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Effect of RE on molybdenum partitioning and resultant mechanical and microstructural behavior of a duplex stainless steel during hot working condition

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Abstract: The effect of rare earth (RE) on Mo partitioning and resultant mechanical and microstructural behavior of a duplex stainless steel during hot working condition was investigated. It was found that RE effect was sensitive to temperature. At the high temperature, the development of dynamic recovery (DRV) in α phase was slowed down while the dynamic recrystallization (DRX) process in γ phase was accelerated by RE, whereby both work hardening rate (at low strain) and dynamic softening rate (at high strain) increased and moreover, the discrepancy on the hardness of the both phase reduced. Whereas at the low temperature, the effect of RE was opposite as compared with those in the high temperature. Mo partitioning analysis by EPMA indicated that RE enhanced the partitioning of Mo in α phase while reduced Mo concentration in γ phase at higher temperature whereby the mismatch between two phases could be improved indicated by the elimination of voids and cracks at α/γ interface, but it was contrary to that at the low temperature. Mo partitioning was believed to be an important cause for the RE effect on the differences of mechanical and microstructural behavior. Also this result provided a reasonable evidence for micro-alloying of RE in DSSs.

Keywords: duplex stainless steel; rare earths; partitioning; hot working

Duplex stainless steels (DSSs) comprised of a mixture with approximately equal amount of γ-austenite and α-ferrite exhibit a better combination of mechanical properties and stress corrosion resistance, whereby they have been widely used in the marine and petrochemical industries[1]. When the two phases are deformed together, the α-ferrite phase, as a softer constitution, can obtain most strain at the commencement of straining, while the harder γ-austenite is nearly undeformed. As deformation proceeds, the strain gradient can decrease as a result of accommodation mechanism such as recovery and recrystallization[2,3], which is known to affect mechanical behavior and cause cracking. During hot working of DSSs, the accommodation mechanism would dominantly depend on the differences in composition of both phases when the deformation conditions such as strain, strain rate and temperature are the same[2,3]. Jorge et al.[4], working with samples of three kinds of DSSs, observed that the shapes of high-temperature flow curves exhibited different characteristics due to changes in composition. In particular, the alloying element Mo, which is generally added to control structural balance and to improve corrosion resistance, was also found to be beneficial for the hot ductility of 2205 DSS compared with a Mo-free DSS[5].

Rare earth (RE) had been reported that it can improve the hot ductility of DSSs and other alloys, and some mechanism was discussed[5–8]. These works had mainly focused on evaluation of stress, calculation of constitutive equations, modification of inclusions and deep purifying. Limited studies, however, investigated the micro-alloying effect of RE. In this paper, an attempt was made to describe the effect of RE on the partitioning of Mo between γ-austenite and α-ferrite and resultant mechanical and microstructural behavior. Furthermore, it is possible to obtain a more fundamental understanding of the micro-alloying mechanism of RE in the DSSs.

1 Experimental

Two test steels were prepared by vacuum induction melting in an argon atmosphere with nominal compositions of C (0.02 wt.%–0.03 wt.%), Cr (22.85 wt.%–23.02 wt.%), Ni (5.51 wt.%–5.72 wt.%), Mo (2.80 wt.%–2.90 wt.%), Si (0.38 wt.%–0.46 wt.%), Mn (1.11 wt.%–1.30 wt.%), N (0.17 wt.%–0.19 wt.%), S (0.0015 wt.%–0.003 wt.%), P (0.02 wt.%–0.03 wt.%), O (0.002%), and Fe in

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balance. Specimens were divided into two groups according to different RE contents: Steel $0^{\#}$ (RE=0), Steel $1^{\#}$ (RE=0.046%). The cast billets were forged to steel bars (10 mm diameter) at 1423–1473 K and annealed at 1323 K for 30 min. Specimens with a size of Φ8 mm×15 mm were machined from the steel bars. Hot compression tests were carried out on a Gleeble-3800 thermal-mechanical simulator. The specimens were preheated at different deformation temperatures for 5 min, and were deformed at a strain rate of 1 s^{-1}. All the specimens were deformed to the strain of 0.25 and 0.7, respectively, and then instantly quenched into water.

Microstructure was revealed using a solution of $HCl+HNO_3$ (2:1) by immersion. The distributions of concentration of alloying element were analyzed by an electron probe micro analyzer (EPMA) installed on a Hitachi S-4200 scanning electron microscopy (SEM). The hardness on both phases of the specimens after deformation was analyzed by a HVS-1000 Vickers hardness tester. A load of 25 g was used and the holding time for the measurements was 15 s. Each test for every testing location was reproduced at least five times to ensure the reliability of the experimental data and the results were averaged.

2 Results and discussion

2.1 Analysis of mechanical characteristics

2.1.1 Effect of RE on the flow curve

Typical flow curves of both test steels at different temperatures are shown in Fig. 1. The stress for both steels increases with the increasing of strain, namely the work hardening happens, and there is a degree of softening when the stain is higher, especially at higher temperature. However, some differences can be observed between both steels at different stages of deformation when the temperature is the same. At 1173 K, the work hardening rate of steel $1^{\#}$ with RE is lower than that of steel $0^{\#}$ without RE, indicated by higher stress of steel $0^{\#}$ at the beginning of strain, also, the stress of steel $1^{\#}$ is higher which indicates lower softening rate when the dynamic softening develops (Fig. 1(a)). In contrast, at 1273 and 1373 K, both the work hardening rate at lower strain and the soften rate at higher strain of steel $1^{\#}$ are higher, as can be seen in Fig. 1(b) and (c).

2.1.2 Effect of RE on the hardness of the two phase

Fig. 2 shows the hardness of test steels after hot deformation at different temperatures. It can be seen that α phase is softer than γ phase in two test steels at the same condition, and with increasing of temperature, the hardness of both phase decreases (Fig. 2(a)). RE addition can increase the hardness of softer α phase while reduce that of harder γ phase when the temperature is higher than 1173 K, but the result on the hardness of both phases is opposite at the temperature of 1173 K. In steel $1^{\#}$ with RE, the discrepancy on the hardness of the both phase at

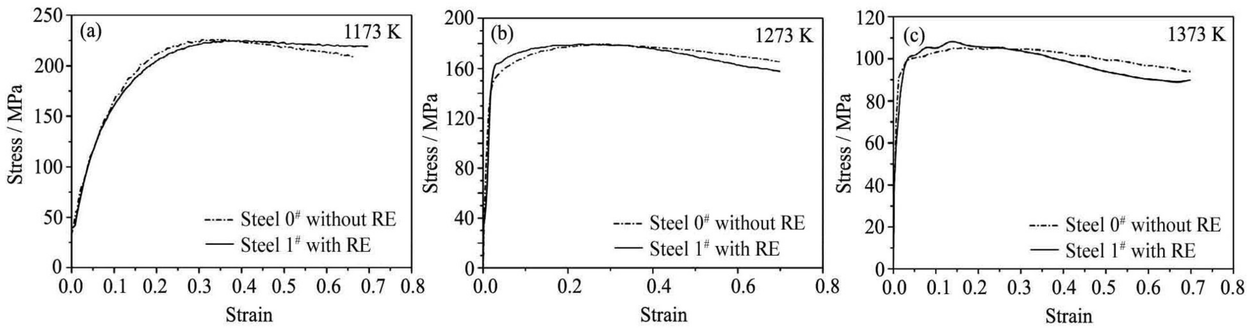

Fig. 1 Typical flow curves at different temperatures

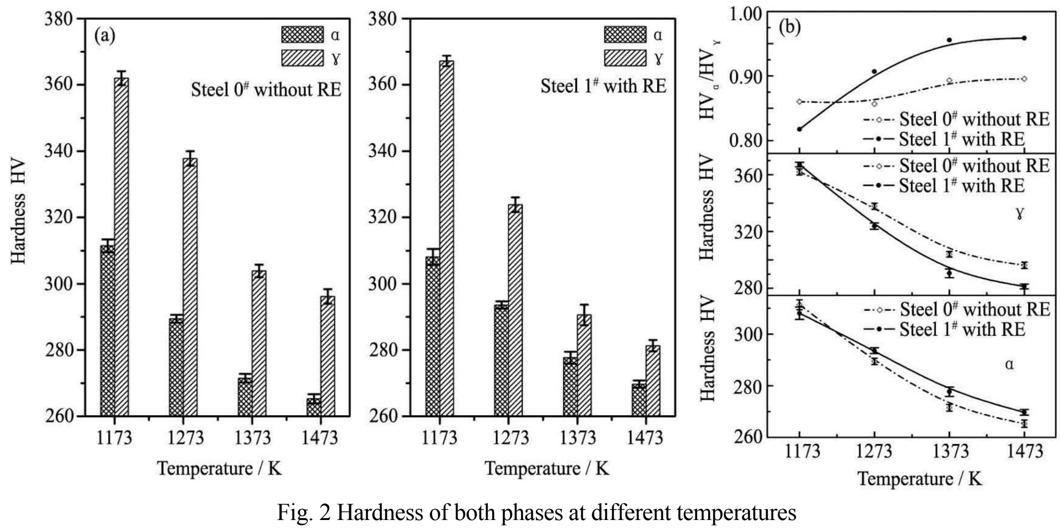

Fig. 2 Hardness of both phases at different temperatures

(a) Column chart; (b) Curves for variation