Niobium Bearing Structural Steels
Edited by: Steven G. Jansto and Jitendra Patel
TMS (The Minerals, Metals & Materials Society), 2010

THE DEVELOPMENT OF A HIGH STRENGTH NB-BEARING SHIP PLATE STEEL FOR HIGH HEAT INPUT WELDING

Ching-Yuan Huang, Fon-Jen Chiu and Yeong-Tsuen Pan

Steel & Aluminum Research & Development Department
China Steel Corporation, Taiwan, Republic of China

Keywords: Acicular Ferrite, EH40 Ship Steel, High Heat Input Welding, Nb-Bearing, Ti-Boron

Abstract

Large thickness, high strength EH40 steel plates with excellent low temperature toughness are required for the construction of 8000 TEU container ships. In order to improve the construction efficiency of the huge ship, increasing heat input was applied by the one-pass welding process. Two challenges are encountered during the development of the EH40 plate for high heat input welding. The first is the softening of the joint plate and the other is the deterioration of the HAZ toughness. In order to cope with the softening that accompanies the high heat welding input process, a promising strengthening strategy by increasing the Nb content and adding Cu and Ni is proposed. Also, in order to improve the toughness of the HAZ that is subjected to high heat input welding, Ti-B treatment is found to be a quite effective countermeasure. The BN particles that form on prior austenite grain boundaries can prevent the formation of bainite and Widmanstatten ferrite, while those forming inside the austenite grains can contribute to the formation of intragranular acicular ferrite. The predominantly intragranular ferrite microstructure thus improves the low temperature toughness of the HAZ.

Introduction

In order to increase the transport efficiency and reduce the delivery cost, the size of the container ships is increasing. In Taiwan, several 8000 TEU (twenty feet Equivalent Unit) container ships are under construction. These large-size container ships are designed with ultra-thick EH40 ship steel plates with thickness approaching 75mm. As the thickness increases, the weld labor cost increases. A high heat input welding process (400 kJ/cm heat input) was adopted by a Taiwan ship building company to join the plate in one pass to reduce cost. China Steel Corporation (CSC) has developed the high heat input welded (HHIW) structural plate (SM570) for the construction of the Taipei 101 high rise building a few years ago. This application had only a room temperature toughness requirement. In comparison to the HHIW-SM570 plate, the HHIW EH40 plate is a new challenge for CSC because it requires an excellent low temperature toughness (-40°C).

The two challenges encountered during HHIW EH40 plate development involve retardation of softening of the joint plate when welded with an ultra high heat input (400 kJ/cm) and the other is maintaining toughness of the HAZ. Regarding softening, a promising strengthening strategy which can avoid a remarked drop in strength and a decrease in toughness is investigated. It is well known that the deterioration of toughness is attributed to the formation of huge grains adjacent to the weld metal which promotes the development of undesired bainite and/or Widmanstatten ferrite. Since it is difficult to avoid the austenite grain growth next to the weld metal under such high heat input, the toughness improvement countermeasure is to control the austenite transformation within the coarse grain zone to obtain the intragranular acicular ferrite which retards crack propagation.

Today, two metallurgical strategies are proposed to obtain an acicular ferrite microstructure within the coarse zone during high heat input welding. The first is to control the size and distribution of oxides and sulphides, such as TiO, MgO and MnS, which are thermally stable at the temperature over 1400°C, which can pin the austenite grain boundary movement and act as nucleation sites for ferrite. [1-4] However, the toughness of the plate sometimes decreases because the oxides that usually precipitate during steelmaking are not easily controlled. The second aspect involves the addition of boron to form BN, thereby promoting the acicular ferrite formation. [5,6] BN precipitates during the slow cooling stage of a high heat input welding operation and can act as nucleation sites of acicular ferrite and decrease the free N in the steel plate, thereby improving the HHIW HAZ toughness. Compared with the oxides technology, the behaviour of B is much easier to control during the manufacturing process. Within this paper, the strengthening strategy to overcome softening and the improvement of the HHIW HAZ of the Ti-N treated Nb-bearing EH40 steel will be introduced.

Materials and Experimental Procedure

Ti-boron treated Nb-bearing steels with Cu and Ni additions were prepared from vacuum melt heats and cast into 210 x 210x 600 mm ingots. In order to control the particle size and distribution of TiN, the ratio of Ti/N is controlled to less than 3.4 in all of the steels. Cu and Ni were added to increase the strength of the steel during the high heat input welding procedure. A typical chemical composition of the steels is listed in Table 1.

Table 1. Typical chemical composition of the steel plates used in this research

	C	Mn	Si	P	S	Nb	Others	C_{eq}
EH40	0.08	1.45	0.20	0.01	0.002	0.01-0.03	Cu, Ni, Ti, B	0.35

$C_{eq} = C + Mn/6 + (Cr+Mo+V0/5 + (Cu+Ni)/15$

The ingots were rolled in a laboratory rolling mill by using a simulated thermo-mechanical controlled process (TMCP). The ingots were heated at 1200°C for 1.5 hours and then thermo-mechanically processed to a final plate thickness of 60 mm with a finish rolling temperature of 800°C. after finish rolling, the plates were subjected to accelerated cooling to the finish cooling temperature of 500°C.

After rolling, the plates were welded at the Taiwan Ship Building Corporation (TSBC). The SEGARC II welding method [7] with a heat input of approximately 400 kJ/cm was applied for the evaluation of the high heat input welding of the 60 mm thick EH40 grade steel plates. This welding method is a high performance process which can successfully join the 60 mm thick plates in one pass. The welding parameters are shown in Table 2.

Table 2. Welding parameters of the SEGARC II process

Groove Angle	Root Gap (mm)	Voltage (volts)	Current (amps)	Speed (cm/sec)	Heat Input (kJ/cm)
20	9	38	400	2.3	395

Figure 1 below illustrates the thermal simulation.

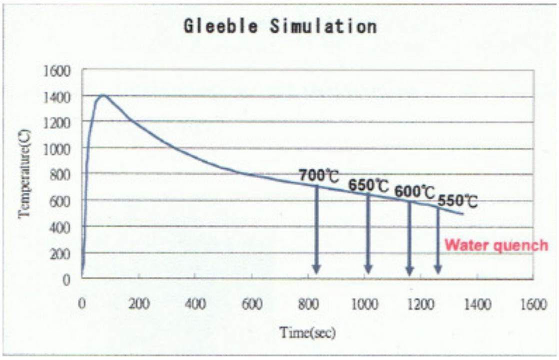

Figure 1. Schematic illustration of the thermal cycle of simulated HAZ.

Microstructure and Properties of the As-Rolled Plates

The typical microstructure of the as-rolled Ti-B treated steel plates is shown in Figure 2a. The microstructure consists of a few allotriomorphic ferrite and predominantly Widmanstatten ferrite and acicular ferrite. Such a microstructure is different from that without the Ti-B treatment, which is composed of allotriomorphic ferrite, Widmanstatten ferrite and acicular ferrite (Figure 2b). In Ti-B treated steel, the soluble B atoms segregate on the austenite grain boundary and can retard the allotriomorphic ferrite transformation and increase the bainitic hardenability. Therefore, it can retard promotion of the formation of Widmanstatten ferrite and acicular ferrite. Since the Ti/N ratio had been controlled properly, a high fraction of (Ti,Nb)(C,N) particles were dispersed in the Ti-B treated steel as shown in Figure 3.

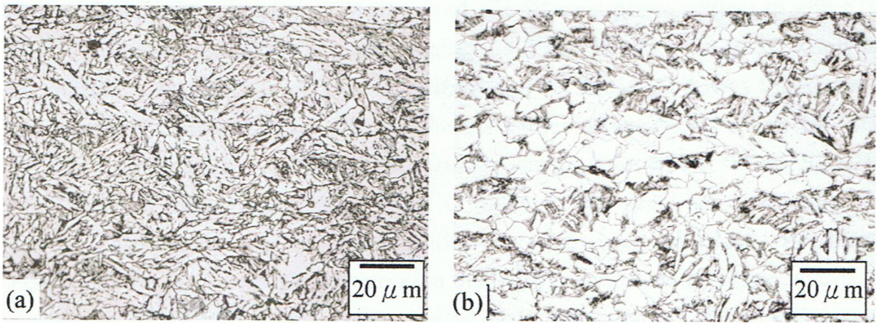

Figure 2. Optical micrographs showing the microstructures of the as-rolled steels: (a) Ti-B treated and (b) B-free.

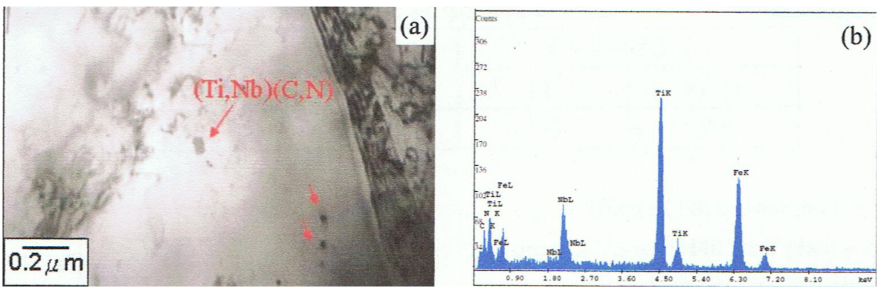

Figure 3. (a) TEM photograph showing the (Ti,Nb)(C,N) particles on the prior austenite grain boundary of the Ti-B treated steel, (b) EDAX analysis pattern.

The average mechanical properties of the as-rolled HHIW EH40 steels are listed in Table 3, which does meet the requirement of the EH40 specification.

Table 3. Mechanical properties of the as-rolled Ti-B treated HHIW EH40 steel.

TiB EH40	Yield Strength (MPA)	Tensile Strength (MPa)	Elongation (%)	CVN at -40°C (Joules)
Minimum	418	554	23.7	215
Average	444	574	25.9	253
Maximum	465	596	27.9	265
EH40 spec.	390 min	510-650	22 min	41 min

Mechanical Properties of HAZ

A significant softening of the Ti-B treated EH40 steel plates subjected to 400 kJ/cm HHIW was experienced. In some cases, the yield strength (YS) of the HHIW joint is lower than the minimum requirement of EH40 specification (YS 390MPa). It was found that the increase in Nb content will enhance the anti-softening capability of HHIW EH40 steels as shown in Figure 4.

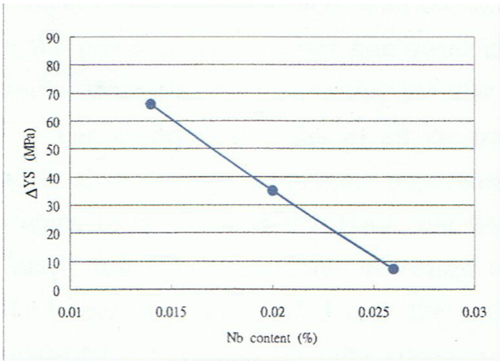

Figure 4. Effect of Nb on the drop of YS (anti-softening behaviour) of EH40 steel plate subject to 400 kJ/cm high heat input welding.

The typical mechanical properties of the 400 kJ/cm HHIW HAZ of the Ti-B treated steels is listed below in Table 4.

Table 4. Typical mechanical properties of the 400 kJ/cm HHIW joint.

Yield strength (MPa)	Tensile Strength (MPa)	CVN at -40°C	
		FL	FL+1
405	540	133	226

The yield strength of the Ti-B treated EH40 joint can meet the minimum requirement of EH40 specification (390MPa). Figure 5 presents the variation of Charpy impact energy tested at -20°C as a function of notch positions for the HAZs of Ti-B treated and B-free EH40 steels. Note that the absorbed energies of the HAZ of Ti-B treated steel (B1) are much higher than that of the B-free steel (A1).

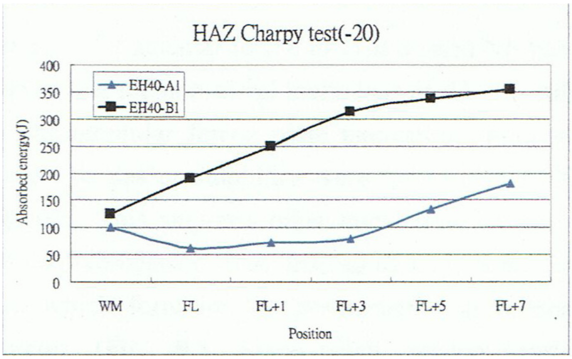

Figure 5. Charpy impact energy versus notch locations of the 400 kJ/cm HHIW HAZ specimens (T-direction). (B1: Ti-B treated, A1: B-free)

Microstructure of HAZ

The macrostructures of the two experimental plates welded by SEGARCII were quite similar as illustrated in Figure 6.

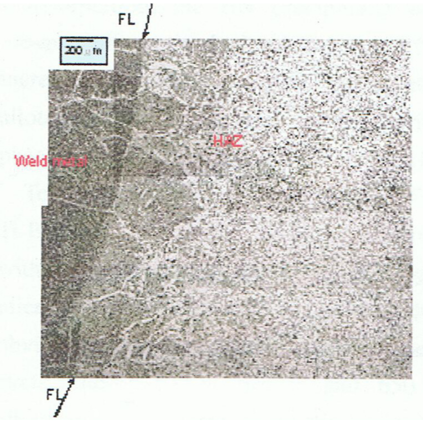

Figure 6. Optical micrograph showing the macrostructure of HAZ of Ti-B treated steel welded using the SEGARC II.

The width of the coarse-grain region just adjacent to the fusion line was about 400μm. Only 1-2 austenite grains appeared in the coarse grain region. Since the Ti/N ratio was well controlled in the experimental plate steels, the grain growth of austenite was retarded by fine and dispersed

(Ti,Nb)(C,N) particles when the peak temperature was less than 1400°C as shown in figure 3. However, the peak temperature of the coarsened-grain region just next to the fusion line (FL) was higher than 1400°C, causing the dissolution of (Ti,Nb)(C,N0 particles and resultant austenite grains larger than 300μm. The austenite grain growth of the other regions next to the coarse grain zone was retarded by the (Ti,Nb)(C,N) particles which caused the formation of a polygonal ferrite structure due to the fine austenite grains.

The microstructures of the coarse-grain HAZ of the Ti-B treated steel consisted of predominantly fine allotrimorphic ferrite along pre-austenite grain boundaries and interlocked ferrite within the pre-austenite, as shown in Figure 7.

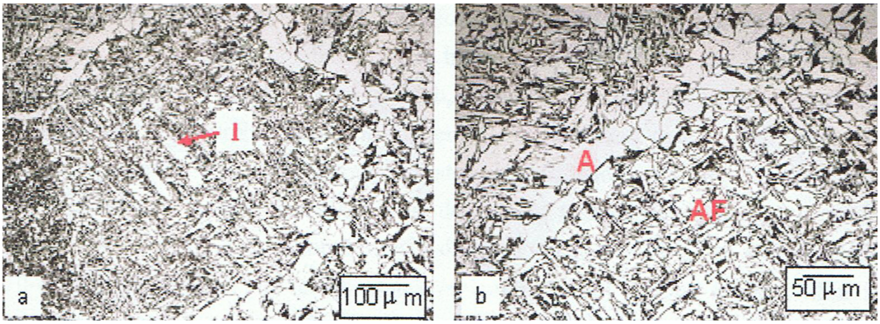

Figure 7. (a) The coarse-grain microstructure in the HAZ of Ti-B treated steel welded by 400 kJ/cm heat input, 9b0 high magnification of (a), (A: Allotriomorphic ferrite, AF: Acicular ferrite and I: Idiomorphic ferrite.

The interlocked acicular ferrite is similar to the structure that usually exists in the weld deposits shown in figure 8.

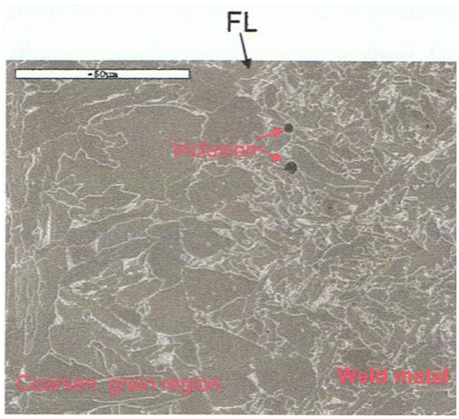

Figure 8. Scanning electron micrograph of coarse-grain microstructure in HAZ of Ti-B steel.

The size of the acicular ferrite plates in the HAZ of Ti-B treated Nb-bearing steel was one order larger than that in the weld deposits. It is well accepted that he formation of interlocked acicular ferrite in weld deposits is attributed to the presence of abundant non-metallic inclusions, such as sulphides, oxides, etc. A similar structure with interlocking acicular ferrite is found in the HAZ of the Nb-steel [9].

The absorbed energies of all the positions in the HAZ of Ti-B treated EH40 steels exceeded the minimum requirement of 46J, indicating that predominantly acicular ferrite in the HHIW HAZ contributes to excellent toughness. Although the Charpy test temperature decreased to-40°C, the absorbed energies of FL and FL+1 locations were 133J and 226J (see Table 4), respectively, indicating the Ti-B treated Nb-bearing steel is quite suitable for HHIW EH40 steel.

Formation Mechanism of Acicular Ferrite in Ti-B Treated Nb-Bearing Steel

It is well accepted that the non-metal inclusions (oxides or sulphides) in the weld deposit act as intragranular ferrite plate nucleation sites, as shown in Figure 8. However, no abundant levels of oxides or sulphides were found in the HHIW HAZ of Ti-B treated Nb-bearing steel. This observation suggests that other nucleation sources for acicular ferrite. Instead of inclusions, BN precipitates were found in the HAZ, which formed on the pre-austenite grain boundary and within acicular ferrite plates (see Figure 9).

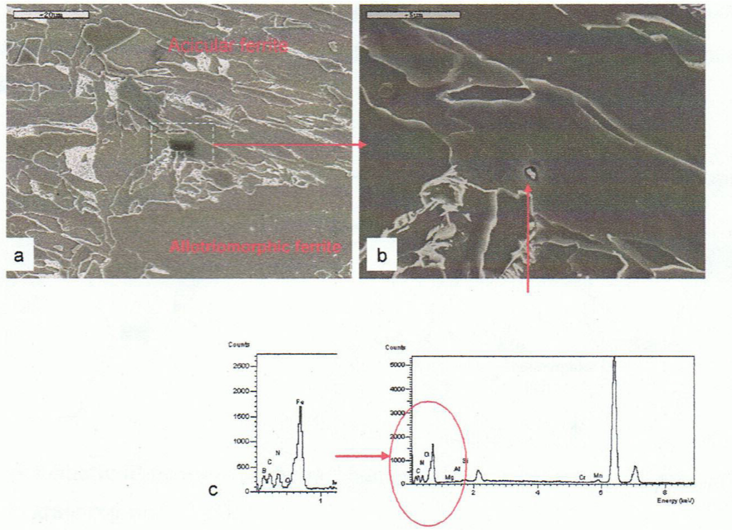

Figure 9. (a) Scanning electron micrographs of BN particle within HAZ of Ti-B treated Nb-bearing steel welded by 400 kJ/cm heat input, (b) high magnification of (a), and (c) the EDS analysis of BN particle.

Since such predominantly acicular ferrite microstructures cannot be observed I the B-free steel, it is reasonable to relate the formation of acicular ferrite with the BN precipitates. It is thought that during the γ to α transformation, the BN precipitated on a pre-austenite grain boundary or within a pre-austenite grains which are depleted of the B and N solutes around the precipitates. This situation would cause an increase in the transformation temperature that promotes the nucleation of allotriomorphic ferrite and acicular ferrite, respectively. The same effect of Mn on phase transformation has been reported elsewhere [10].

Verification of the formation mechanism of the intergranular interlocking ferrite plate in Ti-B treated Nb-bearing steels was made through the interrupted cooled simulated HAZ microstructures with thermo cycles observed and illustrated in Figure 1. Figure 9 shows the microstructures of simulated HAZ with the various interrupted temperatures. It is evident that the microstructure of the specimens experiencing the simulated thermal cycle interrupted at 700°C and 650°C, respectively, mainly consists of allotriomorphic ferrite along the austenite grain boundary and idiomorphic ferrite along with a few ferrite plates within the austenite grain. The nearly equiaxed introgranular idiomorphic ferrite transformed by the diffusion mechanism usually possesses better defined crystallographic boundaries with the matrix. By comparing the microstructures in Figure 10 (a) and Figure 10 (b), the volume fraction of intragranular idiomorphic ferrite is higher in Figure 10 (b) than that in figure 10 (a). This implies that idiomorphic ferrite transformation is a diffusion-controlled mechnaism, i.e. the transformed fraction increases with decreasing temperature (increasing the driving force). As the temperature continuously dropped down to 600°C, as shown in Figure 10 (c), a high fraction of interlocking ferrite plates (acicular ferrite) can be found within the austenite grains and only a few Widmanstatten ferrite nucleating on the boundaries between allotriomorphic ferrite and austenite.

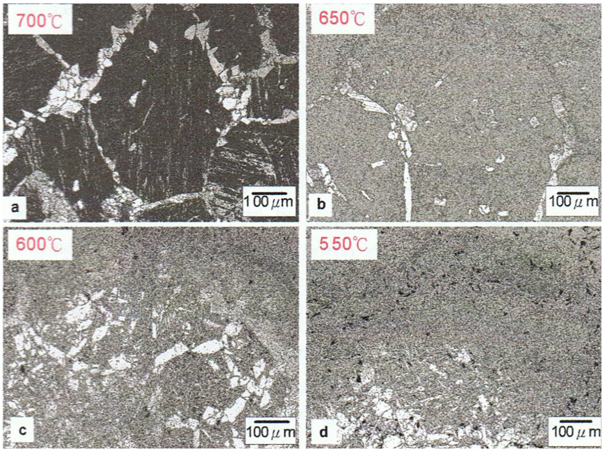

Figure 10. Optical micrographs obtained from four simulated HAZ thermal cycles interrupted at various temperatures: (a) 700°C, (b) 650°C, (c) 600°C and (d) 550°C.

As the temperature continuously dropped down to 550°C, the microstructures consists of predominantly acicular ferrite, which is similar to that of the welded coarse grain regions as shown in Figure 7. It is noted that when the temperature drops below the phase transformation temperature of allotriomorphic ferrite and idiomorphic ferrite (650°C), acicular ferrite dominates the phase transformationrather than Widmanstatten ferrite or bainite.

It is reported [11] that the microstructure can change from bainite to acicular ferrite by simply introducing thin layers of allotriomorphic ferrite at the austenite grain boundary. In this research, BN precipitated on austenite grain boundaries during post cooling and can act as nucleation sites of allotriomorphic ferrite. The formation of grain boundary allotriomorphic ferrite destroys the most potential nucleation sites for bainite or widmanstatten ferrite. Furthermore, since the area close to allotriomorphic ferrite is carbon-enriched due to the rejection of carbon from allotriomorphic ferrite, the bainite or Widmanstatten ferrite cannot develop even when the α/γ orientation is appropriate. This occurs from the decrease of the transformation temperature of bainite or Widmanstatten ferrite associated with the carbon enrichment. On the other hand, BN precipitated within the austenite grains and can act as the nucleation site for intragranular ferrite plate formation. Therefore, the microstructure of a HHIW Ti-B treated Nb-bearing EH40 steel consists of grain boundary allotriomorphic ferrite and predominantly intragranular acicular ferrite. Such a mechanism is schematically illustrated in Figure 11.

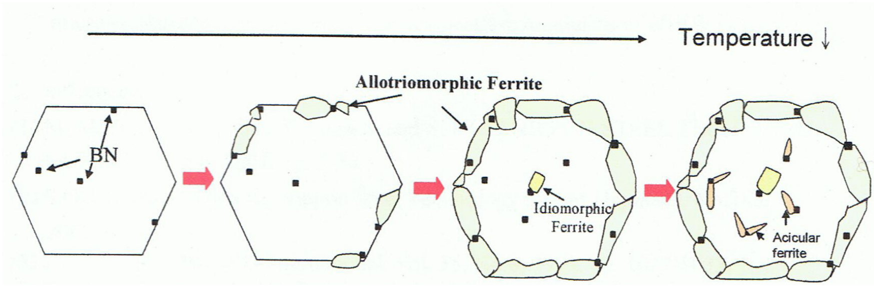

Figure 11. Schematic illustration of the mechanism of boron affecting the phase transformation of the coarse grain region of HAZ.

Conclusions

Large thickness, high strength EH40 steel plates with excellent low temperature toughness and good weldability for high heat input are required for the construction of 8000 TEU container ships for safety considerations and increased construction-time efficiency. Two challenges were encountered during the development of high heat input welded (HHIW) EH40 plate. The first is the softening of the joint plate and the other is the deterioration of the HAZ toughness, A Ti-B treated Nb-bearing steel was developed to work out these challenges. The main findings are as follows:

1) The typical microstructure of the as rolled Ti-B treated Nb-bearing steel consists of a small amount of allotriomorphic ferrite and predominantly Widmanstatten ferrite and acicular ferrite due to the segregation of soluble boron atoms on austenite grain boundaries. The soluble B atoms on the grain boundary can retard the allotriomorphic ferrite transformation and increase the bainitic hardenability, thereby promoting the formation of Widmanstatten ferrite and acicular ferrite resulting in higher strength and toughness than a B-free steel.

2) The strength drop of the HHIW joint decreases with increasing Nb content. By increasing the Nb content and adding Cu and Ni, the softening accompanied with high heat input welding can be compensated and the resultant HHIW joint can meet the minimum strength requirement of the EH40 specification.

3) The deterioration in toughness of HHIW HAZ is improved by Ti-B treatment with a control of the Ti/N ratio to less than 3.4. The excellent low temperature toughness is attributed to the predominantly acicular ferrite microstructure developed within the coarsen-grain zone in HHIW HAZ.

4) The BN particles forming on prior austenite grain boundaries during post peak cooling can prevent the formation of bainite and/or Widmanstatten ferrite, while those forming inside the austenite grains, can contribute to the formation of intragranular acicular ferrite. The

predominantly intragranular ferrite microstructure thus improves the low temperature toughness of the HHIW HAZ.

References

[1] M. Minagawa, K. Ishida, Y. Funatsu and S. Imai, Nippon steel Technical Report, No. 90, 2004, pp.7-10.

[2] S. Ohkita and H. Oikawa, Nippon Steel Technology Report (Japanese), No. 385, 2006, pp.2-6.

[3] J.L. Lee, Y.T. Pan, ISIJ International, Vol.35, No. 8, 1995, pp.1027-1033.

[4] J.L. Lee and Y.T. Pan, Metallurgical Transactions A, 24A, 1993, pp.1399-1408.

[5] Y. Ohno, Y. Okamura, S. Matsuda, K. Yamamoto and T. Mukai, Tetsu to Hagane, No. 8, 1987, pp.1010-1017.

[6] S. Shinichi, I. Katsuyuki and A. Toshikazu, JFE Technical Report, No. 5, 2005, pp. 24-29.

[7] Web-site: www.kobelco.co.jp, Kobelco Welding Today, Vol. 9, No. 2, p.5.

[8] Bjorn E.S. Lindblom, Berthold Lundqvist and Nils Erik Hannerz, Scandanavian Journal of Metallurgy, Vol. 20, 1991, pp. 305-315.

[9] J.R. Yang, C.Y. Huang and C.S. Chiou, Materials transactions, JIM, Vol. 40, No. 3, 1999, pp. 43-48.

[10] S. Aihara, G. Shigesato, M. Sugitama and R. Uemori, Nippon Steel Technical Report, No. 91, 2005, pp. 43-48.

[11] H.K.D.H. Bhadeshia, "Bainite in Steel", second edition, IOM Communications Ltd., London, UK, 2001, p. 265.