Effect of Boron on the Hot Ductility of Low-Carbon Nb-Ti-Microalloyed Steel

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Introduction

Slab cracking during continuous casting of microalloyed steels has always been a serious issue. The occurrence of cracking is strongly associated with the ductility of steel in the temperature range of the straightening stage of continuous casting (ranging from 700 to 1000°C), besides casting parameters, such as casting speed and secondary cooling pattern. Boron-containing steels are very susceptible to slab corner cracking because of poor hot ductility. The hot ductility is an effective parameter for evaluating the susceptibility of cracking during straightening of steel slab. The hot ductility of steels is greatly influenced by a series of microstructural constituents, such as austenite/ferrite transformation, precipitation and dynamic recrystallization. Furthermore, these changes in microstructure are closely related to the microalloying elements in the steel.

Many researchers attributed the improvement of hot ductility of steels with boron addition to preferential boron nitride (BN) precipitation and delay of the austenite/ferrite transformation. Lopez-Chipres et al. demonstrated that boron addition improved the ductility of steel by enhancing grain boundary cohesion leading to an easier flow in the austenite lattice. Zarandi and Yue showed that the addition of boron improved the hot ductility of Nb-microalloyed steel in austenite region due to its enhancement of segregation and diffusion of Nb, as well as atomic boron segregated to the grain boundary. Cho et al. reported that the precipitation of BN rather than niobium carbonitride (Nb(C,N)) at austenite grain boundaries led to the loss of ductility of B-Nb-containing steel. However, these previous studies showed conflicting opinions on the effect of boron on the hot ductility of steel.

The present study was undertaken to reveal the influence of boron on the hot ductility of Nb-Ti-microalloyed steel. The area reduction of sample cross section after tensile test was taken as a measure of the hot ductility. The formation of precipitates in the steel was calculated using Thermo-Calc (TCFE 7 database). The microstructure, precipitates and fracture surfaces of deformed steel were determined. The fracture mechanism was analyzed based on steel microstructural examination.

Experimental

Materials

A 25-kg scale vacuum induction furnace was used for melting the studied steel. Ferroboron (with boron content of 20 mass%) was added to obtain boron-containing steel. The steel was subjected to chemical analysis. The chemical compositions of the steels are listed in Table 1. Cylindrical specimens of 120 mm in length and 10 mm in diameter were machined from the ingots along the longitudinal axes of casting direction. These cylindrical specimens were prepared for hot tensile tests. The dimensions of hot tensile test specimen are schematically described in Fig. 1.

Hot tensile test

The hot tensile testing of the steel was performed using a Gleeble 3500 thermomechanical simulator. The thermomechanical test profile of hot tensile test is schematically illustrated in Fig. 2. The steel samples were heated up to 1350°C at a heating rate of 10°C/s, and held for 5 minutes to homogenize microstructure, and then cooled to different test temperatures ranging between 700°C and 1000°C at a cooling rate of 3°C/s. Before deformation, the steel samples were held at test temperatures for 60 seconds to homogenize the temperature. Finally, at each test temperature, the specimen was stretched until complete failure at a constant strain rate of 1.0 × 10⁻³/s, followed by water quenching for retaining the original microstructure at test temperature. The reduction of area of the tested samples until fracture was measured to quantify the hot ductility of the studied steel. The strain-stress curves of the steels obtained from hot tensile tests were constructed.

Keywords: boron, hot ductility, fracture, precipitates, austenite/ferrite transformation, dynamic recrystallization

1. Introduction

Hot tensile tests were performed to examine the effect of boron on the hot ductility of Nb-Ti-microalloyed steels. The equilibrium precipitation in the steel was predicted by Thermo-Calc calculation. The microstructure, fracture surface and precipitates in the deformed steel were examined. The results show that boron addition is favorable to improving the hot ductility of Nb-Ti-microalloyed steel. This beneficial effect is caused by the soluble boron instead of coarse BN in the steel. The hot ductility of the steel decreases less from 1000°C with increasing boron addition. The hot ductility trough shifts toward lower temperatures because ferrite formation was restrained with increasing boron content of the steel. The formation of NbC, TiN and thin film-like ferrite along austenite grain boundaries lead to the decrease in the hot ductility of the steel. Boron addition has negligible influence on the precipitation temperature and amount of TiN and NbC precipitates in Nb-Ti-microalloyed steel. The amount of NbC precipitates is largest in the steel, followed by TiN and BN. The precipitation temperature of BN increases considerably with further increasing the boron content. The fracture mode of Nb-Ti-microalloyed steel tends to be more ductile with the increase in the boron content of the steel.

2. Experimental

2.1 Materials

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2.3 Microscopic observation

After the hot tensile test, specimens were quenched and then longitudinally sectioned. Both the microstructure and fracture surfaces of the specimens were examined by optical microscope (OM) and scanning electron microscope (SEM). The fractured specimens were etched with 4% nital to reveal their microstructure prior to microstructural examination. Carbon extraction replicas taken from deformed samples were observed using transmission electron microscope (TEM) equipped with energy dispersive X-ray spectroscopy (EDS) to determine the morphology and compositions of precipitates.

3. Results

3.1 Hot ductility evaluation

The reduction of area of sample cross section after the tensile test is an effective parameter for quantifying the hot ductility of steel. The hot ductility curves of the studied steel with various boron contents were plotted based on the determined values of area reduction as shown in Fig. 3. It is clear from Fig. 3 that the area reduction of each steel sample decreases monotonically from 1000°C to lower temperatures, and reaches the minimum value of about 20% at 850°C and 800°C for steel samples A1 and A2, respectively. The hot ductility of sample A2 decreases less significantly than that of A1 as shown in Fig. 3. With further decreasing temperature, the reduction of area rapidly recovers. Moreover, it was observed that the hot ductility trough of sample A2 shifted toward lower temperature compared with sample A1. These results indicate that the hot ductility of Nb-Ti-microalloyed steel was improved with boron addition of 0.0025%. With further increasing boron content up to 0.0045%, the hot ductility trough of the steel almost disappeared. Mintz16) showed that the temperature range in which the reduction of area is lower than or equal to 40% is a crack-sensitive range (also called hot brittle range) during continuous casting or hot working. The reduction of area of sample A3 after tensile test is higher than 50% in the tested temperature range. The hot brittle range tends to disappear when the boron content was increased up to 0.0045 mass%. It can be concluded that boron addition is favorable for improving the hot ductility of Nb-Ti-microalloyed steel.

3.2 Stress-strain curves of the steel with various boron contents

Figure 4 shows the true stress-strain curves of the studied steel with different boron contents obtained from the hot tensile tests at 700°C, 800°C, 900°C and 1000°C, respectively. It can be seen from Fig. 4 that, for each sample, the peak stresses decreases and the elongation increases with the increase in test temperature. The softening phenomenon caused by dynamic recrystallization (DRX) exhibits distinctly. Temperature has a great effect on dynamic recrystallization. At lower temperatures, the activation of dynamic recrystallization is quite difficult. It also applies to the softening phenomenon. Therefore, the shortest elongation and the highest stresses are found in samples tested at 700°C for each steel sample as shown in Fig. 4.
Although the strain-stress curves obtained from hot tensile tests are not ideal method to study dynamic recrystallization because of the occurrence of necking, the fluctuations of strain-stress curves shown in Fig. 5 proves the occurrence of dynamic recrystallization. The effect of boron addition on strain-stress curves is shown Fig. 5. At test temperatures of 700°C, 800°C, 900°C and 1000°C, the boron-free steel shows the maximum stresses and minimum elongations at each test temperature. As can be seen in Fig. 5(d), the stress of Nb-Ti-microalloyed steel slightly decreases at the strain value of about 0.15 regardless of the boron amount at test temperature of 1000°C. It is attributed to the occurrence of dynamic recrystallization. The peak stresses of steel decrease and the elongations increase with the increase in boron content of the steel, except for the elongation of samples A1 and A2 at the test temperature of 800°C. This exception is due to the better hot ductility of sample A1 at 800°C, as shown in Fig. 3. It is clear from Fig. 5 that boron addition promotes dynamic recrystallization.

4. Discussion

4.1 Precipitates in Nb-Ti-microalloyed steel with various boron contents

Figure 6 shows the equilibrium precipitation during solidification of molten steel with varying boron contents calculated using Thermo-Calc software (TCFE 7 database). In boron-free Nb-Ti-microalloyed steel, titanium nitride (TiN) and niobium carbide (NbC) precipitated in sequence as shown in Fig. 6(a). It can be seen from Fig. 6 that boron addition has negligible influence on the precipitation temperature and amount of TiN and NbC precipitates. The precipitation of TiN started at 1400°C which is much higher than that of NbC and BN. Although the amount of BN in Nb-Ti-microalloyed steel is small, the precipitation temperature of BN greatly increases with further increasing boron content. It is clear from Fig. 6 that the precipitation temperature of aluminum nitride (AlN) decreases considerably with increasing boron contents. In these three steels, the amount of NbC precipitates is extremely small. As shown in Fig. 6, the amount of NbC precipitates decreases with increasing boron content.
Fig. 7 presents the TEM micrographs of precipitates formed in the steels deformed at 900°C. These precipitates are about 20 nm in size and cube-like in morphology as shown in Fig. 7. The precipitates were identified as NbC and TiN in sample A1. NbC and TiN were also observed in samples A2 and A3. In addition, the precipitates with larger size were occasionally found in samples A1, A2 and A3 as shown in Fig. 8 and Fig. 9. These large precipitates are in the form of a thin NbC film surrounding a TiN core. These coarse precipitates are about several hundred nanometers, and invalid for pinning grain boundary.18)

It appears from Fig. 6 that the amount of fine Nb-Ti-containing precipitates increases with the decrease in temperature. The precipitates formed in the studied steel are shown in Fig. 7. These fine precipitates could play a role in pinning grain boundaries. Consequently, the migration ability of grain boundaries was hindered, and the development degree of dynamic recrystallization was also decreased.12) Therefore, the hot ductility of the steel decreases sharply from 1000°C as shown in Fig. 3. It was also found that the hot ductility decreased less with increasing boron content.

Figure 10 presents the TEM micrograph of typical BN complex precipitate in boron-containing steel deformed at 900°C. It was identified as the precipitate in the form of BN layer forming on a TiN particle. This suggests that BN nucleates on TiN during its formation. The similar finding has been reported by Cho et al.3) The complex precipitates are about 500 nm in size. These coarse BN cannot play a role in pinning grain boundaries. Consequently, coarse BN would not make a contribution to the improvement in hot ductility. Therefore, the improvement in hot ductility is expected to be associated with soluble boron.

4.2 Microstructure and fractography of the steel with various boron contents

The hot ductility is greatly affected by microalloy elements and temperature in terms of precipitation, microstructural transformation (austenite/ferrite) and dynamic recrystallization. Combining the findings given in Section 4.1 with calculated results by Thermo-Calc shown in Fig. 6, it appears that the formation of BN did not lead to the decrease in precipitates amount. This demonstrates that the difference in decreasing trend shown in Fig. 3 is caused by the varying amount of soluble boron in the steel. Mejia et al.19–21) demonstrated that boron atoms segregated on the grain boundaries reduced the energy needed for grain boundary migration, simultaneously, the activation energy needed for the occurrence of DRX also decreased. It indicates that the hot ductility of
steel would be improved with increasing soluble boron due to more sufficient DRX, which can be proved in Fig. 3 and Fig. 4(b). Therefore, different boron additions would lead to a difference in fracture mode of the steels.

Figure 11 presents the quenched longitudinal microstructure and corresponding fracture surfaces of Nb-Ti-microalloyed steels tested at 900°C. It can be seen that austenite/ferrite transformation has not occurred at 900°C as shown in Figs. 11(a), 11(b) and 11(c). The fracture surface of sample A1 is characterized by typical intergranular ductile fracture as shown in Fig. 11(d), which is suggested by the fracture surface consisting of faceted regions and tearing edges. The fracture surfaces of samples A2 and A3 contain many dimples with varying depth and tearing edges as shown in Figs. 11(e) and 11(f), which are typical characteristics of ductile fracture.22) This is associated with good ductility of boron-containing steel at 900°C.

It was observed from Fig. 12(a) that thin film-like ferrite formed along austenite grain boundaries in sample A1 at 850°C, indicating that austenite/ferrite transformation occurred between 900°C and 850°C. When sample A1 was stretched at 850°C, a strain concentration within much softer ferrite film at austenite grain boundaries occurred,12,23) resulting in voids formation at grain boundaries as evidenced by the fracture surface shown in Fig. 12(d). Flat facets were clearly observed on the fracture surface of sample A1. The facet and its large edge correspond to the grain surface and grain edge, respectively. As shown in Fig. 12(d), the grain surfaces of sample A1 at 850°C are much smoother than that at 900°C. The fracture surface of sample A1 exhibited grain structure and intergranular failure, suggesting brittle fracture. The fracture surface illustrated that sample A2 experienced intergranular ductile deformation at 850°C. There are deep dimples on the fracture surface of sample A3 as shown in Fig. 12(f), which is an indication of intragranular ductile fracture.
The amount and thickness of film-like ferrite increases as the temperature decreases (compare Fig. 13(a) with Fig. 12(a)). Under this condition, the stress concentration on ferrite could be released. Therefore, the austenite grains deformed more uniformly, and the hot ductility of sample A1 was improved. This is the reason that the fracture mode of sample A1 becomes intergranular ductile fracture, which was evidenced by the observations that the grain surfaces were covered with a large amount of fine honeycomb-like dimples as shown in Fig. 13(d). The intergranular ferrite film formed along austenite grain boundaries in sample A2 tested at 800°C as shown in Fig. 13(b), compared with Fig. 12(b). It led to the decrease in the hot ductility of sample A2 to the minimum. Thus, the fracture mode changed from intergranular ductile fracture at 850°C to intergranular brittle fracture at 800°C. No ferrite formed in sample A3 at 800°C. It can be seen from Fig. 13(f) that the fracture surface is characterized by a coexistence of intergranular ductile fracture and intragranular ductile fracture. The former was evidenced by the presence of dimples and tearing edges, and later by deep dimples.

As discussed above, the precipitation of BN did not decrease the amount of fine Nb-Ti-containing precipitates. It is these Nb-Ti-containing precipitates that the hot ductility of the steels was decreased from 1000°C. It was found based on hot tensile test that boron addition could improve the hot ductility of low-carbon Nb-Ti-microalloyed steels. This beneficial effect is caused by the soluble boron instead of the coarse BN.

It has been widely accepted that a small amount of soluble boron could greatly restrain the formation of ferrite.\(^\text{(24,25)}\) Comparing quenched longitudinal microstructure of samples tested at 850°C and 800°C shown in Figs. 12 and 13, it was found that ferrite formed only in the steel with lower boron content. The formation of ferrite was restrained with increasing boron content. This is attributed to the increase in soluble boron content.

5. Conclusions

The effect of boron on the hot ductility of low-carbon Nb-Ti-microalloyed steels was experimentally investigated. The conclusions are summarized as follows:

1) Boron addition is beneficial to improving the hot ductility of low-carbon Nb-Ti-microalloyed steels because of the presence of soluble boron instead of coarse BN in the steel.

2) The hot ductility of the steels decreases more gently from 1000°C with increasing the boron addition. The hot ductility trough roughly disappeared when boron content was increased up to 0.0045 mass%. The formation of NbC, TiN and thin film-like ferrite along grain austenite boundaries leads to the decrease in the hot ductility of Nb-Ti-microalloyed steel.

3) Boron addition in Nb-Ti-microalloyed steel exerts negligible influence on the precipitation temperature and amount of TiN and NbC in the steel. The amount of NbC precipitates is largest, followed by TiN and BN. The precipitation temperature of BN increases considerably with further increasing the boron content.

4) The fracture mode of Nb-Ti-microalloyed steel tends to be more ductile with increasing the boron content of the steel. At the temperatures corresponding to lowest hot ductility trough, the steels without boron and with 0.0025 mass% boron exhibit intergranular brittle fracture, while the steel with 0.0045 mass% boron shows ductile fracture.

Acknowledgments

The authors would like to express their sincere thanks to the State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing (USTB) for the financial support (Grant No. 41603017). This work was also funded by Nanjing Iron and Steel Co. Ltd.

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