High Tensile Strength Steel Plates with Excellent HAZ Toughness for Shipbuilding —JFE EWEL Technology for Excellent Quality in HAZ of High Heat Input Welded Joints—†

SUZUKI Shinichi*1 ICHIMIYA Katsuyuki*2 AKITA Toshikazu*3

Abstract:

In order to meet the increased heat input in welding for improved productivity of shipbuilding, JFE Steel developed "JFE EWEL," a new technology for improving HAZ toughness in high heat input welding. Technical factors of JFE EWEL include the control of grain size in HAZ through optimization of TiN, control of microstructure in HAZ grain through advanced microalloying technology, and optimized alloy design through application of Super-OLAC. By applying JFE EWEL to the steel used in shipbuilding, such as YS390 N/mm² class heavy section plate for container ships, low-temperature service steel plate for LPG carriers, and YS355 N/mm² class F-grade plate for hull structures, excellent properties in both base plates and welded joints for high heat input welding were achieved.

1. Introduction

In the shipbuilding industry, the size of container ships has increased rapidly over the past several years, against a background of increased long-distance freight.

Container ships in the 8 000 TEU (twenty-foot equivalent unit) class are now being built instead of 6 000 TEU ships, and plans to build container ships greater than 10 000 TEU are underway. The steel plates for large container ships have higher strength, such as YS390 N/mm² class, and heavier thickness at a maximum of 65 mm or more. In the welding of these heavy section plates, high heat input welding such as EGW (electro-gas arc welding) is adopted to prevent the low building efficiency encountered with conventional multi-pass welding, and the heat input can exceed 500 kJ/cm. Also, for ships other than container ships, building efficiency is improved against the background of great demand for shipbuilding, and single-side one-pass submerged arc welding and EGW are applied.

During high heat input welding, microstructures in the heat-affected zone (HAZ) become extremely coarse, and the toughness of welded joints decreases drastically. Additionally, increased carbon equivalent (C_{eq}) is necessary to achieve higher strength and heavier thickness with the conventional thermo-mechanical control process (TMCP), which leads to decrease performance in both weldability and welded joint toughness.

To solve these problems, JFE Steel developed "JFE EWEL," a new technology for improving HAZ toughness in high heat input welding, with advanced microalloying and state-of-the-art TMCP technology, and applied JFE EWEL to the development of steel plates for high heat input welding for container ships and LPG carriers[1)]. This paper presents an overview of JFE EWEL and the properties of the steel plates using this technology, such as YS390 N/mm² class plates for container ships, plates for low-temperature service and YS355 N/mm² class F-grade plates.

† Originally published in *JFE GIHO* No. 5 (Aug. 2004), p. 19–24

*1 Senior Researcher Manager,
Plates & Shapes Res. Dept.,
Steel Res. Lab.,
JFE Steel

*2 Senior Researcher Deputy Manager,
Plates & Shapes Res. Dept.,
Steel Res. Lab.,
JFE Steel

*3 Staff Deputy Manager,
Plate Rolling Technology Sec.,
Plate Rolling Dept.,
East Japan Works (Keihin),
JFE Steel

2. Overview of JFE EWEL

2.1 Problem with High Heat Input Welding

The microstructure in HAZ of conventional steel after high heat input welding is schematically shown in **Fig. 1** (a). During welding, the area near the fusion line is reheated to temperatures exceeding 1 400°C, and austenite grains become very coarse. Thus, during cooling after welding, coarse ferrite side plate, which has poor toughness, is generated from austenite grain boundaries, and upper bainite is generated inside prior austenite grains, drastically decreasing the toughness of the welded joint. Especially, the carbon equivalent is relative high for high-strength and heavy section plate, and this leads to the formation of ferrite side plate and upper bainite, which deteriorates the toughness.

2.2 Technical Factors of JFE EWEL

To solve the problem with high heat input welding mentioned in section 2.1, JFE EWEL was developed as a technology for improving HAZ toughness in high heat input welding. This concept integrates three technical factors (**Fig. 2**): (1) control of HAZ grain size through optimization of TiN, (2) control of intragranular microstructure through microalloying and original atomic concentration ratio (ACR) control[2), (3) optimum carbon equivalent and alloy design through utilization of the high cooling rate of *Super*-OLAC. The technical factors are selected according to the required steel properties. Figure 1 (b) schematically shows the microstructure in HAZ in developed steel using JFE EWEL technology. The width of the coarse grain region in HAZ is reduced by austenite grain size control, and intragranular microstructure is improved by microstructure control and optimum alloy design. Details of each technical factor are given in the following section.

2.2.1 Control of grain size in HAZ

In order to minimize the coarse grain region after high heat input welding, it is necessary to control the austenite grain growth at high temperature. Nitrides and oxides, which are stable at elevated temperatures, are generally used to control austenite grain growth[3–7)], and JFE Steel studied the optimization of TiN from the point of ease of industrial control. In conventional steel, as the solution temperature of TiN is not high enough, TiN resolves and austenite grain size increases at areas even a few millimeters from the fusion line, as well as at areas near the fusion line where the temperature exceeds 1 500°C. To solve this problem, the amount of Ti and N, the ratio of Ti/N, and other alloying elements are optimized to make the best use of TiN, based on thermodynamic studies using Thermo-calc, as well as experimental studies. The studies clearly showed that it was possible to increase the solution temperature of TiN from less than 1 400°C to more than 1 450°C, for fine dispersion and significantly suppressed austenite grain coarsening in HAZ. **Photo 1** shows the HAZ microstructures in one-pass EGW joints ((heat input) = 400 –450 kJ/cm) in conventional steel (60 mm in thickness)

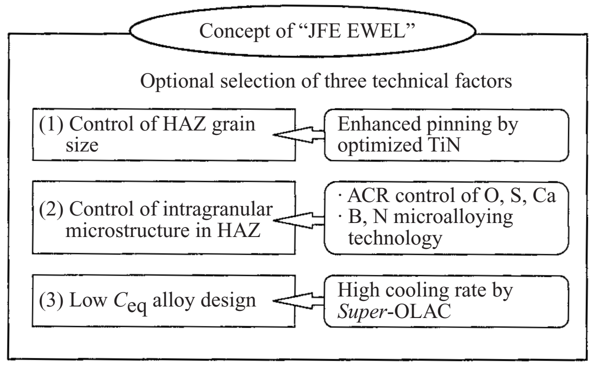


Fig. 2 Concept and technical factors of HAZ toughness improvement in "JFE EWEL" for high heat input welding

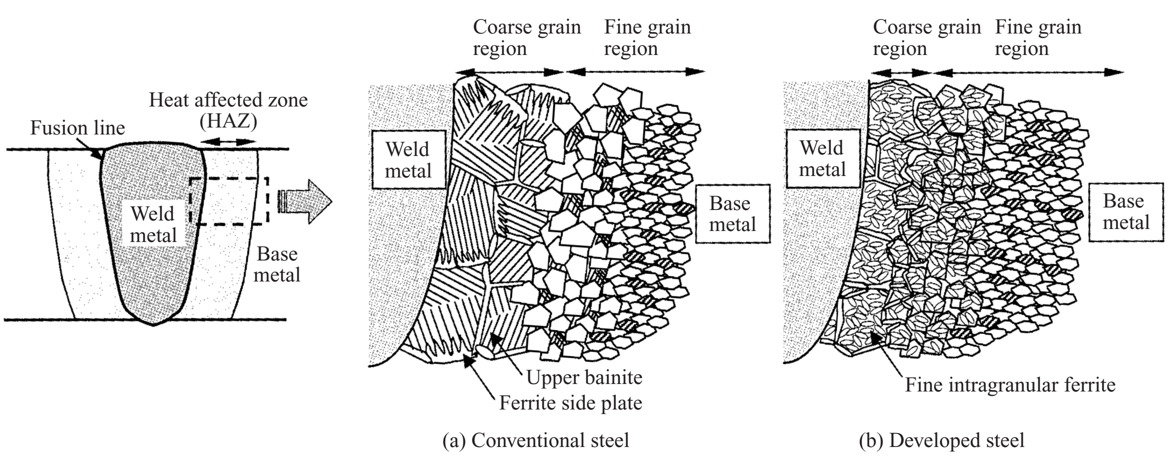


Fig. 1 Schematic diagram of high heat input welded joint

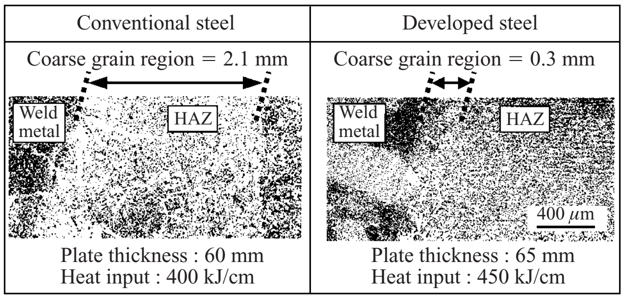


Photo 1 Microstructure of HAZ in electro-gas arc welded joint

and in the developed steel (65 mm in thickness). It can be clearly seen that the width of the coarse grain region is drastically decreased from 2.1 mm in conventional steel to 0.3 mm in the developed steel.

2.2.2 Control of intragranular microstructure in HAZ

In JFE EWEL, further improvement of HAZ toughness is achieved by applying intragranular microstructure control, which suppresses the formation of coarse ferrite side plate and upper bainite, and generates fine intragranular ferrite. Various types of oxides and nitrides are effective for the nucleation of intragranular ferrite[8,9], and therefore Ca-type nonmetallic inclusion and BN are used according to the welding conditions in JFE EWEL. Details of each technology are given below.

(1) Controlling ACR

One of the nucleation sites for intragranular ferrite is (Ca, Mn) S-type nonmetallic inclusion, in which formation of ferrite side plate and upper bainite is suppressed and fine intragranular ferrite is generated, resulting in improved HAZ toughness. Precise control of O, S, and Ca is necessary for using the inclusion as the nucleation site of intragranular ferrite, and ACR, JFE Steel's original index for controlling Ca-type inclusion, is properly controlled by optimizing the amount of O, S, Ca, and the complex inclusions of CaS, MnS can be finely dispersed.

(2) Controlling B and N

JFE EWEL also utilizes B as a means for generating intragranular ferrite. As the cooling rate after high heat input welding is slow, BN precipitates from added B during cooling. It is possible to improve HAZ toughness by utilizing BN as the nucleation site of intragranular ferrite during transformation from γ to α and it is also effective for decreasing free N in the steel, which is one of the causes of decreased toughness.

The authors also found a phenomenon whereby B in weld metal diffuses into HAZ during high heat input welding[10], and they used this to improve HAZ toughness as a new technology for controlling B and N in coarse grain regions. **Figure 3** schematically shows the dissolution of TiN and diffusion of B from weld metal near the fusion line. The dissolution of TiN, which has a rather high solution temperature, is inevitable in the vicinity of the fusion line, and free N is generated. On the other hand, B diffuses from weld metal to HAZ because the consumables for high heat input welding have a rather high content of B. Because the diffused B, as well as the B added to the base steel, combines with the free N, the nucleation site for intragranular ferrite increases, and the free N in HAZ decreases. As the amount of diffused B changes according to the plate thickness and other welding conditions, it is possible that intragranular ferrite is generated throughout the HAZ by controlling the amount of B added to the base steel. Also, the utilization of B in weld metal is more effective as the heat input is higher and the cooling rate after welding is slower, one of the novel effects established by JFE EWEL technology.

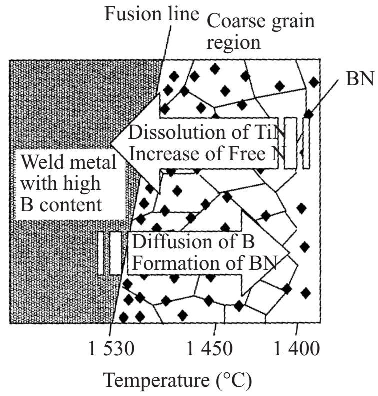


Fig. 3 Schematic diagram of dissolution of TiN and diffusion of B near fusion line

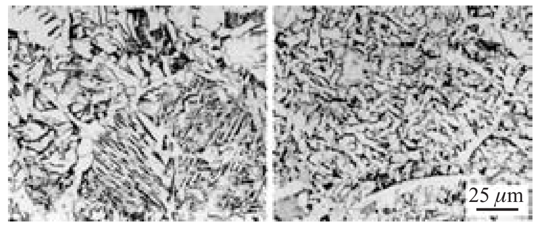


Photo 2 Microstructure of simulated HAZ (Peak temperature: 1 400°C, cooling time from 800°C to 500°C: 390 s)

Photo 2 shows the microstructure of the developed steel with added B and ACR control after a simulated welding heat cycle, compared with conventional steel. It is obvious that the microstructure of the developed steel is mainly fine ferrite, in contrast to coarse ferrite side plate and upper bainite.

2.2.3 Optimum alloy design by utilizing high cooling rate of *Super*-OLAC

The high strength and heavy section plates using YS390 N/mm^2 class 65 mm thick are now used for

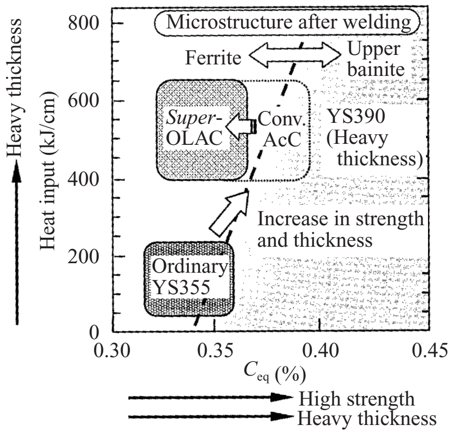


Fig. 4 Schematic diagram of the relationship between C_{eq}, heat input, and microstructure after welding

building large container ships. Although C or other alloying elements are generally added to obtain the high strength and heavy thickness, this leads to increased C_{eq} and decreased HAZ toughness, and the increase of C_{eq} should be minimized. **Figure 4** schematically shows the relationship between C_{eq} of the steel plate, heat input in one-pass welding and microstructure in HAZ after welding. In YS355 N/mm^2 class light section plate, ferrite is mainly generated after one-pass welding because of low C_{eq} and small welding heat input. On the other hand, in YS390 N/mm^2 class heavy section plate for container ships, C_{eq} increases to nearly 0.40% according to the increased strength and thickness when conventional accelerated cooling is applied, and upper bainite with poor toughness is generated after welding. To solve this problem, based on high tensile strength technology with extremely low C_{eq} and *Super*-OLAC[11)], which can achieve the theoretical limit of cooling rate, the formation of upper bainite in HAZ is maximally suppressed, and toughness is greatly improved.

The three technical factors explained above are properly combined according to the plate thickness, required base plate properties, welding method and so on when applied to the various types of plate, and the properties of the base plate and welded joints are optimized.

3. Application to Plates for Shipbuilding

Application examples of JFE EWEL technology to plates used in shipbuilding are introduced below.

Table 1 shows an example of chemical composition and base plate properties of YS390 N/mm^2 class steel for container ships. Ti, B, and Ca are added to control the grain size and intragranular microstructure in HAZ. Through the optimum alloy design using *Super*-OLAC, the plate has enough strength with C_{eq} less than 0.36 mass% in spite of the thickness of 80 mm. The plate is welded with one pass using 2-electrode EGW. The welding conditions, the macrostructure of the welded joint and the properties of the welded joint are shown in **Table 2**, **Photo 3**, and **Fig. 5**, respectively. Although the welding heat input is more than 600 kJ/cm, the welded joint has very good properties at −40°C, which is the same test temperature as the base plate, as well as at −20°C.

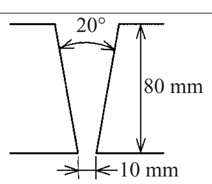
The low-temperature service steel plate for LPG carriers and F-grade plate for hull structures, in which excellent toughness at low temperature is required, are also developed with JFE EWEL technology. For welding of these steels, although the value of heat input is small compared with that of YS390 N/mm^2 class heavy section plate for container ships, some measure against high heat input welding is necessary due to the large relative heat input to plate thickness when welded by one-side submerged arc welding or one-pass EGW and low test temperature. **Table 3** shows an example of chemical

Table 1 Chemical composition and mechanical properties of YS390 N/mm^2 class plate

Thickness (mm)	Chemical composition (mass%)							Tensile property (Transverse)			Charpy impact property (Longitudinal)
	C	Si	Mn	P	S	Others	C_{eq}*	YS (N/mm^2)	TS (N/mm^2)	El (%)	$_{V}E_{-40}$ (J)
80	0.08	0.22	1.54	0.007	0.001	Ti, B, Ca, etc.	0.36	411	532	28	265

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

Table 2 Welding conditions for YS390 N/mm^2 class plate

Thickness (mm)	Welding method	Edge preparation	Welding consumable	Pass	Electrode	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)	Heat input (kJ/cm)
80	EGW		DWS-50GTF DWS-50GTR KL-4GT (Kobe Steel, Ltd.)	1	Face side	400	42	2.9	680
					Root side	400	40		

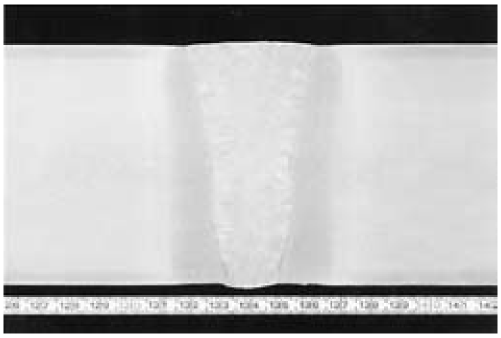


Photo 3 Macrostructure of YS390 N/mm^2 class welded joint (Electro-gas arc welding, heat input = 680 kJ/cm)

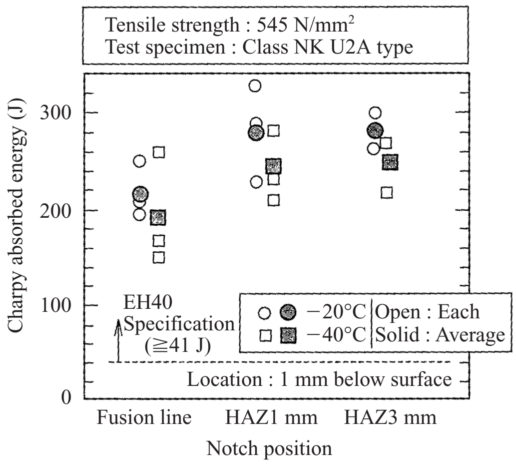


Fig.5 Mechanical properties of electro-gas arc welded joint of YS390 N/mm^2 class plate

composition and mechanical properties of YS355 N/mm^2 class low-temperature service plate (thickness: 17.5 mm) for an LPG carrier. This plate has good base plate properties as low-temperature service plate including toughness. **Tables 4** and **5** show the one-side submerged arc welding conditions with 108 kJ/cm heat input and the mechanical properties of the welded joint, respectively. The joint has sufficient strength and excellent toughness at low temperature.

Table 6 shows the chemical composition and mechanical properties of YS355 N/mm^2 class F-grade plate for hull structures with 50 mm thickness. The double-sided one-pass welding condition using the KX method[12)], which is high-efficiency submerged arc welding for very thick plate, is shown in **Table 7**. The KX method is used for welding with high welding current to obtain deep melting depth, and the heat input is as high as 130 kJ/cm for each pass. **Figure 6** shows the HAZ toughness of the joint at −40°C. The plate using JFE EWEL technology has very good welded joint properties including those required for FH36 plate.

4. Conclusion

This paper presented an overview of JFE EWEL, a new technology for improving HAZ toughness in high input welding, and its application to various types of steel plates for shipbuilding. Plates using JFE EWEL technology are applied to many ships such as large-scale container ships and LPG carriers, and the amount of

Table 3 Chemical composition and mechanical properties of YS355 N/mm^2 class plate for low temperature service

Thickness (mm)	Chemical composition (mass%)							Tensile property (Transverse)			Charpy impact energy (Transverse)
	C	Si	Mn	P	S	Others	C_{eq}*	YS (N/mm^2)	TS (N/mm^2)	El (%)	$_VE_{-53}$ (J)
17.5	0.08	0.19	1.56	0.013	0.002	Ti, Ca, etc.	0.34	426	522	22	351

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

Table 4 Welding conditions of YS355 N/mm^2 class plate for low temperature service

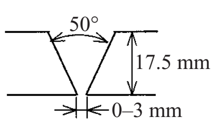
Thickness (mm)	Welding method	Edge preparation	Welding consumable	Pass	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)	Heat input (kJ/cm)
17.5	1 side SAW (FAB)	 50°, 17.5 mm, 0–3 mm	US255 PFI-50LT RR-3 FAB-1 (Kobe Steel, Ltd.)	1	950	38	20	108

Table 5 Mechanical properties of welded joint of YS355 N/mm^2 class plate for low temperature service

Thickness (mm)	Welding method	Heat input (kJ/cm)	Tensile strength* (N/mm^2)	Charpy impact energy, $_VE_{-55}$ (J)**			
				Fusion line	HAZ1 mm	HAZ3 mm	HAZ5 mm
17.5	1 side SAW (FAB)	108	523	84	100	262	301

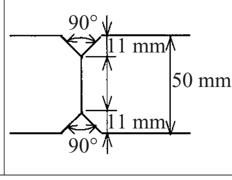
* Test specimen : Class NK U2A type
** Location of specimen : 1 mm below surface

Table 6 Chemical composition and mechanical properties of YS355 N/mm^2 class F grade plate

Thickness (mm)	Chemical composition (mass%)							Tensile property (Transverse)			Charpy impact energy (Transverse)
	C	Si	Mn	P	S	Others	C_{eq}*	YS (N/mm^2)	TS (N/mm^2)	El (%)	$_{V}E_{-60}$ (J)
50	0.07	0.19	1.56	0.008	0.002	Ti, Ca, etc.	0.36	399	546	30	292

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

Table 7 Welding conditions for YS355 N/mm^2 class F grade plate

Thickness (mm)	Welding method	Edge preparation	Welding consumable	Pass	Electrode	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)	Heat input (kJ/cm)
50	Double side SAW (KX)		KW-101B KB-110 (JFE Steel)	1	L	1 600	35	50	132
					T	1 200	45		
				2	L	1 700	35	55	129
					T	1 300	45		

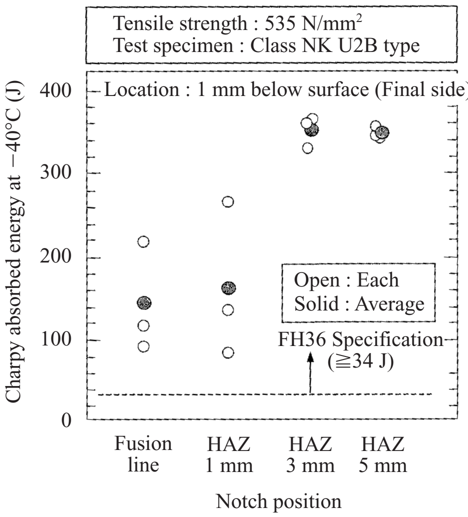


Fig. 6 Mechanical properties of arc welded joint of YS355 N/mm^2 class F grade plate

production exceeds 40 000 t. JFE Steel is presently making efforts to expand the adoption of plate for high heat input welding capable of achieving excellent base plate properties and high heat input welded joints in the field of shipbuilding, and is also applying JFE EWEL to other fields including construction, crude oil tanks, line pipe, and offshore structures.

References

1) Suzuki, S.; Oi, K.; Ichimiya, K.; Kitani, Y.; Murakami, Y. Materia. vol. 43, no. 3, 2004, p. 232–234.
2) Haida, O.; Emi, T.; Kasai, G.; Naito, M.; Moriwaki, S. Tetsu-to-Hagané. vol. 66, 1980, p. 354–362.
3) Kanazawa, S.; Nakashima, A.; Okamoto, K.; Kanaya, K. Tetsu-to-Hagané. vol. 61, no. 11, 1975, p. 2589–2603.
4) Kasamatsu, Y.; Takashima, S.; Hosoya, R. Tetsu-to-Hagané. vol. 65, no. 8, 1979, p. 1232–1241.
5) Nakanishi, M.; Komizo, Y.; Seta, I. J. of Jpn. Welding Soc. vol. 52, no. 2, 1983, p. 117–124.
6) Deshimaru, S.; Hirai, M.; Amano, K.; Ueda, S.; Uemura, H.; Tsubota, K. Kawasaki Steel Giho. vol. 18, no. 4, 1986, p. 295–300.
7) Kojima, A.; Kiyose, A.; Minagawa, M.; Hirano, A.; Yoshii, K.; Nakashima, T.; Hoshino, M.; Ueshima, Y. CAMP-ISIJ. vol. 16, 2003, p. 360–363.
8) Funakoshi, T.; Tanaka, T.; Ueda, S.; Ishikawa, M.; Koshizuka, N.; Kobayashi, K. Tetsu-to-Hagané. vol. 63, no. 2, 1977, p. 303–312.
9) Yamamoto, K.; Hasegawa, S.; Takamura, J. Tetsu-to-Hagané. vol. 79, no. 10, 1993, p. 1169–1175.
10) Kitani, Y.; Ikeda, R.; Oi, K.; Ichimiya, K. Preprints of National Meeting of JWS, no. 72, 2003, p. 108–109.
11) Omata, K.; Yoshimura, H.; Yamamoto, S. NKK Technical Review. no. 88, 2003, p. 73–80.
12) Akahide, K.; Ukibe, T.; Akusa, K.; Tsuboi, J. Kawasaki Steel Giho. vol. 10, no. 1, 1978, p. 34–47.