International Journal of Minerals, Metallurgy and Materials
Volume 17, Number 5, October 2010, Page 567
DOI: 10.1007/s12613-010-0358-9

Toughening mechanisms of a high-strength acicular ferrite steel heavy plate

Zhi-qiang Cao[1,2], *Yan-ping Bao*[1], *Zheng-hai Xia*[2], *Deng Luo*[3], *Ai-min Guo*[3], *and Kai-ming Wu*[3]

1) Engineering Research Institute, University of Science and Technology Beijing, Beijing 100083, China
2) Research & Development Center, Xiangtan Iron and Steel Co. Ltd., Xiangtan 411101, China
3) Hubei Province Key Laboratory for Systems Science on Metallurgical Processing, Wuhan University of Science and Technology, Wuhan 430081, China
(Received: 8 November 2009; revised: 12 December 2009; accepted: 20 December 2009)

Abstract: An ultra-low carbon acicular ferrite steel heavy plate was obtained with an advanced thermo-mechanical control process-relaxed precipitation controlled transformation (TMCP-RPC) at Xiangtan Steel, Valin Group. The heavy plate has a tensile strength of approximately 600 MPa with a lower yield ratio. The impact toughness of the heavy plate achieves 280 J at –40°C. The fine-grained mixed microstructures of the heavy plate mainly consist of acicular ferrite, granular bainite, and polygonal ferrite. The high strength and excellent toughness of the heavy plate are attributed to the formation of acicular ferrite microstructure. The prevention of blocks of martensite/retained austenite (M/A) and the higher cleanness are also responsible for the superior toughness.

Keywords: high-strength; steel; microstructure; mechanical properties; acicular ferrite

[*This work was financially supported by the National Natural Science Foundation of China (Nos.50471107 and 50734004).*]

1. Introduction

Toughness is a very important factor for materials design and applications. High impact toughness in the base metal and heat-affected zone (HAZ) is required for high strength steels [1-3]. In recent years, extensive studies on the toughness improvement of weld metal and HAZ have been carried out [4-8]. Heavy plates are usually used to manufacture important structural parts such as bridges, buildings, and pressure vessels *etc.* [9-10]. Therefore, good toughness and low yield ratio are main considerations for heavy plate manufacturing and applications.

To improve the weldability and reduce welding costs for heavy plates, carbon content has been reduced gradually in the last decades. Many kinds of ultra-low carbon bainitic steels (ULCB) have been developed for structural applications with optimal mechanical properties in recent years [10-13]. Although the weldability is improved by carbon content reduction and the strength is raised by bainitic microstructure, the higher yield ratio and lower temperature toughness are still to be solved. In addition, the essential problems are associated with nonuniform microstructures in the production of heavy plates. The present work is to investigate the microstructural evolution in a steel heavy plate. It aims to obtain a microalloyed steel heavy plate with a good combination of high strength with lower yield ratio and good toughness at lower temperatures.

Since the last decades, various techniques of thermomechanical control process have been developed to refine the microstructures of steels [14]. It was reported recently that a thermo-mechanical control process-relaxed precipitation controlled transformation (TMCP-RPC) was attempted to refine the microstructures of low-carbon microalloyed bainitic steels [15-16]. Wang *et al.* [15] indicated that fine-grained microstructures were obtained by means of the precipitation of Nb-Ti carbides and/or carbonitrides and the interaction of dislocations in this process. In the present work, an ultra-low carbon acicular ferrite steel heavy plate

Corresponding author: Kai-ming Wu E-mail: wukaiming@wust.edu.cn

with the uniform microstructure and superior toughness was attempted to produce by an advanced TMCP-RPC process.

2. Experimental

The liquid steel was made and refined by hot metal desulphurization, combined blowing converter steelmaking, vacuum degassing, and then continuously cast into slabs. The chemical composition of the steel heavy plate is shown in Table 1. The production route is schematically illustrated in Fig. 1. Slabs are reheated to 1180°C, and then deformed at the recrystallized zone (stage 1) and the non-recrystallized zone (stage 2), followed by relaxing for a fixed time. As relaxing finished, plates are immediately cooled to a lower temperature and then air-cooled.

Table 1. Chemical composition of the steel plate wt%

C	Si	Mn	P	S	Nb	Ti	Cr+Ni+Mo+Cu	Al
0.03	0.15-0.55	1.20-1.60	0.014	0.0040	0.015-0.055	0.008-0.030	≤1.0	0.032

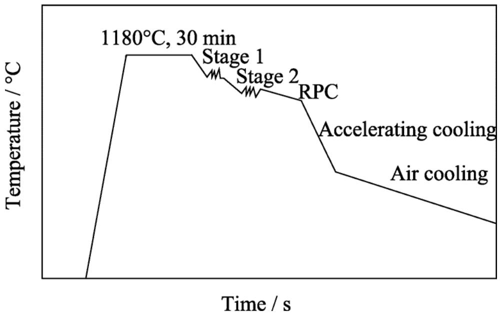

Fig. 1. Schematic illustration of an advanced TMCP-RPC process.

The specimens were mechanically polished and then etched with 3vol% nital solution. Microstructural observations were made using optical microscopy (OM, Olympus PME3-3) and scanning electron microscopy (SEM, Philips XL30W/TMP). The specimens were cut from the 1/4 thickness of the heavy plate for transmission electron microscopy (TEM). Thin foil specimens were prepared by a twin jet unit. TEM observations and electron dispersive X-ray spectroscopy (EDXS) analyses were conducted on a microscope (Tecnai G2.20).

3. Results

3.1. Continuous cooling transformation curves

Continuous cooling transformation (CCT) curves of the heavy plate were calculated by JMatPro with the chemical composition shown in Table 1. The grain size of austenite before transformation was estimated to be about 15 μm according to the practice of similar steel grades at Xiangtan Steel. The CCT curves of the heavy plate are shown in Fig. 2. It shows that ferrite and bainite form in a wide range of cooling rates, from approximately 1 to 50°C/s. This big "cooling rate window" facilitates to obtain a uniform microstructure from the plate surface to the plate center in an industrial scale production.

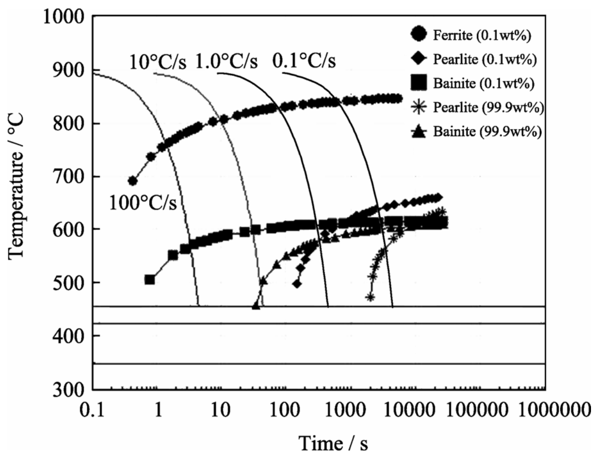

Fig. 2. Calculated CCT curves of the heavy plate steel.

3.2. Microstructure observation

Fig. 3 shows the microstructures in OM through the thickness of the heavy plate obtained by an advanced TMCP-RPC technique. It is seen that the mixed microstructures consist of acicular ferrite (AF), granular bainite (GB), polygonal ferrite (PF), and martensite/retained austenite (M/A). The microstructure of the heavy plate surface is finer than that in the center. The smaller size of ferrite grains on the surface of the heavy plate results from the higher cooling rate. Fig. 4 presents a SEM micrograph of the heavy plate. Granular bainite is equiaxed and nearly 10 μm in diameter. Acicular ferrite is several micrometers in length and 2-3 μm in thickness. Polygonal ferrite is 5-7 μm in diameter. The size of M/A constituents is approximately 1 μm. It can be seen in Figs. 3 and 4 that the fine-grained mixed microstructures are obtained by an advanced TMCP-RPC technique.

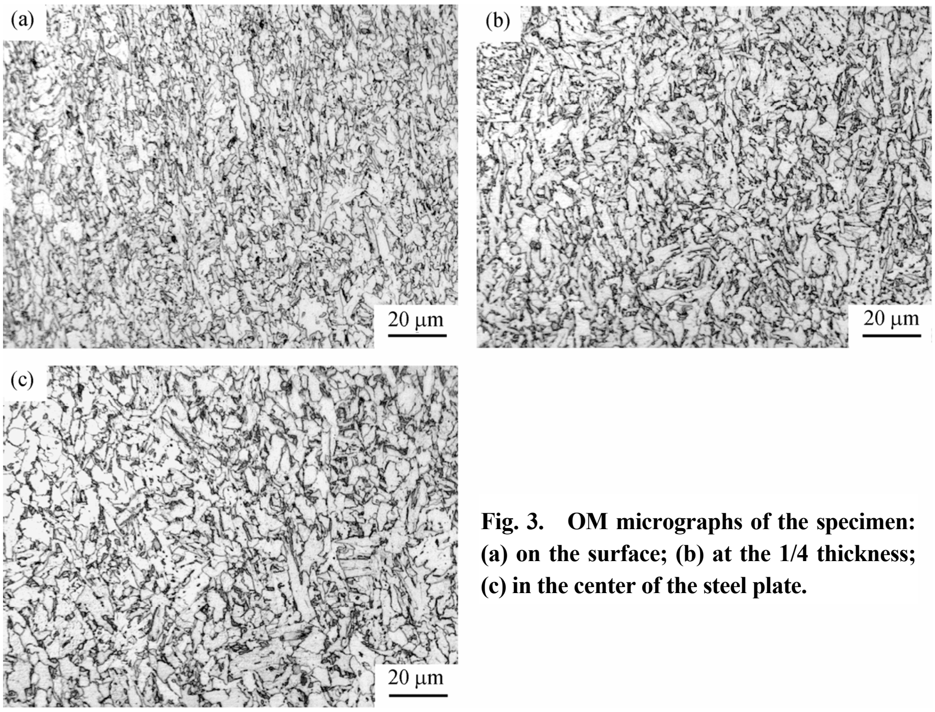

Fig. 3. OM micrographs of the specimen: (a) on the surface; (b) at the 1/4 thickness; (c) in the center of the steel plate.

Acicular ferrite is regarded as an intragranularly nucleated bainite [17]. The CCT curves indicate that bainite can be transformed in a wide range of cooling rates. The cooling rate adopted in the industrial production is approximately 10°C/s. Therefore, the formation of a large amount of acicular ferrite is promoted owing to the proper cooling rate.

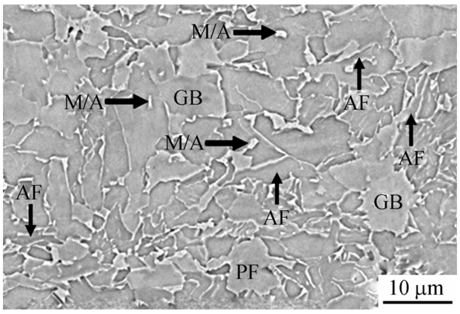

Fig. 4. SEM micrograph at the 1/4 thickness of the steel plate.

3.3. Precipitates and dislocation cells

The heavy plate steel was microalloyed with Nb and Ti. These microalloying elements were strong carbide formers and also acted as grain refinement elements while in solution in austenite. On subsequent cooling, the microalloying elements precipitated as carbides and/or carbonitrides. Fig. 5 shows the TEM micrograph of precipitates in the heavy plate. Small equiaxed particles (as arrowed) of 5-15 nm in size are dispersed in the matrix. The EDXS results of carbides are presented in Fig. 6. These results show that the fine particles are likely to be Nb-Ti carbides and/or carbonitrides [11, 15]. It is reported that Nb-Ti small particles are precipitated by strain induction [11] during relaxing [15]. The precipitation of carbides and/or carbonitrides has an effect on the microstructural evolution and mechanical properties of steel plates.

It is reported that the formation of dislocation cells plays an important role in the grain refinement in the process of TMCP-RPC [15-16]. Small dislocation cells (as arrowed in Fig. 7) are formed in specimens in the present work.

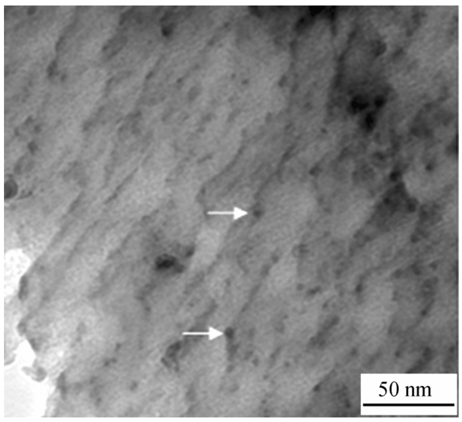

Fig. 5. TEM micrograph of precipitates in the specimen.

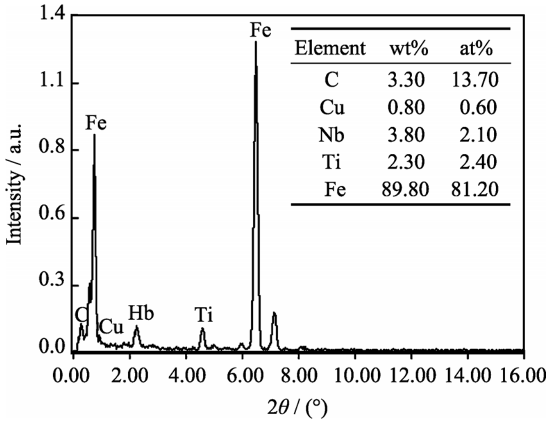

Fig. 6. EDXS results of Nb-Ti carbides.

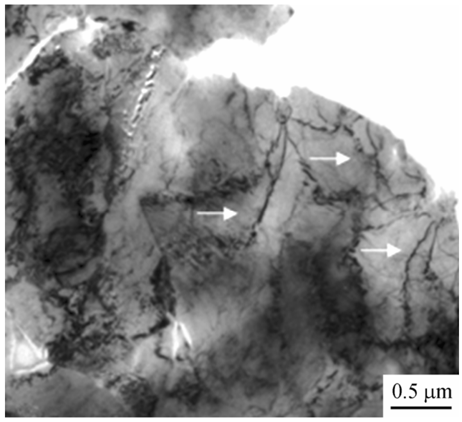

Fig. 7. Dislocation cells in the specimen.

3.4. Mechanical properties

Table 2 shows the mechanical properties of a heavy steel plate (60 mm in thickness). The heavy steel plate has a tensile strength of approximately 600 MPa. The yield ratio is 0.79 on an average. It also has a good elongation, ranging from 24% to 32%. The average V-notch impact toughness at –40°C achieves 280 J. Fig. 8 shows an example of the measured V-notch impact values at –40°C along the plate thickness. The values just vary slightly through the surface to the center of the heavy plate. These results demonstrate that the heavy steel plate has a good combination of high strength, excellent toughness, and low yield ratio.

Table 2. Mechanical properties of steel plates

Value	σ_s / MPa	σ_b / MPa	σ_s/σ_b	Elongation / %	A_{KV} (–40°C) / J
Average	468	591	0.79	26.3	280
Range	420-500	560-625	0.71-0.85	24-32	194-293

Note: σ_s—yield strength; σ_b—tensile strength; and A_{KV}—V-notch impact toughness.

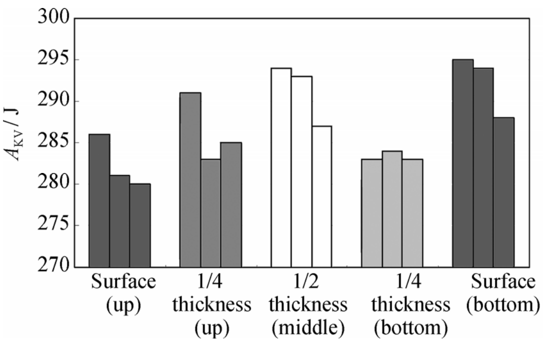

Fig. 8. Measured V-notch impact values at –40°C along the plate thickness.

4. Discussion

4.1. Acicular ferrite formation in the heavy plate

Acicular ferrite is intragranularly nucleated bainite [17]. It is originated on small nonmetallic inclusions [17-18]. It is reported that acicular ferrite is radiated in many different directions from nucleation sites. Therefore, acicular ferrite tends to form interlocked microstructures [8, 17-19]. Propagating cracks are then deflected when they encounter a differently oriented acicular ferrite plate. This gives rise to superior mechanical properties, especially toughness, for acicular ferrite microstructure.

As the CCT curves show in Fig. 2, acicular ferrite can be obtained in a wide range of cooling rates during continuous cooling. Consequently, acicular ferrite becomes a dominant transformation product through the surface to the center of the steel plate. The excellent toughness of the heavy plate is remarkably attributed to the formation of fine-grained acicular ferrite microstructure (as shown in Figs. 3 and 4).

4.2. Grain refinement in the heavy plate

Fine mixed microstructures consisting of predominant acicular ferrite and a lot of granular bainites and polygonal ferrites were obtained in the present ultra-low carbon Nb-Ti microalloyed steel by means of an advanced TMCP-RPC technique. On the one hand, grain refinement is attributed to the formation of small dislocation cells owing to the interaction of dislocations and the precipitation of Nb-Ti carbides and/or carbonitrides [15]. On the other hand, plate-like or lath-like acicular ferrite plays an important role in the grain refinement of mixed microstructures [16].

The interlocked acicular ferrite network in the present work is resulted from the formation of acicular ferrite at earlier transformation stages, which halts the growth of acicular ferrite transformed subsequently [16]. It is therefore proposed that lath-like or plate-like acicular ferrite grains formed at earlier transformation stages effectively partition the prior austenite into the smaller and separated regions, and thus acicular ferrite grains transformed at later stages or at lower temperatures are confined in these smaller regions [16, 19-22], as schematically illustrated in Fig. 9. In the present work the grain refinement of mixed microstructures is resulted from not only the precipitation of Nb-Ti carbides and/or carbonitrides, but also the formation of lath-like or plate-like acicular ferrite grains.

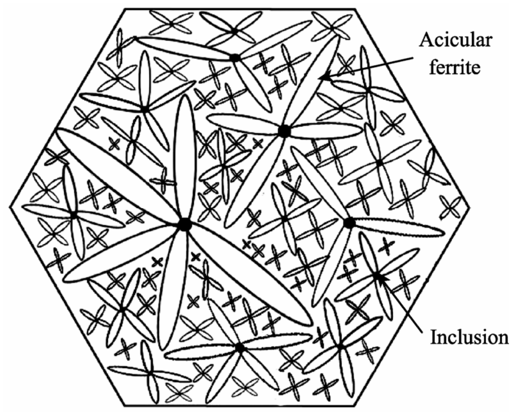

Fig. 9. Schematic illustration of the formation mechanism of interlocked acicular ferrite microstructures.

4.3. Toughness of the heavy plate

Conventional upper bainite consists of a non-lamellar mixture of bainitic ferrite plates with intervening particles of cementite. The cementite is detrimental to properties, but its precipitation can be prevented by adding sufficient silicon to the steel [21], leaving a microstructure of bainitic ferrite plates and carbon-enriched residual austenite. The retained austenite is in two forms, the desirable films between the fine plates of ferrite and the blocks between different crystallographic variants of bainite. The films of austenite, intimately dispersed between the ferrite, are barriers to the propagation of crack and the diffusion of hydrogen. This kind of bainitic steel has an optimization of high strength and good toughness [23]. On the one hand, the superior toughness (as shown in Fig. 8) is attributed to the fine-grained acicular ferrite. On the other hand, blocks of retained austenite are prevented in the microstructures. Only a very few amount of small M/A constituents (as shown in Fig. 4) is observed in the matrix owing to the special alloy design, in which an ultra-low carbon content and a low silicon content are adopted. In addition, the homogeneously distributed small M/A constituents rather than blocks are also responsible for the enhancement of toughness of the heavy plate.

Fig. 10 shows the fracture of the tensile specimens consisting of many small and deep dimples. A few small oxides and sulfides are observed in the dimples. No cluster of sulfides is found in the fracture specimen. Because the liquid steel is made by hot metal desulphurization and refined by vacuum degassing, the liquid steel is very clean. The superior toughness of the heavy plate is also attributed to the cleanness of the steel.

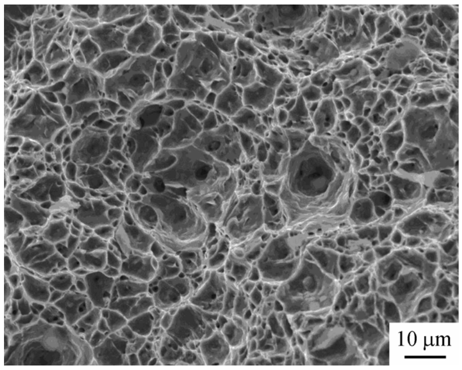

Fig. 10. SEM image of the tensile fracture specimen.

5. Conclusions

(1) An ultra-low carbon acicular ferrite steel heavy plate with a good combination of high strength and excellent toughness was produced in an industrial scale at Xiangtan Steel. The heavy steel plate has a tensile strength of approximately 600 MPa with a lower yield ratio of ~0.79. It also has a good elongation, ranging from 24% to 32%. The average V-notch impact toughness at –40°C achieves 280 J.

(2) The excellent toughness was realized by means of a special alloy design with ultra-low carbon microalloying and an advanced TMCP-RPC process, by which fine-grained microstructures were obtained. The formation of acicular ferrite plays an important role in the grain refinement of mixed microstructures.

References

[1] B. Hwang, Y.G. Kim, S. Lee, *et al.*, Effective grain size and Charpy impact properties of high-toughness X70 pipeline

steels, *Metall. Mater. Trans. A*, 36(2005), p.2107.

[2] F.R. Xiao, B. Liao, Y.Y. Shan, *et al.*, Challenge of mechanical properties of acicular ferrite pipeline steel, *Mater. Sci. Eng. A*, 431(2006), p.41.

[3] S.Y. Shin, B. Hwang, S. Kim, and S. Lee, Fracture toughness analysis in transition temperature region of API X70 pipeline steels, *Mater. Sci. Eng. A*, 429(2006), p.196.

[4] T. Funakoshi, T. Tanaka, S. Ueda, *et al.*, Improvement in microstructure and toughness of large heat-input weld bond of high strength steel due to addition of rare earth metals and boron, *Trans. Iron Steel Inst. Jpn.*, 17(1977), p.419.

[5] S. Kanzawa, A. Nakajima, K. Okamoto, *et al.*, Improved toughness of weld fusion zone by fine TiN particles and development of a steel for large heat input welding, *Tetsu-to-Hagané*, 61(1975), p.2589.

[6] Y. Tomita, N. Saito, T. Tsuzui, *et al.*, Improvement in HAZ toughness of steel by TiN-MnS addition, *ISIJ Int.*, 34(1994), p.829.

[7] M. Enomoto, Nucleation of phase transformations at intragranular inclusions in steel, *Met. Mater. Int.*, 4(1998), p.115.

[8] K.M. Wu, Y. Inagawa, and M. Enomoto, Three-dimensional morphology of ferrite formed in association with inclusions in low-carbon steel, *Mater. Charact.*, 52(2004), p.121.

[9] C. Miki, K. Homma, and T. Tominaga, High strength and high performance steels and their use in bridge structures, *J. Constr. Steel Res.*, 58(2002), p.3.

[10] A.K. Lis, L. Lis, and L. Jeziorski, Advanced ultra-low carbon bainitic steels with high toughness, *J. Mater. Process. Technol.*, 64(1997), p.255.

[11] A. Ghosh and S. Chatterjee, Characterization of precipitates in an ultra-low carbon Cu bearing high strength steel: A TEM study, *Mater. Charact.*, 55(2005), p.298.

[12] A.K. Lis, Mechanical properties and microstructure of ULCB steels affected by thermomechanical processing, *J. Mater. Process. Technol.*, 106(2000), p.212.

[13] A.M. Guo, X.L. Song, J.Q. Tang, and Z.X. Yuan, Effect of tempering temperature on the mechanical properties and microstructure of an copper-bearing low carbon bainitic steel, *J. Univ. Sci. Technol. Beijing*, 15(2008), p.38.

[14] T. Maki, Current state and future prospect of microstructure control in steels, *Tetsu-to-Hagané*, 81(1995), p.N547.

[15] X.M. Wang, X.L. He, S.W. Yang, *et al.*, Refining of intermediate transformation microstructure by relaxation processing, *ISIJ Int.*, 42(2002), p.1553.

[16] K.M. Wu, Z.G. Li, A.M. Guo, *et al.*, Microstructure evolution in a low carbon Nb-Ti microalloyed steel, *ISIJ Int.*, 46(2006), p.161.

[17] H.K.D.H. Bhadeshia, *Bainite in Steels*, The Institute of Materials, London, 2001, p.237.

[18] K.M. Wu, T. Yokomizo, and M. Enomoto, Three-dimensional morphology and growth kinetics of intragranular ferrite idiomorphs formed in association with inclusions in an Fe-C-Mn alloy, *ISIJ Int.*, 42(2002), p.1144.

[19] K.M. Wu, Three-dimensional analysis of acicular ferrite in a low-carbon steel containing titanium, *Scripta Mater.*, 54(2006), p.569.

[20] M. Enomoto, K.M. Wu, Y. Inagawa, *et al.*, Three-dimensional observation of ferrite plate in low carbon steel weld, *ISIJ Int.*, 45(2005), p.756.

[21] X.L. Wan, R. Wei, and K.M. Wu, Effect of acicular ferrite formation on grain refinement in the coarse-grained region of the heat-affected zone, *Mater. Charact.*, 61(2010), p.726.

[22] L. Cheng and K.M. Wu, New insights into intragranular ferrite in a low-carbon low-alloy steel, *Acta Mater.*, 57(2009), p.3754.

[23] H.K.D.H. Bhadeshia and R.W.K. Honeycombe, *Steels Microstructures and Properties*, 3rd Ed., Elsevier Ltd., Oxford, 2006, p.152.