Effects of Pretreatment before Austenitization on Mechanical Properties in a Bainitic Steel*

Sanae Konishi*, Kiyomichi Nakai**, Tatsuaki Sakamoto***, Sengo Kobayashi***, Hiroaki Ohfuji**** and Tetsuo Irifune****

Effect of cold rolling before austenitization on mechanical properties in bainitic steels has been investigated. Cold rolling of ferrite (α) and isothermal holding above A1 before austenitization were done to harden ferrite and to form thin layer of austenite (γ) at/around both α grain boundaries and annealing twin-boundaries. Both coherency stress around (γ/α)-interface and transformation stress might introduce dislocations into γ. The dislocations within γ might react with each other, resulting in formation of dislocation network, whose constituent dislocations have different Burgers vectors with each other. In the high temperature region of γ, the climbing of constituent dislocations in dislocation network might occur through absorption of vacancies with an individual rate, resulting in bowing of each constituent dislocation out (increasing in dislocation energy). Therefore, the absorption of vacancies with the constituent dislocations in dislocation network would be suppressed, resulting in the dislocation network being stable. Nucleation of bainite laths might be enhanced to relax the strain field around dislocation network, resulting in refining bainite lath. The refining of bainite lath would improve both strength and ductility in bainitic steel.

Key Words: Bainitic Steel, Transformation Stress, Dislocation Network, Strength, Ductility

1. Introduction

Refining the crystal grains is important to improve the strength and toughness in low carbon steel. Finer bainite formed within austenite grain (BWING) in steel has the potential to increase strength and toughness largely in steels1, 2). Also aggregate of bainite laths with nearly parallel slip systems between neighboring bainite laths (ALPS) is considered to greatly affect elongation in steels1). Inclusions are often used to nucleate BWING in austenite (γ). However, inclusions easily induce cracks under deformation, resulting in deterioration of elongation1). Therefore, an alternative nucleation site, namely, dislocation network is noticed1). In order to introduce dislocation network into γ, treatments before austenitization (hereafter, referred to as pretreatments) were adopted. The pretreatments are cold rolling and isothermal holding at 750°C.

The combined pretreatment is effective to introduce dislocation network into γ. However, the reason why cold rolling is effective to introduce of dislocation network into γ has not been understood.

In the present investigation, effect of cold rolling on introduction of dislocation network into γ is investigated using specimens subjected to cold rolling with various reduction rates. Furthermore, the nucleation of BWING at dislocation network and the formation of ALPS are discussed. Effects of the sizes of BWING and ALPS on strength and elongation are also discussed.

2. Experimental procedure

2.1 Procedures for heat treatment

The chemical composition of steel used in present study is listed in Table 1. The steel is designated as SP (sulfur poor). Steel SP had heat treatments as illustrated in Fig. 1.

The pretreatments of both 0, 5 and 10% cold rolling and isothermal holding at 1023 K for 60 s were performed before austenitization at 1673 K for 300 s.

After austenitization, isothermal holding at 773 K for 20 s was performed to form BWING followed by quenching into iced brine.
2.2 Microstructure and mechanical properties

Microstructure was observed with an optical microscope after mechanical polishing and etching. The etchant was 2% nital.

Tensile specimen as shown in Fig. 2 was prepared and tensile test was carried out at a strain rate of $5 \times 10^{-4}$/s at room temperature. After tensile test, fracture surface was observed with a scanning electron microscope (SEM).

Thickness of BWING was measured. BWING has habit planes of \{111\}$^\gamma$ under the Kurdjumov – Sachs orientation relationship (K-S OR). The inclination angle ($\theta$) between BWING and specimen surface was analyzed based on the K-S OR. Thickness of BWING was determined using $\theta$.

3. Result

3.1 Microstructure

Figure 3 shows optical micrographs taken from steel SP with (a) 0, (b) 5 and (c) 10 % cold rolling followed by isothermal holding at 1023 K for 60 s. In Fig. 3 (a), martensite remarkably formed\(^4\). Under the formation of $\gamma$ only at/around grain and annealing-twin boundaries in $\alpha$, coherent stress around ($\gamma$/\alpha) interface and transformation stress generate. These stress fields are mainly relaxed through deformation of $\alpha$ under the pretreatment of 0 % cold rolling. In this case, $\alpha$ might be largely deformed, because $\alpha$ without cold rolling is soft. Therefore, dislocation would not be dominantly introduced into $\gamma$, resulting in scarce formation of dislocation network as nucleation site of BWING in $\gamma$. As a result, it is likely that martensite forms dominantly instead of BWING\(^3\). Amounts of BWINGs increase with increasing the rate of cold rolling as shown in Fig. 3. Thickness of BWING decreases with increasing the rate of cold rolling as shown in Figs. 3(b) and 3(c). BWING forms dominantly in the cases of Figs. 3(b) and 3(c). Thickness of BWING in 10 % cold-rolled steel SP is smaller than that in 5 % cold-rolled one. It suggests that cold rolling enhances nucleation of BWING.

3.2 Mechanical property

Figure 4 shows stress vs. strain curves taken from steel SP with (a) 5 and (b) 10 % cold rolling. In Figs. 4(a) and 4(b), 0.2 % proof stresses are 587 and 597 MPa, respectively. 0.2 % proof stress is higher in 10 % cold-rolled steel SP than in 5 % cold-rolled one.
Elongation is also larger in 10% cold-rolled steel SP than in 5% cold-rolled one. Figure 5 shows the result of measurements of BWING thickness. Average thickness of BWINGs formed under the cold-rolling rates of 5% and 10% are 2.1 and 1.6 μm, respectively.

4. Discussion

4.1 Effect of cold rolling on formation of dislocation network in γ

Figure 6 shows processes of formation of dislocation network in γ of steel SP. Dislocation density is higher in 10% cold-rolled steel SP than that in 5% one, because of remarkable deformation in 10% cold-rolled steel SP. Thin γ layer formed preferentially at/around grain and annealing-twin boundaries of α through reverse transformation, α→γ, at 1023 K.

Ferrite in 5% cold-rolled steel SP would be softer than that in 10% cold-rolled one. Of course, γ is the softest in all the region. Therefore, the thin γ layer mainly might deform by both coherent stress around (γ/α) interface and α→γ transformation stress. Ferrite would also deform to relax the stresses mentioned above. Softer α in 5% cold-rolled steel SP than that in 10% one might be deformed remarkably. It might lead that γ in 10% cold-rolled steel SP deforms remarkably, resulting in the introduction of higher dislocation density as well as dislocation network into γ. Namely, the relaxation of both the stresses mentioned above would occur by the deformation of both α and γ. However, both higher density of dislocations and its network might be introduced into γ in steel SP cold-rolled 10% compared with that in steel SP cold-rolled 5%.

Segment of dislocation in dislocation network, hereafter referred to as component dislocation, might have different edge component of Burgers vector. The rates of climbing motion of component dislocations are different among them, resulting in
bowing the component dislocations out. Dislocation energy might increase by the bowing-out. It suggests that dislocation network scarcely absorbs vacancies even in the high temperature region of \(\gamma\). It could be suggested that dislocation network is stable in \(\gamma\) (Fig. 6(e)) and acts as nucleation site for BWING through the relaxation of strain field around the dislocation network.

4.2 Effect of microstructure on strength and elongation

Optical micrographs in Fig. 3 suggest that both cold rolling and isothermal holding could introduce dislocation network into \(\gamma\). Smaller thickness of BWING in 10% cold-rolled steel SP could induce higher 0.2% proof stress than that in 5% cold-rolled steel SP.

Elongation is larger in 10% cold-rolled steel SP than that in 5% cold-rolled one from Fig. 4. Elongation is related to the size of the ALPS\(^5,6\).

Figure 7 shows SEM micrographs taken from fracture surface after tensile test in (a) 5 and (b) 10% cold-rolled steel SP. Average size of dimples in 10% cold-rolled steel SP is smaller than in 5% cold-rolled one. Figures 8 (a) and 8 (b) show schematic illustration of two ALPSs containing (a) small and (b) large number of BWINGs. If the number of BWINGs contained in an ALPS is large, a lot of BWINGs with the largest Schmid factor would be contained in the ALPS. When a same strain is given to two steels, the area swept by dislocations in an ALPS is same in the two steels. Local accumulation of dislocations to the region around the BWING with the largest Schmid factor might occur. The distribution of dislocations would be more homogeneous in the ALPS (b) than in the ALPS (a), resulting in the suppression of cracking in (b). Then, the number of BWINGs contained in an ALPS of 10% cold-rolled steel SP might be larger than that in 5% cold-rolled one.

5. Conclusions

(1) It could be clarified that dislocation network is stable even in the high temperature region of \(\gamma\) and acts as a nucleation site for BWING, resulting in refinement of BWING.

(2) Cold rolling with higher rolling reduction rate enhances the formation of dislocation network. The increase in nucleation site for BWING increases 0.2% proof stress.

(3) The large number of BWINGs in an ALPS results in large elongation, because a lot of BWINGs with a large Schmid factor suppress localization of deformation, that is, piling dislocations up locally.

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