible to identify the deformation conditions under which one of these mechanisms may be dominant in the overall softening by means of model-based approaches and microstructural characterization techniques.

253 MA is an austenitic chromium–nickel steel alloyed with nitrogen and rare earth Ce. It offers an excellent combination of creep strength along with good resistance to oxidation and corrosion. This steel finds a wide range of high-temperature applications such as in metallurgical, petrochemical and power industries [11]. Numerous studies have focused on the oxidation and high temperature corrosion resistance of this steel [12,13]. However, to the best of the authors' knowledge, there has been no study on the flow softening of 253 MA austenitic stainless steel under hot deformation especially at higher strain rates. This information is very important for industrial hot working processes such as primary ingot breakdown and secondary processing.

The objective of the present study was to investigate the flow softening of 253 MA austenitic stainless steel deformed at elevated temperature in the high-strain rate regime. The effect of strain rate and deformation temperature on the mechanisms which control dynamic softening was examined.

2. Materials and experimental procedures

2.1. Material

The chemical composition of the 253 MA austenitic stainless steel used in this investigation is provided in Table 1. The steel was hot-rolled to a 16 mm plate which was subsequently annealed at 1120 °C and quenched by water. The microstructure of the as-received steel consisted of austenite grains with average size of approximately 20 μm. Cylindrical specimens of 10 mm in diameter and 15 mm in height were machined from the as-received plate for the hot compression tests.

2.2. Hot compression tests

A Gleeble-3500 testing system was used for the hot compression tests. MoS_2-coated tantalum foils were applied to each side of the specimen to minimize friction which exists between the contacting surfaces of the specimens and the dies. The specimens were preheated to 1200 °C at 20 °C/s, homogenized at that temperature for 180 s, cooled at 5 °C/s to various temperatures in the range of 900–1150 °C with an interval of 50 °C, held for 30 s and deformed at constant strain rates of 0.01 s^{-1}, 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1} and 20 s^{-1} to a target true strain of about 0.91. After the cessation of compression, every specimen was water quenched immediately within 1–2 s. The actual strain was measured to be 0.91 ± 0.04.

2.3. Microstructural characterization

The tested specimens were sectioned parallel to the compression direction. Samples for optical microscopy (OM) were carefully hand-grinded, then mechanically polished and finally etched with Kroll's reagent for about 90 s. Microstructural analysis was conducted using a Zeiss optical microscope.

Samples for electron backscattered diffraction (EBSD) were prepared by standard mechanical polishing. The polished surfaces were then electropolished in a solution of 130 ml ethanol, 10 ml perchloric acid and 20 ml deionized water at 25 V for 30 s. The EBSD measurements were carried out using a Zeiss Supra 55 scanning electron microscope. An accelerating voltage of 20 kV at a working distance of 15 mm was used. The step size in the EBSD scan was 0.5–0.7 μm. The HKL Channel 5 software was utilized to analyze the EBSD scan data.

3. Results and discussion

3.1. Flow behavior

Representative true stress–true strain curves are shown in Fig. 1 from which the effect of strain rate and temperature on the flow behavior can be inferred. It can be observed from Fig. 1a that, at lower strain rates (0.01 s^{-1} and 0.1 s^{-1}), the flow curves exhibit a broad stress peak, which is the typical characteristic of DRX [1]. In the case of 1 s^{-1}, the stress peak becomes broader followed by a steady-state behavior at higher strain levels. At the strain rates of 10 s^{-1} and 20 s^{-1}, the flow curves display continuous flow softening after a stress peak is achieved. Flow curves at 10 s^{-1} and 20 s^{-1} for different temperatures are shown in Fig. 1b and c, respectively.

It is noted that during hot deformation tests various lubricants are commonly used to minimize friction between the specimens and the dies. However, the use of lubricant could only provide sufficient lubrication up to a certain strain level, but will never eliminate the friction completely [14]. In contrast to the effect of DRX and deformation heating, friction can cause an increase in flow stress [15]. In order to study the flow softening of the investigated steel, it is, therefore, necessary to quantify the level of friction and to correct the as-measured flow curves with frictional effect.

The effect of friction on flow stress is usually estimated using the following relation [16]:

$$\sigma_{\mathrm{F}} = \frac{C^2}{2[\exp(C) - C - 1]}\sigma = k\sigma \tag{1}$$

with

$$C = \frac{2\mu R_0}{H_0} \tag{2}$$

and

Table 1
Chemical composition (in wt%) of the as-received steel.

Cr	Ni	Si	Mn	Cu	Co	Nb	N	P	S	Ce	C	Fe
20.85	11.90	1.67	0.59	0.22	0.10	0.01	0.16	0.024	0.001	0.06	0.088	Balance