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Influence of Cooling Rate on Transformation Behavior of 0.15% V Microalloyed Steel

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Dilation study was carried out in a thermo-mechanical simulator to understand the phase transformation behavior of a 0.15% vanadium microalloyed steel at three different cooling rates, i.e., 2, 5, and 10 °C/s. Results of the study showed that the phase transformation temperatures, namely Ar_3, Ar_1, and B_s of 0.15% vanadium microalloyed steel increased with increase in the cooling rate from 2 to 10 °C/s. It was also observed that a cooling rate of 5 °C/s was sufficient to form bainite microstructure in the plates while both bainite and martensite were formed when cooling rate was increased to 10 °C/s. The findings of dilation study were used to design a rolling programme for commercial production of high strength steel plates of 0.15% vanadium steel chemistry.

Keywords carbon/alloy steels, optical microscopy, transformation behavior

1. Introduction

Vanadium is one of the most potent microalloying elements used for achieving high strength in steel plates through precipitation strengthening. Currently, a large number of steel makers are producing as-rolled plates with yield strength of about 550 MPa from microalloyed steels having about 0.15% vanadium. To fully exploit the potential of vanadium in steel as strength enhancer, thermo-mechanical control processing (TMCP) technology has to be adopted during plate rolling. Cooling rate of rolled plates on run out table is a significant constituent of TMCP technology that plays a vital role in deciding the final microstructure and properties of plates. High cooling rates refine the ferrite-grain size and, thereby, improve the strength and toughness properties of plates (Ref 1). Also, higher cooling rates facilitate formation of hardened phases such as bainite and martensite which further contributes toward increase in the strength of steel (Ref 2).

In the present study, influence of cooling rate on the transformation temperatures and microstructure for 0.15% vanadium microalloyed steel was studied by examining the dilation behavior of the steel. The findings of this study helped in designing a suitable TMCP rolling practice for commercial production of high strength steel plates having about 0.15% vanadium.

2. Experimental

A commercially produced 25-mm-thick plate with following steel composition was selected for the study: C: 0.16%, Mn: 1.50%, Si: 0.4%, S: 0.01%, V: 0.15%, Ti: 0.02%, Al: 0.02%.

From the plate, cylindrical specimens of 10 mm diameter and 90 mm length were fabricated. Dilation behavior of these specimens at three different cooling rates was examined in a thermo-mechanical simulator (Gleeble 3500). The dilation experiments included soaking of specimens at 1000 °C for 2 min and then cooled at three different cooling rates namely 2, 5, and 10 °C/s. All the dilation experiments were carried out under high vacuum ($\sim 10^{-5}$ Torr) condition. Dilation behavior of the steel during heating to 1000 °C and subsequent cooling was recorded in the form of dilation curves. Linear slope method was applied on dilation curves to determine various transformation temperatures such as (i) austenite to ferrite transformation start temperature (Ar_3), (ii) austenite to ferrite transformation finish temperature (Ar_1), (iii) bainite transformation start temperature (B_s), (iv) bainite transformation finish temperature (B_f), (v) martensite transformation start temperature (M_s), and (vi) martensite transformation finish temperature (M_f) attained by specimens during cooling.

Optical microscopy was used to examine the microstructure of specimens cooled at different cooling rates. Finally, hardness value of specimens was evaluated with the help of Rockwell Hardness Tester.

3. Results and Discussions

3.1 Transformation Behavior at 2 °C/s Cooling Rate

Dilation curve (Fig. 1) indicates that the Ar_3 and Ar_1 temperatures were 742 and 610 °C, respectively, for cooling rate of 2 °C/s. However, no bainite transformation tem-2 peratures, i.e., B_s and B_f could be detected in dilation curve

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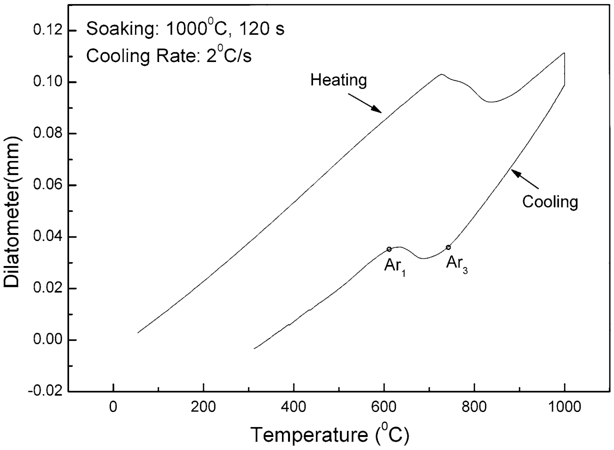

Fig. 1 Dilation plot of 0.15% vanadium microalloyed steel for cooling rate of 2 °C/s

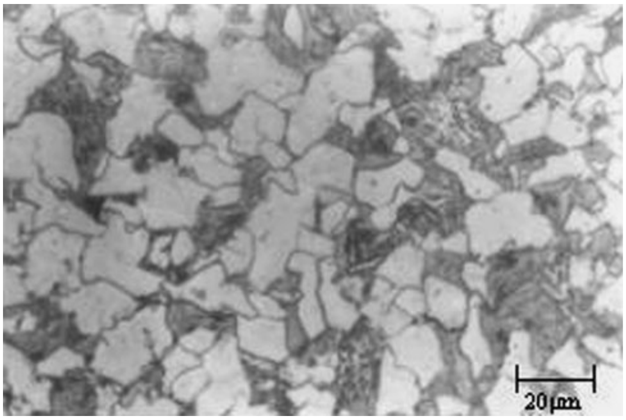

Fig. 2 Microstructure of specimen cooled at 2 °C/s showing predominantly ferrite-pearlite structure

which indicated that bainite did not form when cooling rate was 2 °C/s. Further, optical metallography showed that the microstructure comprised predominantly ferrite and pearlite phases (Fig. 2) and hardness of this specimen was found to be 85 HR_B. These results further confirmed that mainly ferrite and pearlite were formed in 0.15% vanadium microalloyed steel at 2 °C/s cooling rate.

3.2 Transformation Behavior at 5 °C/s Cooling Rate

The Ar_3 and Ar_1 temperatures were 793 and 627 °C, respectively, for cooling rate of 5 °C/s as shown in dilation curve (Fig. 3). Also, distinct bainite transformation temperatures with B_s temperature at 577 °C and B_f temperature at 447 °C could be observed in the dilation curve. This observation indicated that the cooling rate of 5 °C/s was sufficient to ensure bainite formation in 0.15% vanadium steel. Optical metallography showed lath type structure in the specimen indicating the presence of bainite (Fig. 4) which was further confirmed by higher hardness in the specimen which was about 25 HR_c. However, no evidence of martensite transformation temperatures (M_s and M_f) were detected in the dilation curve which showed that even cooling rate of 5 °C/s was not sufficient to form martensite.

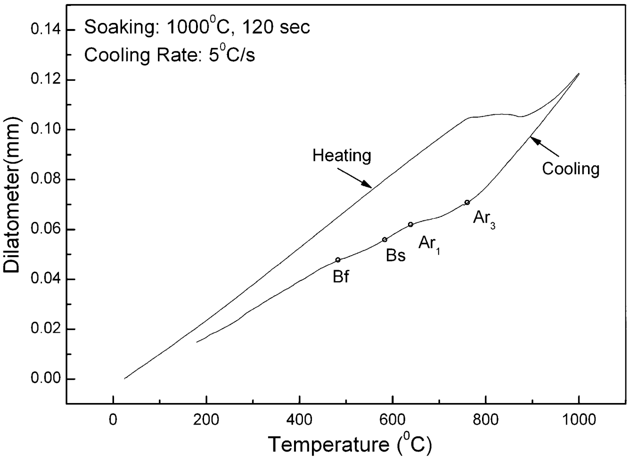

Fig. 3 Dilation plot of 0.15% vanadium microalloyed steel for cooling rate of 5 °C/s

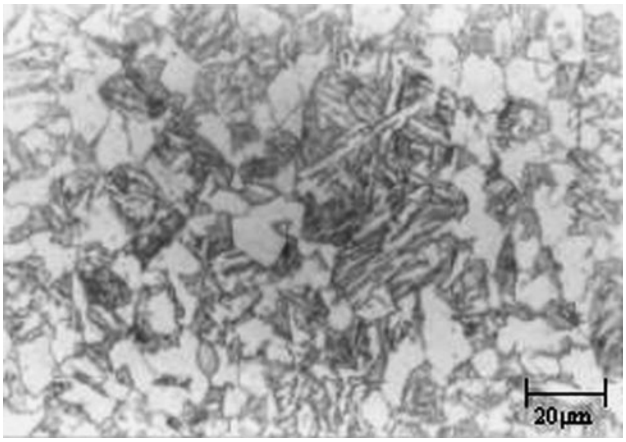

Fig. 4 Microstructure of specimen cooled at 5 °C/s showing predominantly bainite structure

3.3 Transformation Behavior at 10 °C/s Cooling Rate

Finally, dilation curve of specimen cooled at the rate of 10 °C/s showed that B_s and B_f temperatures were 567 and 413 °C, respectively (Fig. 5). Interestingly, dilation curve did not show any evidences of Ar_3 and Ar_1 temperatures which indicates that cooling rate of 10 °C/s was too rapid to form ferrite and pearlite. On the other hand, distinct M_s and M_f temperature at 370 and 298 °C, respectively, were observed in dilation curve which shows that 10 °C/s cooling rate was adequate to achieve martensite formation. Optical microscopy of specimen showed that the microstructure was predominantly a mixture of martensite and bainite (Fig. 6). The hardness of this specimen was found to be ~40 Rc which further confirmed the presence of low transformation temperature products such as bainite and martensite at higher cooling rate of 10 °C/s.

3.4 Variation in Transformation Temperatures with Cooling Rate

One interesting observation was made from this study that the transformation temperatures namely Ar_3, Ar_1, and B_s increased with increase in cooling rate from 2 to 10 °C/s as is evident from the Table 1. In general, transformation temperatures in steels are lowered when the cooling rate increases and,

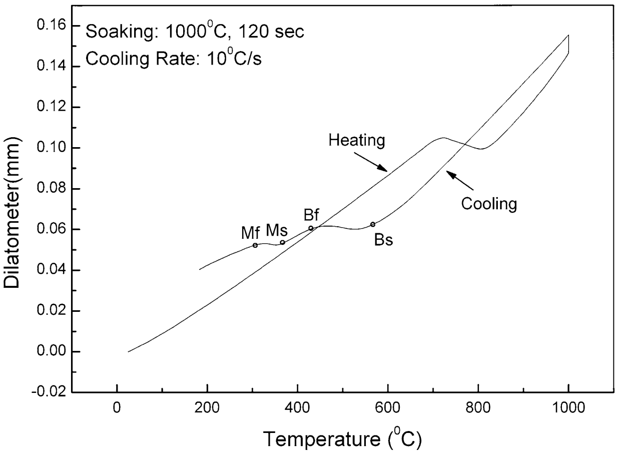

Fig. 5 Dilation plot of 0.15% vanadium microalloyed steel for cooling rate of 10 °C/s

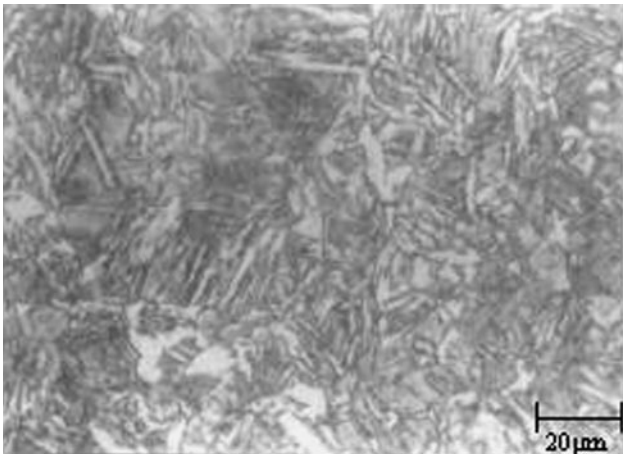

Fig. 6 Microstructure of specimen cooled at 10 °C/s showing combination of bainite and martensite structure

therefore, the results of present study were contrary to the normal effect of cooling rate on transformation temperatures. This finding indicates that higher amount of dissolved vanadium led to increase in transformation temperatures. It may be mentioned here that vanadium was completely in solution when specimens were heated to 1100 °C since dissolution temperature of vanadium carbonitride particles is normally below 1000 °C (Ref 3). During subsequent cooling of specimens, lesser amount of vanadium had precipitated out and larger amount of vanadium remained dissolved at higher cooling rates while more vanadium had come out as precipitates and lesser amount remained in solution at slower cooling rate. It has been shown by Pickering through his empirical formula (Ref 4) that Ar_3 temperature increases with increase in dissolved vanadium content in steel and, therefore, confirms the finding of present study regarding increase in Ar_3 temperature with cooling rate for 0.15% vanadium microalloyed steel. However, authors of this letters have not come across any formula showing the effect of vanadium on other transformation temperatures such as Ar_1 and B_s, though empirical formulae are available which shows the effect of various elements such as Mn, Si, Mo, Cr, and Ni on these transformation temperatures (Ref 5, 6).

Table 1 Various transformation temperatures observed at different cooling rates in a 0.15% vanadium microalloyed steel

Cooling rate, °C/s	Transformation temperatures, °C					
	Ar_3	Ar_1	B_s	B_f	M_s	M_f
2	742	610	···	···	···	···
5	793	627	577	447	···	···
10	···	···	567	413	370	298

The above findings on the phase transformation behavior of 0.15% vanadium steel were used for industrial production of 12.5-mm-thick plates with yield strength of about 550 MPa. A steel chemistry with 0.15% vanadium was specially designed for the production of these plates in a plate mill having limited rolling load capacity. The plates were allowed to cool in the air with a cooling rate of about 2 °C/s because dilation study showed that a cooling rate of 5 °C/s was sufficient to form bainite that would have adversely affected the impact toughness properties of the plates. Finishing temperature during plate rolling was maintained at about 800 °C as it was not feasible to reduce the finishing temperature below 800 °C due to limitation of plate mill.

4. Conclusions

- For a microalloyed steel containing 0.15% vanadium, a cooling rate of 5 °C/s was sufficient to evolve bainite while cooling rate of 10 °C/s produced a microstructure comprising both bainite and martensitic.
- With increase in cooling rate, the transformation temperatures namely Ar_3, Ar_1, and B_s of 0.15% vanadium microalloyed steel increased.

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