

EFFECT OF AUSTENITE GRAIN SIZE ON THE BAINITIC TRANSFORMATION IN A HOT-ROLLED LOW CARBON MICROALLOYED STEEL*

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Abstract

In this presentation, a low carbon high strength steel microalloyed with Nb and Ti was processed by thermo-mechanical controlled process (TMCP) containing two stages of controlled rolling. The austenite with various grain sizes was obtained by austenitizing this hot-rolled steel at different temperatures. And the effect of austenite grain size on bainitic transformation was investigated in a dilatometer to reveal microstructural change. The results showed that the microstructure of the hot-rolled steel was mainly composed of granular bainite, lath-like bainite, and martensite/austenite constituents (M-A constituents). With increasing the austenitizing temperature, or increasing the austenite grain size, the microstructure was changed from granular bainite to lath bainite. When the steel was reheated to a lower temperature of 860 °C, a relatively higher start temperature (B_s) was measured for bainitic transformation. This was mainly caused by the formation of solute-depleted region in the austenite and the promotion of the granular bainitic nucleation. The highest reaction rate occurred at austenitizing temperature of 1000 °C with fine grain size, while the coarse austenite grain can lead to a sharp increase in the amount of bainite. An analysis was made on the kinetics of bainite transformation which was controlled by the volume diffusion of C atom.

Keywords: Hot-rolled low carbon steel; Bainite transformation; Austenite grain size; Austenitizing temperature.

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1 INTRODUCTION

Hot-rolled low carbon microalloyed steels are widely used in the fields of engineering machinery, heavy vehicles, shipbuilding, bridges and construction due to their higher strength, excellent low-temperature toughness and heat-resistance at elevated temperature [1, 2]. The typical benefit from these microalloyed steels is the grain refinement due to the Zener pinning effect from fine microalloy (Ti, Nb, V) nitrides or carbides [3-5]. Understanding solid-state phase transformation is of vital importance to design superior microstructures and to optimize mechanical properties of the steels [6]. Bainitic microstructure in hot-rolled low carbon microalloyed steel is of great importance for achieving a sound combination of strength and toughness. To do this, a better understanding of bainite formation and satisfactory modeling of the transformation kinetics and microstructural evolution is required. There are many factors that influence the kinetics of bainitic transformation which include chemical composition, austenitizing temperature, deformation of austenite and phase transformation temperature etc. Girault et al. [7] believed that the total bainitic transformation kinetics depends on the austenitizing temperature.

Austenitizing temperature is well known to have a significant influence on the austenite grain size (AGS) and mechanical properties of the steels. Lee et al. [8] and Umemoto et al. [9] reported that the rate of bainite reaction is increased by a decrease in AGS, while Hu et al. [10] suggested that the transformation of bainite is accelerated by a coarse AGS. This is due to the fact that coarse austenite grains provide less nucleation sites and this is beneficial for bainite sheaf growth. Matsuzaki and Bhadeshia [11] found that different steels can show opposite effects of the AGS on the bainitic reaction rate and that the difference in kinetic behavior is accompanied by obvious distinctions between the bainite microstructures. They

also derived a general equation describing the reaction rate considering the bainite morphology. The equation predicts that the overall kinetics of bainitic transformation is increased by decreasing the AGS when the overall kinetics is limited by a slow growth rate, whereas the grain refinement reduces the overall kinetics for rapid growth from a limited number of nucleation sites. Yamamoto et al. [12] reported that the AGS has no appreciable effect on the bainitic transformation temperature under continuous cooling conditions. Because of inconsistent results among above researchers, the effect of AGS on the bainitic transformation kinetics is controversial and disunified.

In this study, therefore, the aim of the research is to investigate the detailed relationship between the AGS and kinetics of bainitic transformation occurring during continuous cooling in a hot-rolled low carbon microalloyed steel.

2 MATERIAL AND METHODS

The experimental material used in this study is a novel low carbon microalloyed steel for high-performance construction. The chemical composition contains (in wt pct) 0.07 C, 0.25 Si, 1.10 Mn, 1.6 (Ni+Cu+Mo+Cr), 0.12 (V+Nb+Ti), 0.007 (N+B) and balanced Fe. After vacuum induction melting, casting and forging, the steel slab was subjected to two-stage controlled rolling and cooling. At the first stage of controlled rolling, the slab was hot-rolled by four passes in temperature range of 1080-1050 °C. At the second stage, the steel slab was hot-rolled to plates of 20 mm in thickness by nine passes in temperature range of 930-880 °C. When the temperature dropped to 780 °C, the plate was rapidly cooled to 480 °C by the UFC (ultra-fast cooling) system. The specimens for dilatometric test were cut from the hot-rolled plate near the surface and the specimen size is $\phi 3$ mm \times 10 mm. In order to obtain various austenite grain sizes, the specimens were reheated to different

temperatures of 1250 °C, 1000 °C and 860 °C at a heating rate of 20 °C/s. The simulated heat treatment process is presented in Figure 1. And this was carried out in a full automatic phase transformation tester (Formaster-FII). Each specimen was first austenitized at peak temperature for 5 s, and then it was cooled to 800 °C in 8 s from peak temperature, respectively. After that, they were cooled to room temperature at a cooling rate of 10 °C/s. The changes in length of the three specimens were recorded in the whole heat treatment process.

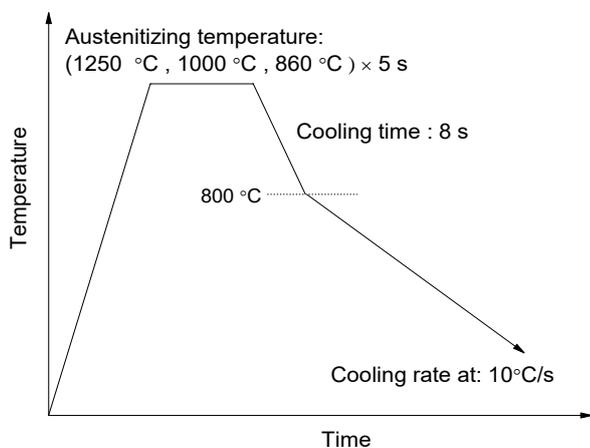


Figure 1. Schematic diagram of the simulated heat treatment process.

After mechanically polished and etched in 4 vol.% nital solution at room temperature, the microstructures of this low carbon microalloyed construction steel were observed in an optical microscope (OM, LEICA Q550IW). To reveal the morphology of M-A constituents, the polished specimens were etched with LePera reagent. Average prior austenite grain size was measured with the line intercept method based on low magnification optical micrographs.

3 RESULTS AND DISCUSSION

3.1 Microstructural observation

Figure 2 shows the optical microstructures of the specimens under three heat treatment conditions. As the austenitizing

temperature was raised from 860 °C to 1250 °C, the average AGS was increased from 8 µm to 60 µm. When the specimen was austenitized at 860 °C (slightly higher than the A_{c3} temperature 790 °C of the steel), the microstructures consisted of typical fine quasi-polygonal ferrite and a small fraction of granular bainite (Figure 2(a)). And the block martensite and small M-A constituents occurred frequently along the grain boundary, which can be revealed in white after etched with LePera reagent as shown in Figure 3(a).

Increasing austenitizing temperature to 1000 °C resulted in a visible amount of lath bainite (or bainitic ferrite) along with granular bainite and less M-A constituents as shown in Figures 2(b) and 3(b), and the normal grain growth of austenite occurred due to pinning effect on the grain boundary migration of nano-precipitates. The austenite grain boundaries are clear and complete in the product phase because the bainite transformation is always limited within the austenite grain by displacive and ledge growth mechanisms [13]. The microstructure changed into a mixture of lath bainite and lath martensite when the specimen was austenitized at 1250 °C (Figures 2(c) and 3(c)), and the abnormal growth takes place in prior austenite grains.

3.2 Dilatometric curve

The dilatometric curves in the length of the specimens treated with different austenitizing temperatures at the cooling rate of 10 °C/s are shown in Figure 4. The bainite start (B_s) and finish (B_f) temperatures were taken as the temperatures corresponding to the points deviating from the thermal expansion lines of austenite and bainite on the dilatometric curve, respectively [8]. In Figure 4, arrows indicate the B_s and B_f temperature of samples at the austenitizing temperature of 860 °C. Moreover, it can be seen that austenitizing temperatures have a certain effect on bainite transformation behavior

and B_s/B_f temperature of the hot-rolled low carbon microalloyed steel.

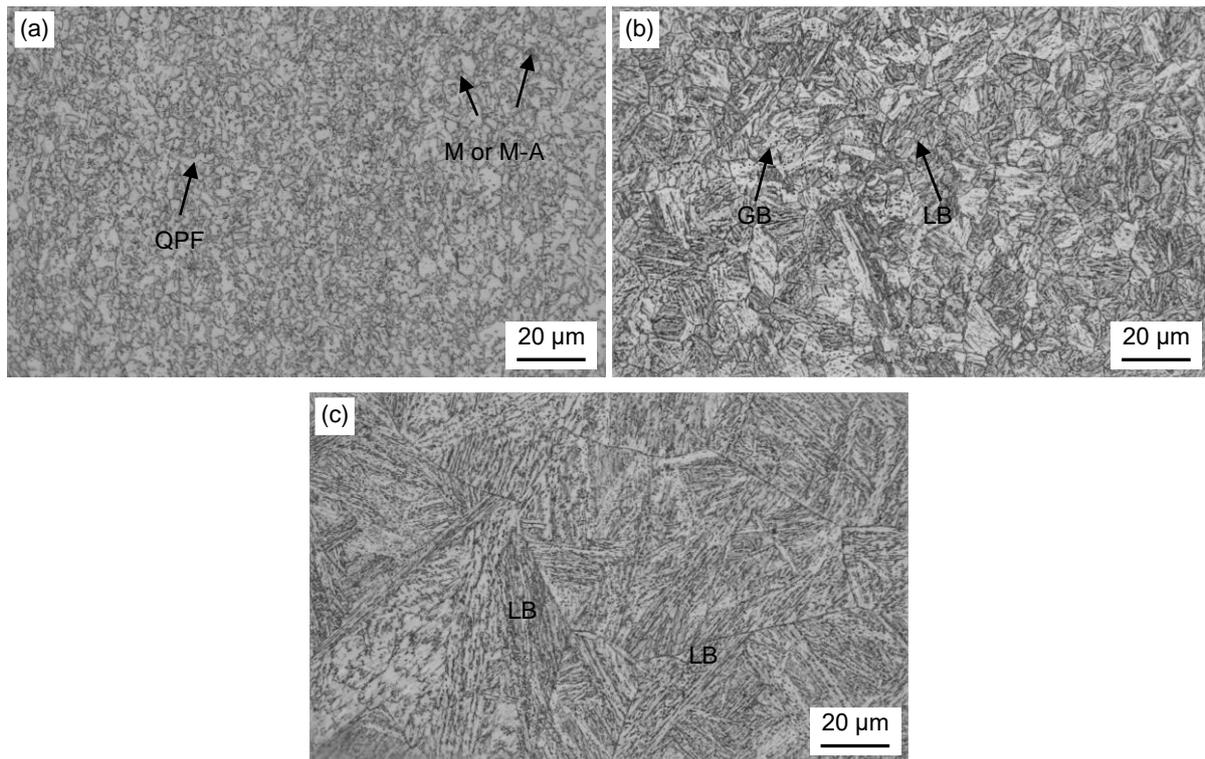


Figure 2. Optical microstructures of low carbon microalloyed steel with different austenitizing temperatures: (a) 860 °C; (b) 1000 °C; (c) 1250 °C. (QPF: quasi-polygonal ferrite; M: martensite; M-A: martensite-austenite constituents; GB: granular bainite; LB: lath bainite)

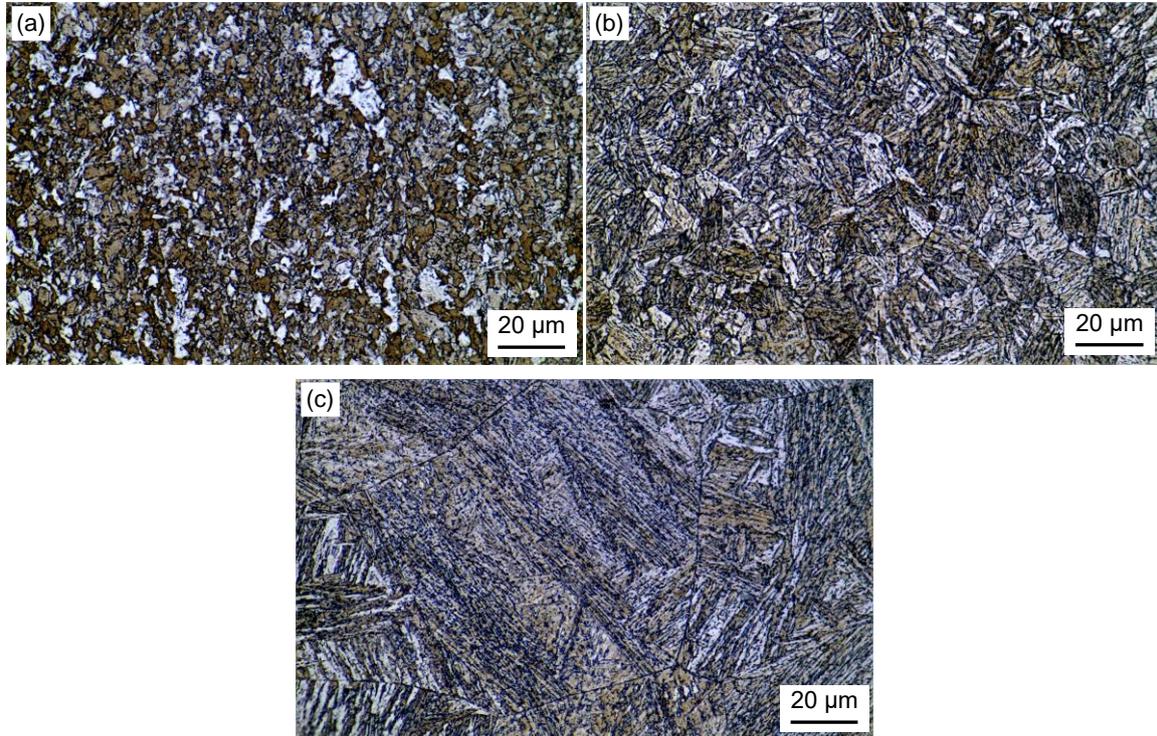


Figure 3. Optical micrographs showing the distribution and morphology of M-A constituents etched with LePera reagent with different austenitizing temperatures: (a) 860 °C; (b) 1000 °C; (c) 1250 °C.

The B_s and B_f temperatures of the specimen austenitized at 1000 °C was

lower than those for the specimens of 860 °C and 1250 °C austenitization, especially

for the B_s temperature. Austenitizing temperature of 1000 °C was lower than the austenite coarsening temperature for this hot-rolled steel, so the austenite grain only grew normally, and the fine-grained austenite was obtained. The bainitic nucleation mechanism is proposed for the shear transformation mechanism, which is generally considered that crystal nucleus with BCC structure forms by the separation of the original dislocation. Fine austenite grains with high density dislocation retards the bainite nucleation by inhibiting the mobility of incipient crystal with BCC structure. Thus, the higher supercooling can compensate for the higher driving force required for phase transformation in fine-grained austenite. As for the specimen with the lowest austenitizing temperature of 860 °C, its B_s temperature was relatively higher due to the inhomogeneous chemical composition in the austenite. The solute-depleted region in the austenite can promote the nucleation of product phase [14]. Therefore, in combination with the microstructural characteristics in Figure 2, the polygonal ferrite formed firstly at the lowest austenitizing temperature with higher B_s temperature. When the heating temperature was 1250 °C, the AGS was coarse, which leads to the reduced bainitic nucleation site. Moreover, the austenite stability was improved due to the full dissolution and uniform distribution of alloying elements. Thus, lower B_s temperature was resulted from the bainite.

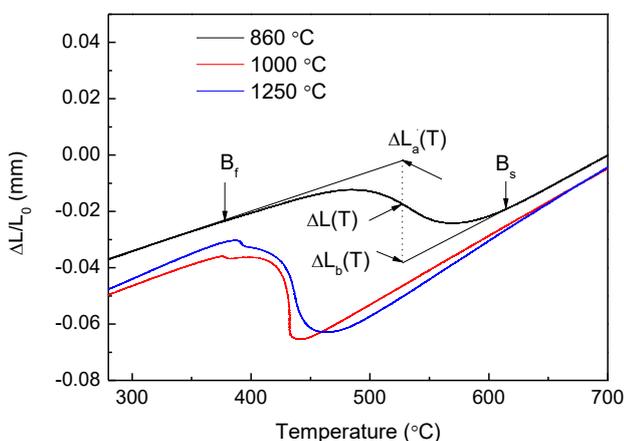


Figure 4. Dilatometric curves for the low carbon

microalloyed steel dealt with different austenitizing temperatures.

3.3 Kinetics of continuous cooling bainitic transformation

The volume fraction of transformed phase ($f_v(T)$) can be evaluated by Equation (1) according to the classical lever rule based on the dilatometric curves, as shown in Figure 4.

$$f_v(T) = \frac{\Delta L(T) - \Delta L_b(T)}{\Delta L_a(T) - \Delta L_b(T)} \quad (1)$$

where $\Delta L(T)$ is the actual value of relative length of the specimen at a temperature T , while $\Delta L_a(T)$ and $\Delta L_b(T)$ can be obtained by extrapolating of the linear thermal expansion portions of the fully austenite and bainite to T , respectively.

Figure 5 shows the kinetic curve of hot-rolled low carbon microalloyed bainitic steel with a typical s-type. It was assumed that austenite transformed to bainite completely. Although there is retained austenite in the transformed products, the small volume fraction of the retained austenite can be neglected in the calculation. The s-shape of kinetic curve is controlled by the phase transformation driving force and temperature. As the phase transformation temperature decreases, the undercooling and driving force increases, but the carbon diffusion is uneasy. Thus the fastest transformation rate of bainite transformation occurs at the middle temperature [15].

The influence of the AGS on the bainitic transformation does not appear to be continuous. When the austenitizing temperature was lower than 1000 °C, the increased AGS had a significant role in accelerating the bainitic transformation. However, when the austenitizing temperature was higher than 1000 °C, the acceleration effect was not so obvious. Hu et al. [10] suggested that there is a critical AGS, below which there is a distinct grain size effect and above which this is not evident, and the bainite sheaf length of

critical AGS is equal to AGS. So it is thought that below the critical AGS there is large number bainite nucleation at grain boundary and that there exists a lot of hard impingement. Above the critical AGS the nucleation density is markedly reduced and the bainite sheaves grow across the austenite grain.

The transformation kinetic curves further show that the austenite grain austenitized at 1000 °C reduces the bainite transformation temperature ranges. And the bainite sheaf length austenitized at 1000 °C was close to AGS (Figure 2). Besides, the transformation rate for the sample austenitized at 860 °C decreased obviously near the intermediate stage of phase transformation, which was mainly attributed to the carbon concentration in austenite discharged from polygonal ferrite. Therefore, the transformation kinetics is partly controlled by the carbon diffusion at the final stage of transformation [16].

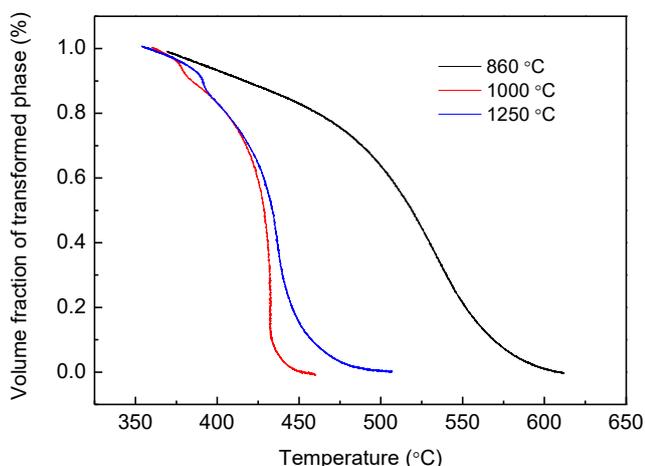


Figure 5. Kinetic curves of bainite transformation in low carbon microalloyed steel austenitized at different temperatures.

The detailed variation of bainite reaction rate with different austenitizing temperature is shown in Figure 6. It can be found that the reaction rate of austenitizing temperature of 1000 °C was higher than that of the other two austenitizing temperatures. There are two main reasons for promoting the bainitic transformation by this AGS. One is that the preferential nucleation site in critical AGS is much

more than that of the above critical AGS, when the phase transformation driving force provided by Gibbs free energy is greater than the nucleation potential barrier. The other reason is that the higher supercooling temperature leads to a higher nucleation rate. It can be also found that the low carbon microalloyed steel after austenitized at 1000 °C has a transformation stasis at the initial stage, indicated by dotted arrow in Figure 6. The stagnation of the phase transformation was mainly resulted from solid solution dragging of elements Ti and Nb at the ferrite/austenite interface which inhibits bainitic phase nucleation. The phase transformation temperature was relatively higher at the initial stage of bainitic transformation, the coupled solid solution dragging effect between atoms Ti, Nb and carbon can inhibit the migration of the phase interface, which was identical to reduction of the phase transformation rate. After the formation of (Ti, Nb)C precipitates, the solid solution drag effect weakened or disappeared, and the migration of the phase interface was reactivated again. In addition, the other peak transformation rate appeared at the final stage of transformation indicated by the full line arrow in Figure 6. Gupta et al. [17] considered that the occurrence of the second peak is attributed to the formation of interplate precipitates or secondary M-A constituents. In the present study, the lath bainite (or bainitic ferrite) formed, and the carbon atoms can be deposited in the form of carbides as well as the M-A constituents (Figure 3). Thus, the growth of bainite lath can be accelerated again at the final stage of transformation.

The phase transformation rate has a close relation to the nucleation, growth and impingement of product phase. According to the microstructure analysis, the primary positions of lath bainite nucleation were the grain boundaries and its simultaneous nucleation on the pre-existing bainite lath (see in Figure 2). And the nucleation mechanism is always regarded as the

martensite-like shear mechanism. The morphology of the parallel lath structure represents a highly anisotropic and one-dimensional growth. On the contrary, the polygonal ferrite as well as the ferrite matrix was inclined to transform with constant nucleation rate and three- or two-dimensional growth at the lower cooling rate. Liu et al. [18] proposed analytical model to determine the kinetic information from maximum transformation rate analysis and concluded that the impingement mode can be determined by the position of the maximum of transformation rate for isochronal phase transformations. According to Figures 5 and 6, the position of peak transformation rate occurs in the vicinity of fifty percent volume fraction transformed for the cooling rates of 10 °C/s, which indicates that the prevailing type of impingement mode was anisotropic growth because the volume fraction transformed at the position of peak rate was less than 0.632 [18]. Obviously, this result was also fully supported by the morphology of microstructure as mentioned above.

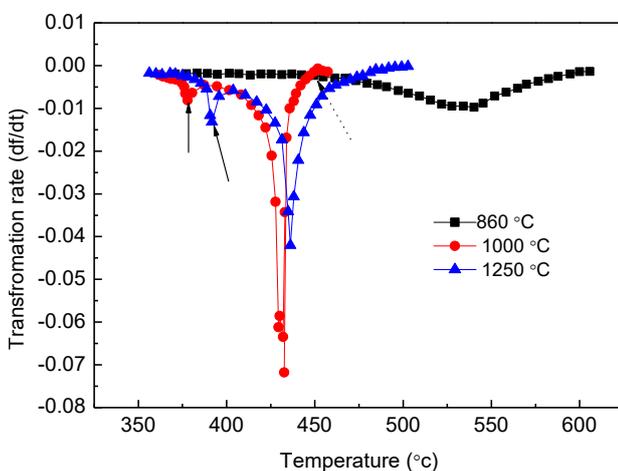


Figure 6. Transformation rate as a function of cooling temperature of the low carbon microalloyed steel with different austenitizing temperatures.

4 CONCLUSIONS

(1) For the hot-rolled low carbon microalloyed steel, as the austenitizing temperature was increased, the microstructure was changed from polygonal ferrite and granular bainite to

lath bainite and lath martensite, and the average AGS was increased from 8 μm to 60 μm .

(2) The B_s temperature and bainitic transformation temperature range of the steel with austenitizing temperature of 1000 °C was lower and narrower than those austenitized at 860 °C and 1250 °C.

(3) The grain growth played more important role in the acceleration of the bainitic transformation. For the prior austenite below a critical grain size (austenitized at 1000 °C), it had a distinct grain size effect. The stagnation of the phase transformation was mainly caused by the solid solution dragging. The prevailing type of impingement mode is anisotropic growth.

Acknowledgments

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REFERENCES

- 1 Das Bakshi S, Javed N, Sasidhar KN, Dhande T, Sharma V, Mukherjee M. Effect of microstructure and crystallographic texture on mechanical anisotropy of Ti-Nb microalloyed hot rolled 800MPa HSLA steel. *Mater Charact.* 2018; 136: 346-357.
- 2 Sasidhar KN, Dhande T, Javed N, Ghosh A, Mukherjee M, Sharma V, Mahashabde VV, Das Bakshi S. Effect of transformation texture on the impact toughness of hot-rolled Ti+Nb microalloyed steel. *Mater Design.* 2017; 128: 86-97.
- 3 Baker TN. Processes, microstructure and properties of vanadium microalloyed steels. *Mater Sci Technol.* 2009; 25: 1083-1107.
- 4 Lee SI, Lee J, Hwang B. Microstructure-based prediction of yield ratio and uniform elongation in high-strength bainitic steels

- using multiple linear regression analysis. *Mater Sci Eng A*. 2019; 758: 56-59.
- 5 Hulka K, Kern A, Schrieffer U. Application of niobium in quenched and tempered high-strength steels. *Mater Sci Forum*. 2005; 500-501: 519-526.
- 6 Luzginova NV, Zhao L, Sietsma J. Bainite formation kinetics in high carbon alloyed steel. *Mater Sci Eng A*. 2008; 481-482: 766-769.
- 7 Girault E, Jacques P, Ratchev P, Van Humbeeck J, Verlinden B, Aernoudt E. Study of the temperature dependence of the bainitic transformation rate in a multiphase TRIP-assisted steel. *Mater Sci Eng A*. 1999; 273-275: 175-182.
- 8 Lee SJ, Parkb JS, Lee YK. Effect of austenite grain size on the transformation kinetics of upper and lower bainite in a low-alloy steel. *Scripta Mater*. 2008; 59: 87-90.
- 9 Umemoto M, Horiuchi K, Tamura I. Transformation Kinetics of Bainite during Isothermal Holding and Continuous Cooling. *Trans ISIJ*. 1982; 22(11): 854-861.
- 10 Hu F, Hodgson PD, Wu KM. Acceleration of the super bainite transformation through a coarse austenite grain size. *Mater Lett*. 2014; 122: 240-243.
- 11 Matsuzaki A, Bhadeshia HKDH. Effect of austenite grain size and bainite morphology on overall kinetics of bainite transformation in steels. *Mater Sci Technol*. 1999; 15: 518-522.
- 12 Yamamoto S, Yokoyama H, Yamada K, Niikura M. Effects of the austenite grain size and deformation in the unrecrystallized austenite region on bainite transformation behavior and microstructure. *ISIJ Int*. 1995; 35(8): 1020-1026.
- 13 Li S, Zhu R, Karaman I, Arróyave R. Development of a kinetic model for bainitic isothermal transformation in transformation-induced plasticity steels. *Acta Mater*. 2013; 61: 2884-2894.
- 14 Wu HD, Miyamoto G, Yang ZG, Zhang C, Chen H, Furuhashi T. Incomplete bainite transformation in Fe-Si-C alloys. *Acta Mater*. 2017; 133: 1-9.
- 15 Xu ZY, Liu SK. *Bainite and bainite transformation*. Beijing: Science Press, 1991.
- 16 Chen H, Zhu K, Zhao L, van der Zwaag S. Analysis of transformation stasis during the isothermal bainitic ferrite formation in Fe-C-Mn and Fe-C-Mn-Si alloys. *Acta Mater*. 2013; 61: 5458-5468.
- 17 Gupta C, Dey GK, Chakravartty JK, Srivastava D, Banerjee S. A study of bainite transformation in a new CrMoV steel under continuous cooling conditions. *Scripta Mater*. 2005; 53: 559-564.
- 18 Liu F, Song SJ, Sommer F, Mittemeijer EJ. Evaluation of the maximum transformation rate for analyzing solid-state phase transformation kinetics. *Acta Mater*. 2009; 57: 6176-6190.