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Development of Shipbuilding Steel Plate with Superior Low Temperature Toughness for Large Heat Input Welding†

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Abstract:

The "JFE EWEL™" technology and optimization of dispersion of martensite-austenite constituent (MA) has been applied to develop YP390 MPa grade steel plate (YP: Yield point) with superior low temperature toughness for large heat input welding. The "JFE EWEL™" technology consists of minimizing the size of coarse-grained heat affected zone (HAZ) through controlling TiN particles, refining the microstructure of HAZ by using B, Ca. Furthermore, dispersion of MA was controlled by optimization of alloy design such addition of as Si. Suppression of MA formation in the coarse-grained HAZ and promotion of MA formation in the softened HAZ was achieved simultaneously in order to improve the HAZ toughness and the strength of welded joint. The developed steel was produced in an actual plate mill, and showed the satisfactory property of base metal and welded joint of large heat input welding and weldability.

1. Introduction

In recent years, upscaling of various types of welded structures, including ships, buildings, industrial plants, etc., has heightened the need for high strength, heavy thickness materials. In the shipbuilding field, grade E steel plate (Base metal toughness: −40°C Specification, Joint toughness: −20°C Specification) are generally used in merchant ships. For this application, heavy thickness E class steel plates with thicknesses exceeding 50 mm have been developed in both the YP390 MPa class and the YP460 MPa class (YP: Yield point)[1–5]. On the other hand, the service environments for welded structures also tend to become more severe. With the development of petroleum, natural gas, and other energy resources now progressing in low temperature regions such as Alaska, Sakhalin, and the Arctic, development of high strength steels with even higher low temperature toughness is demanded in order to respond to the specifications for these cold climates.

Steels up to YP390 MPa class have been developed and applied practically as F class hull structural steels for low temperature specifications (Base metal toughness: −60°C Specification, Joint toughness: −40°C Specification), but in order to guarantee the low temperature toughness of the heat affected zone (HAZ), multilayer welding by CO_2 gas shielded arc welding is applied, as this welding method has a comparatively small heat input. From the viewpoint of improving welding efficiency and reducing welding man-hours with these heavy thickness steel plates, there is an orientation toward large heat input welding (EGW: Electrogas arc welding), in which welding is performed in 1 pass by increasing the welding heat input. However, in large heat input welding, a decrease in joint toughness[6,7] occurs due to coarsening of the HAZ microstructure, while a decrease in joint strength[8] occurs due to expansion of the softened HAZ region. Although hardening of the softened HAZ is effective for securing joint strength, increasing the HAZ hardness simultaneously invites a

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Table 1 Target values in mechanical properties for developed steel plate

Steel plate					Welded joint	
Tensile properties[*1]				Charpy impact properties[*2]	Tensile properties[*2]	Charpy impact properties
Thickness (mm)	YP (MPa)	TS (MPa)	El (%)	vE (J)	TS (MPa)[*3]	vE (J)
50	≧390	510−650	≧20	vE_{-60}≧39	≧510	vE_{-40}≧39

[*1] T. P.: T-direction [*2] T. P.: L-Direction
[*3] T. P.: NK U2A or NK U2B
YP: Yield point TS: Tensile strength El: Elongation vE: Absorbed energy

decrease in HAZ toughness. For this reason, practical application of YP390F class steel for large heat input welding which satisfies both joint toughness and joint strength had been difficult.

To solve this problem, JFE Steel developed the world's first YP390F Class Steel for large heat input welding which satisfies both high strength of the base metal and low temperature specification joint properties by applying advanced microalloying technology.

This paper introduces the features of the developed steel, together with the performance of steel plates and welded joints of the new steel.

2. Target Performance

The target properties of the YP390F Class Steel are shown in **Table 1**. The development target was a maximum plate thickness of 50 mm applying standard values in Table 1 in accordance with standard KF40[9)] of Class NK. Welded joints were prepared by 1-pass large heat input EGW and evaluated.

3. Composition Design of Developed Steel

3.1 Issues in Development of YP390F Class Steel for Large Heat Input Welding

When steels are welded, a HAZ forms, in which the microstructure that was adjusted in the steel manufacturing process changes due to the welding heat. As the maximum attained temperature in welding varies continuously from the weld metal through the base plate, a coarse-grained region with decreased toughness forms in the HAZ due to coarsening of prior austenite (γ) grains, and a softened region which is heated to immediately above the Ac_3 transformation point is also formed in the HAZ. Thus, in order to satisfy the required joint properties, suppressing the toughness decrease in the coarse-grained HAZ, while simultaneously suppressing the decrease in joint strength caused by the softened region, becomes an issue. In large heat input welding, the time of exposure to the high temperature region is long, and this encourages coarsening of the microstructure and reduced toughness (**Fig. 1**①: Coarse-grained HAZ). The strength decrease in the softened HAZ is also remarkable (Fig. 1②: Softened HAZ), and as a result, joint strength decreases.

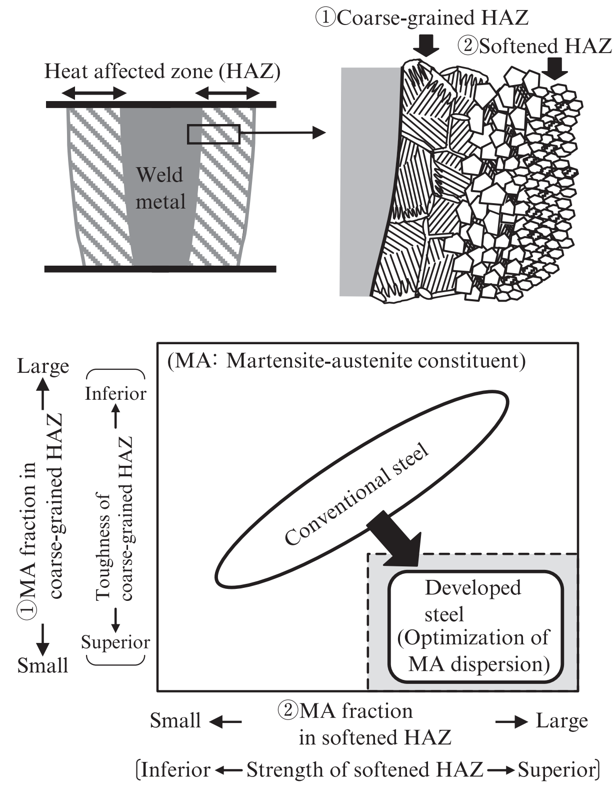


Fig. 1 Concept diagram of MA control for developed steel

Accordingly, in order to obtain a high strength steel having excellent low temperature toughness in large heat input welding, it is essential to satisfy both HAZ toughness and suppression of HAZ softening. To achieve this, the authors focused on martensite-austenite constituent (MA), which is a hard second phase, and optimized the condition of MA dispersion in the respective regions of the HAZ. That is, MA formation in the coarse-grained HAZ was suppressed, as MA reduces HAZ toughness, while MA formation was positively promoted in the softened HAZ in order to realize hardening of the HAZ (Fig. 1).

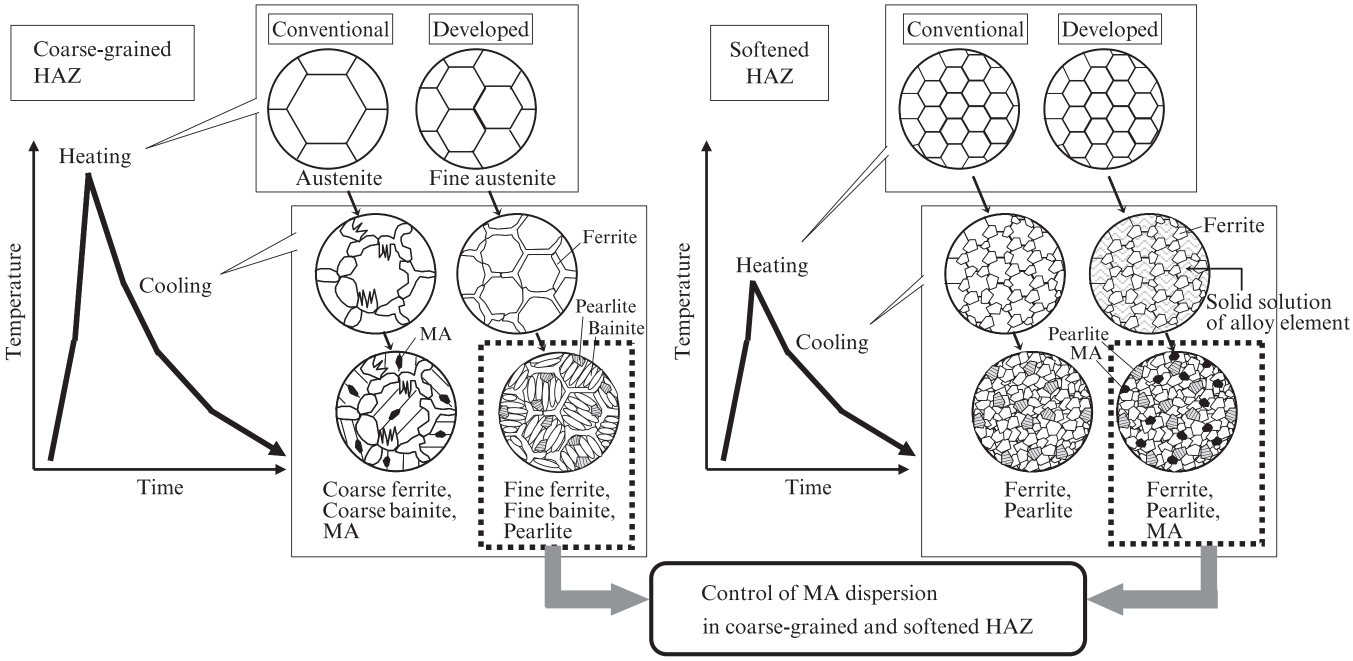


Fig. 2 Concept of heat affected zone (HAZ) microstructure control

3.2 HAZ Microstructure Optimization Technology

Figure 2 shows the concept of HAZ microstructure control. To improve the toughness of the coarse-grained HAZ, JFE Steel developed the "JFE EWEL^{TM}" technology, and established a technology in which the growth of γ grains at high temperature is restrained by optimization of TiN dispersion, and the HAZ microstructure is refined by promoting the $\gamma \rightarrow \alpha$ transformation within prior γ grains by using BN and Ca sulfides as nucleation sites. Furthermore, in this development, in addition to the above-mentioned matrix microstructure control, second phase microstructure control was also intended by focusing on MA, which forms during the bainite transformation.

It has been reported that MA formation in the coarse-grained HAZ depends on the Si content, and in multilayer welding, the amount of MA is reduced by reducing Si[10]. The results of study in this developed steel confirmed that the similar MA reduction effect also occurs in 1-pass large heat input welding. However, if the MA in the HAZ is simply reduced, this will encourage a decrease in the hardness of the softened HAZ, and it will no longer be possible to secure joint strength. Therefore, the authors studied a composition system in which joint strength is improved by suppressing softening by promoting MA formation in the softened HAZ, while continuing to improve toughness by reducing MA in the coarse-grained HAZ.

In order to achieve these mutually-contradictory features, a study was carried out, focusing on elements that display a solution softening phenomenon under low temperature, high strain rate conditions and thereby improve low temperature toughness. The results of this study revealed that the Mn-Cu-Ni balance is critical. By optimizing the addition of these elements, it was possible to promote dispersion of MA in the softened HAZ while avoiding a decrease in the toughness of the coarse-grained HAZ.

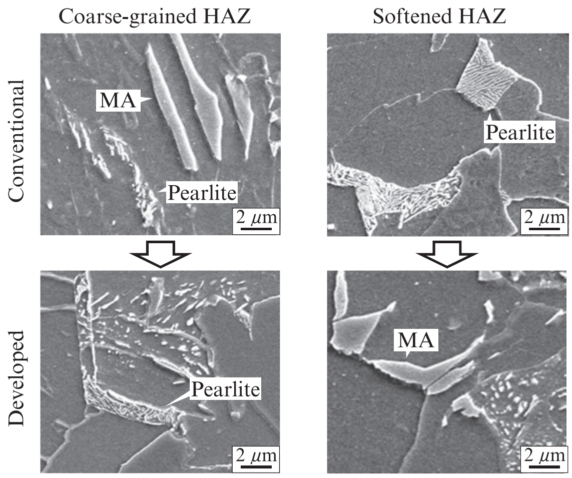


Photo 1 Heat affected zone (HAZ) microstructure of developed steel

In the coarse-grained region, ferrite forms on prior γ grain boundaries, and the bainite transformation then proceeds in the γ former grains. In contrast to this, because diffusional transformation of ferrite is predominant in the softened region, it is thought that the alloying elements are readily distributed to γ, which promotes the formation of MA. **Photo 1** shows examples of the joint microstructures in the coarse-grained HAZ and softened HAZ. The desired HAZ microstructures have been obtained. Specifically, in the conventional steel, the

C-enriched phase in the softened HAZ has undergone pearlite decomposition, whereas, in the developed steel, it has become MA, contributing to an increase in the hardness of the softened HAZ. By using this technique, it has become possible to satisfy both joint −40°C low temperature toughness and joint tensile strength.

4. Features of Developed Steel

4.1 Mechanical Properties of Base Material

Based on the concept of HAZ microstructure control, a YP390F class steel for large heat input welding was manufactured by an actual plate mill. **Table 2** shows the chemical composition of the developed steel. The contents of the various added alloying elements were optimized in order to satisfy both joint strength and joint low temperature toughness in large heat input welding. Applying the above-mentioned JFE EWEL^{TM} technology, the contents of Ti and N were optimized and Ca and B were added. The content of Si was also reduced to suppress formation of MA in the coarse-grained HAZ, and a further improvement of toughness was achieved. In addition, Cu and Ni were also added, resulting in improved joint strength, and a low Pcm design was adopted to enable preheating-free welding. Using thermo-mechanical control process (TMCP) in the plate manufacturing process, the optimum rolling and cooling conditions for satisfying the base material standard of YP390F class steel were derived, and plates with a thickness of 50 mm were produced.

Table 2 Chemical compositions of developed steel

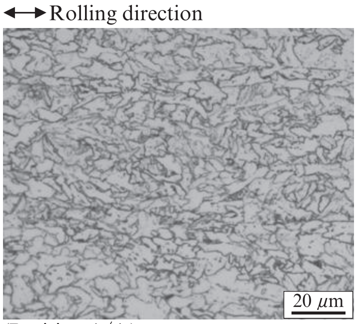
(mass%)

C	Si	Mn	Nb	Ti	Others	Ceq*1	Pcm*2
0.05	0.06	1.56	0.01	0.01	Cu, Ni, Ca, B, etc.	0.38	0.16

*1Ceq=C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15

*2Pcm=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

↔ Rolling direction



(Position:1/4t)

Photo 2 Microstructure of developed steel

The microstructure of the developed steel is shown in **Photo 2**, and the results of the tensile test and Charpy impact test are shown in **Table 3**. By applying the optimum TMCP conditions, it was possible to obtain an fine microstructure, and the properties of the base material amply satisfied the target values for the strength and toughness of YP390F class steel.

Table 3 Mechanical properties of developed steel

Position	YP (MPa)	TS (MPa)	El (%)	$vE_{-60°C}$ (J)
1/4t	476	567	26	334
1/2t	422	518	28	262

Tensile test specimen: NK U14A, T-Direction
Charpy impact test specimen: NK U4, L-Direction
YP: Yield point TS: Tensile strength
El: Elongation vE: Absorbed energy

4.2 Welding Test

For TMCP type high tensile strength steels with carbon equivalent Ceq>0.36 mass%, Japan Shipbuilding Quality Standard (JSQS) provides that preheating is necessary in case the temperature is 5°C or lower, and the bead length must be 50 mm or longer in case short bead welding is performed. The developed steel has a Ceq slight higher than 0.36 mass% in order to secure joint strength. However, excellent weldability of the developed steel was confirmed by performing low temperature crack resistance and weld HAZ maximum hardness tests.

4.2.1 Low temperature crack resistance

y-Groove weld crack tests were performed with steel plate temperatures of 0°C and 25°C and a welding heat input of 17 kJ/cm in a constant temperature/constant

Table 4 Welding condition of y-groove weld cracking test and results

Thickness (mm)	Atmosphere	Preheat temperature (°C)	Welding condition				Crack ratio (%)		
			Consumable	Current (A)	Voltage (V)	Speed (cm/min)	Surface	Section	Root
50	0°C-60%	0	DW-55L (1.2 mmϕ) (Kobe Steel, Ltd.)	200	25	17.6	0	0	0
							0	0	0
							0	0	0
	20°C-60%	25					0	0	0
							0	0	0
							0	0	0

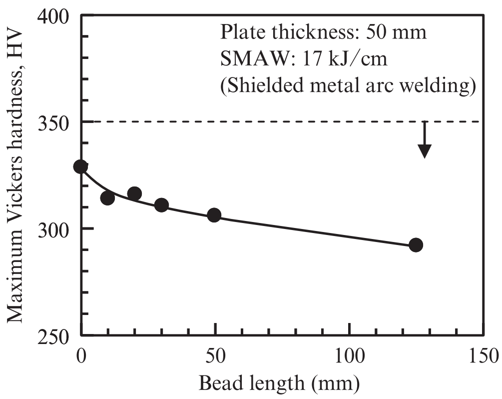


Fig. 3 Results of maximum hardness test for the developed steel[11)]

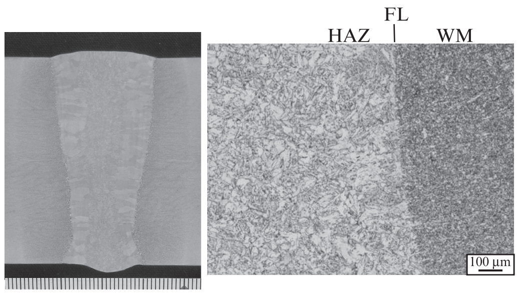
humidity chamber adjusted to an atmosphere with temperature 0°-humidity 60% or room temperature 20°C-humidity 60%, respectively, in accordance with JIS Z 3158 (JIS: Japanese Industrial Standards). The test welding conditions and test results are shown in **Table 4**. Under all conditions, no surface cracks, cross-sectional cracks, or root cracks occurred, demonstrating that the developed steel has excellent low temperature crack resistance as a result of its low Pcm design.

4.2.2 Weld HAZ maximum hardness

A HAZ maximum hardness test was performed in accordance with JIS Z 3101. The thickness of the test specimen was 50 mm (Full thickness), and the bead length was varied from 10 mm to 125 mm. In addition, a test was also performed under arc strike conditions. **Figure 3** shows the relationship of the bead length and maximum hardness of the HAZ. Under all conditions, the maximum hardness of the HAZ is lower than 350 points, and no remarkable hardening has occurred. Although the developed steel has a composition system in which Ceq is slightly higher than the upper limit (0.36 mass%) for preheating-free steels specified by JSQS, preheating-free welding is possible, as hardening during arc strike is suppressed by the low Pcm design.

4.3 Features of Large Heat Input Welding Joints

In order to evaluate the features of large heat input welding joints, 1-pass electrogas arc welding (EGW) joints were fabricated under the conditions shown in **Table 5**. Examples of the macrostructure and the microstructure in the vicinity of the fusion line are shown in **Photo 3**. The tensile strength of the joints is shown in **Table 6**. The joints have adequate joint strength exceeding the lower limit (≧510 MPa) of the standard for joint strength. The results of a test of the Charpy impact properties of the joints are shown in **Fig. 4**. High absorbed



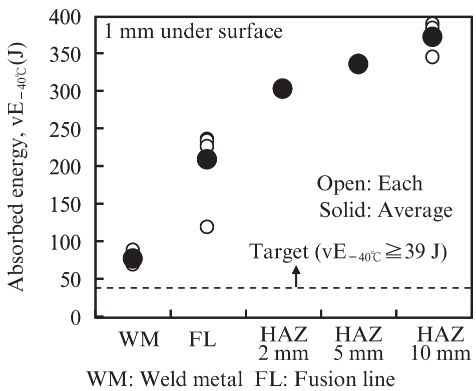
WM: Weld metal, FL: Fusion line, HAZ: Heat affected zone

Photo 3 Macrostructure and microstructure in the vicinity of fusion line of electrogas arc welding (EGW) welded joint[11)]

Table 6 Tensile test results of electrogas arc welding (EGW) welded joint

Test piece	TS (MPa)	Fracture positions
NKU2A	549, 545	Base metal
NKU2B	524, 517	Base metal

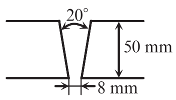
TS: Tensile strength



WM: Weld metal FL: Fusion line
HAZ: Heat affected zone

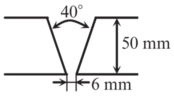
Fig. 4 Charpy impact properties of electrogas arc welding (EGW) welded joint

Table 5 Welding conditions for electrogas arc welding (EGW)[11)]

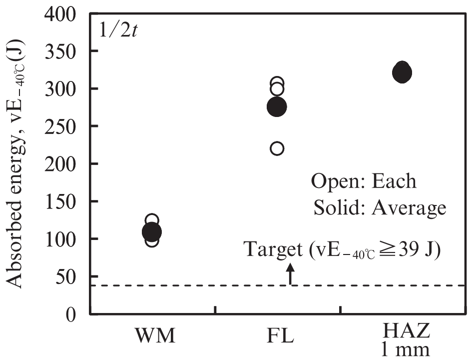
Thickness (mm)	Welding method	Edge preparation	Welding consumable	Pass	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)
50	EGW	 20° 50 mm 8 mm	DW-S1LG (1.6 mmϕ) KL-4 (Kobe Steel, Ltd.)	1	410	42	3.5	302

EGW: Electrogas arc welding

Table 7 Welding conditions for GMAW

Thickness (mm)	Welding method	Edge preparation	Welding consumable	Pass	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)
50	GMAW		DW-55L FB-B3T (Kobe Steel, Ltd.)	15	180–210	21–22	5–9	25–53

GMAW: Gas metal arc welding



WM: Weld metal FL: Fusion line
HAZ: Heat affected zone

Fig. 5 Charpy impact properties of FCW welded joint

energy was obtained at all notch positions, and it was possible to satisfy the property requirements for Charpy toughness in the large heat input welding joints of YP390F class steel, which had been difficult with the conventional technology. It may be noted that excellent low temperature toughness was also confirmed in welded joints produced by multipass welding using CO_2 gas shielded arc welding (Gas metal arc welding: GMAW), which is a conventional welding method. The welding conditions for the multipass welding joints and the results of the Charpy test of the joints are shown in **Table 7** and **Fig. 5**, respectively.

5. Conclusion

The world's first YP390F class steel for large heat input welding specifications was developed by utilizing advanced microalloying technology. Conventionally, multipass welding with a small heat input had been used with F class steels for low temperature specifications in order to guarantee the low temperature toughness of the welding heat affected zone (HAZ). The new technology has made it possible to develop a high strength, heavy thickness steel plate that displays excellent low temperature toughness and is also suitable for high efficiency 1-pass large heat input welding. Steel plates applying the developed technology have been adopted and applied practically in liquefied natural gas (LNG) ships with cold climate specifications.

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