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Effect of Mn addition on deformation behaviour of 23% Cr low nickel duplex stainless steel

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ABSTRACT

Isothermal compression testing of 23% Cr low nickel duplex stainless steels, with different Mn concentrations, was investigated in the temperature range of 1173–1423 K, the strain rate range of 0.01–10 s^{-1} and with a height reduction of 70%. Increasing the Mn content from 6.3 to 14.1% affected the deformation dynamic softening behaviour of flow curves at lower temperature and higher strain rate. It was also observed that increasing the deformation stain rate contributed to flow softening, and was caused by dynamic recrystallization (DRX) as a function of Mn addition. Deformation microstructure analysis demonstrated that more complete austenite phase DRX occurred with 10.3% Mn addition than that with 6.3% Mn addition at 1 s^{-1}, but an excessive Mn content of 14.1% was unfavourable due to the increase of austenite fraction and stacking fault energy enhancement. Increasing the strain rate to 10 s^{-1} promoted austenite phase DRX at 1323 K with the Mn addition under large strain. Meanwhile, the ferrite phase DRX occurred at 1173 K/1–10 s^{-1} with 6.3% Mn, and was weakened with higher Mn addition. Compared to the 6.3% and 14.1% Mn, continuous DRX occurred at 1323 K/1 s^{-1} with 10.3% Mn, due to the larger fraction of high angle misorientations. The values for the activation energy and Zener–Hollomon parameter decreased with Mn addition from 6.3 to 10.3%, and then increased with a higher Mn addition of 14.1%, indicating that a proper content of Mn addition can reduce the thermal deformation resistance and promote DRX. The constitutive equations for different Mn addition alloys were developed using a hyperbolic sine equation. Processing maps with different Mn addition for the strains of 0.3, 0.6 and 1.2 were established. The 10.3% Mn content sample corresponded to the lowest instability region, implying that the workability was improved with the middle Mn addition.

1. Introduction

Duplex stainless steels (DSS) exhibit the best combination of high mechanical properties (high strength and toughness) and corrosion resistance when compared with conventional single phase ferritic or austenitic stainless steels. Thus, the DSS have been extensively used in several industrial applications, such as in the oil, chemical and power industries [1–3]. The increasing price of Ni has made high Ni-containing DSS cost prohibitive for many industrial applications. Mn and N are effective γ-stabilizers, like Ni, and are used to replace it in austenitic stainless steel or DSS. The addition of N requires a special pressurized atmosphere for preparation and it may form gas pores in welding regions of the stainless steel, while the substitution of Mn for Ni has been successfully implemented in austenitic stainless steel [4,5]. Meanwhile, the solubility of nitrogen in stainless steels increases with Mn addition, promoting austenite stabilization and solid solution strengthening [6]. Mn is seven to eight times cheaper than Ni at an equivalent weight [7], so it is an ideal choice to develop less expensive N bearing DSS.

The DSS can be processed by different hot working routes such as forging, extrusion and rolling at high temperature. However, the mechanical behaviour of two phases of DSS was different during deformation due to their different thermal expansion coefficients and stacking fault energy (SFE) [8,9], which may easily cause deformation cracks to initiate and increase hot working difficulty. The SFE is a significant parameter that correlates closely with the plastic deformation. The ferrite phases are characterized by high SFE and mainly undergo dynamic recovery (DRV). On the other hand, the austenite phase has a relatively low SFE and mainly undergoes dynamic recrystallization (DRX), with nucleation and growth of new recrystallized grains when the dislocation density reaches a critical value.

The chemical composition and temperature are the main factors that control SFE [10,11]. Aluminium strongly increases the SFE, but Cr decreases it during high temperature deformation. SongLu et al. [12] pointed out more Mn content increases the SFE of high-Ni austenitic

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stainless steel, thus, the addition of Mn will affect the deformation mechanism of DSS due to the SFE variation. The hot deformation behaviours of some Ni-rich DSS have been studied by previous research. The A. Dehghan-Manshadi and P. D. Hodgson [13] evaluates the effect of co-existence of δ-ferrite on the hot deformation and DRX of austenite using comparative hot torsion tests on AISI 304 austenitic and 2205 DSS, suggesting that the conventional DRX and continuous DRX are the major restoration mechanisms in austenitic and duplex steels, respectively. A. IZA-MENDIA et al. [14] reported that the hot deformation partitions vary heterogeneously between both phases and some austenite areas act as hard nondeforming particles for a Ni-rich as-cast 23% Cr DSS. Guilhem Martin et al. [15] proposed that in the as-cast condition the Ni- and Mo-rich DSS alloy is twice as resistant to hot tearing as the Mn-rich alloy, and the austenite morphology has a significant impact on the high temperature fracture resistance. However, the recent research about the deformation mechanism caused by Mn addition was mainly concentrated on austenitic stainless steel. Farahat et al. [16] found that the tensile strength of austenitic stainless steel increased as the Mn content increased before and after thermomechanical treatment. The Mn was found to delay DRX because the corresponding activation energy increased with increasing Mn content in austenitic binary Fe-Mn alloys [17]. However, there is little research about the effect of Mn addition on deformation behaviour of DSS. For the Mn substitution for Ni DSS, the deformation behaviour will become more complex compared with austenitic stainless steel with different Mn content. Meanwhile, the volume fractions of two phases with different crystallographic structures strongly influences the mechanical characteristics [18], which will be changed due to different Mn content addition.

In the present work, this paper studies effect of different Mn content on the flow behaviour and microstructural changes of 23% Cr DSS containing a certain amount N at high temperature. The approach of producing a processing map has been adopted to understand the high-temperature deformation mechanisms with different Mn addition, and to optimize the hot forming process for low nickel type DSS.

2. Materials and Methods

The designed Fe (23.3–23.7), Cr (2.1–2.2), Ni (0.26–0.28) and N-xMn (x = 6.26–14.13 wt%) alloy ingots were melted in a 25 kg vacuum induction furnace. The chemical compositions of the casting ingots are listed in Table 1, which shows that the Mn content increased equally on the condition that the other alloy elements remained almost the same. The cast ingots were hot forged into 30-mm plates, and then hot rolled into 12 mm plates at a temperature ranging from 1313 to 1453 K. Isothermal deformation tests were conducted on the Gleeble-3800 thermomechanical simulator at temperatures in the range of 1173–1423 K, with various strain rates in the range of 0.01–10 s^{-1}, up to the height reduction of 70% and followed by water quenching. The 120 mm × 500 mm plates were cut from the hot rolled plate and solution treated at 1323 K to keep the composition homogenization and two-phase balance. The cylindrical specimens of Φ 8 mm × 12 mm were machined from a solution treated plate, and the surface finish reached to Ra3.2. To further reduce the friction between the die and the specimen and to avoid the inhomogeneous deformation, a tantalum foil with thickness of 0.05 mm was placed between the die and the specimen. The specimens were heated to different deformation temperatures, held for 180 s, and compression tested. Deformed specimens for optical microscopy (OM) were sectioned at mid plane parallel to the compression axis. The cut sections were mechanically polished and then electrochemically etched for about 16 s in concentrated nitric acid at 1.8 V direct current. A Zeiss Sigma FEGSEM equipped with an OIM EBSD system from EDAX was used for electron backscattered diffraction (EBSD) analysis. An accelerating voltage of 15 kV was applied together with step sizes of 0.5 μm (magnification 1500×) for EBSD runs. The transition angle between the low and high angle boundaries was established as θ = 15°.

3. Results and Discussion

3.1. Flow Behaviour Analysis

Fig. 1 demonstrates the flow curves obtained from hot compression testing with different Mn addition. It was observed that the deformation temperature and strain rate significantly affected flow behaviour with the Mn addition. The flow stress increased with the decrease in temperature and the increase in strain rate. Under the deformation condition of 0.01 s^{-1}/1173 K, the flow stress rapidly increased by increasing strain with a Mn addition of 6.3% (Fig. 1a), exhibiting that work hardening occurred. However, a flow softening phenomena of DRV was observed for the flow curves at higher deformation temperatures of 1323 and 1423 K. Moreover, more Mn addition of 10.3% and 14.1% reduced work hardening in the large strain region at 1173 K, but had little effect on the DRV of flow curves at 1323 and 1423 K (Fig. 1d and Fig. 1g). Increasing Mn content affected the dynamic softening behaviour of the flow curves at higher strain rate. At a higher strain rate of 1 s^{-1}, the flow curve with 10.3% Mn exhibited typical complete DRX characteristics at 1173 K (Fig. 1e). However, the curves with 6.3% and 14.1% Mn exhibited work hardening behaviour with a large strain > 0.8 (Fig. 1b and Fig. 1h), suggesting that comparatively high Mn content favours DRX under large strain deformation. Meanwhile, at a higher deformation temperature of 1323 K, the flow curves are mainly characterized with DRX at the early stage of deformation of 1 s^{-1} strain. At a higher strain rate of 10 s^{-1} and temperature of 1173 K, the flow curves with different Mn addition show single peak stress followed by a gradual steady flow at the large strain level, and this phenomenon is associated with the complete DRX (Fig. 1c, Fig. 1f and Fig. 1i). At a higher temperature of 1323 K, the flow stress dynamic softening with 6.3% Mn and 10.3% Mn were mainly characterized DRX, while higher Mn addition of 14.1% led to DRV softening characteristic, indicating that the process of DRX was sluggish due to enhancement of SFE [19]. However, with an increasing deformation temperature to1423 K, the flow curves show DRV softening characteristics at early strain, and the work hardening occurred with large strain applied due to multiplication of dislocations. Therefore, for different Mn addition specimens, increasing deformation stain rate was contributed to flow softening caused by DRX at deformation temperature of 1173–1323 K.

3.2. Microstructural Examination

The initial solution treated optical microstructure before hot deformation is shown in Fig. 2, where it is seen that the long white strips of austenite are uniformly distributed on the grey ferrite matrix for different Mn concentration specimens. The austenite fractions of 42%,

Table 1
The chemical compositions of 23% Cr duplex stainless steels (wt%).

Specimens	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	N	Fe
Alloy1	0.04	0.22	6.26	0.004	0.008	23.34	2.15	1.41	0.14	0.26	Balance
Alloy2	0.04	0.23	10.27	0.004	0.007	23.39	2.13	1.35	0.14	0.28	Balance
Alloy3	0.04	0.25	14.13	0.003	0.007	23.69	2.20	1.29	0.14	0.28	Balance