460MPa-Yield-Strength-Class Steel Plate with JFE EWEL® Technology for Large-Heat-Input Welding†

ICHIMIYA Katsuyuki[*1] SUMI Hiroyuki[*2] HIRAI Tatsushi[*3]

Abstract:

The "JFE EWEL®" technology for improving the toughness of heat affected zone (HAZ) effected by large heat input welding has been applied to make YP460 MPa class steel plates for very large container carriers. The "JFE EWEL" technology consists of minimizing the coarse grain HAZ region through controlling TiN particles, refining the microstructure of HAZ by using B, Ca and improving the toughness of matrix. Furthermore, the reduction of C, Si, Nb contents improves HAZ toughness with decreasing martensite-austenite constituents. Production of this steel plate was made possible by Super-OLAC® (OLAC: On-Line Accelerated Cooling) and state-of-the-art thermo-mechanical control process. The developed steel has been approved by Nippon Kaiji Kyokai as rolled steel for hull, and is under the application to actual ship.

1. Introduction

The increasing use of long-distance freight by containers in the shipbuilding industry has led to a rapid increase in the size of the container ships over the last several years[1–2].

The building of super-large container ships exceeding 10 000 TEUs (TEU: twenty-feet equivalent unit) has also recently begun. Because container ships are structured with wide openings, high-strength and heavy-wall materials are used in members such as hatch coamings and sheer strakes. In many cases, YP390 MPa-class steel plates with a maximum plate thickness of not less than 65 mm are used. The use of heavy-section plates with plate thicknesses on the order of 80 mm has posed problems, however, and hulls with lighter weights and lower centers of gravity have made it necessary to improve work efficiency by increasing the number of stacked containers and reducing the plate thickness. These changes have given rise to the need for YP460 MPa-class steels that exceed the upper limit of the strength standard for hull structural steels.

Electrogas arc welding (EGW), a high-efficiency vertical welding method, is used for the welding of heavy-section plates. In large-heat-input welding, the structure of the heat-affected zone (HAZ) coarsens remarkably, leading to a deterioration in the toughness of joints. Furthermore, the carbon equivalent is indispensable for ensuring the base metal strength of YP460 MPa-class steel plates, and this results in the deterioration of HAZ toughness.

In order to cope with these problems, JFE Steel has developed a YP460 MPa-class steel with excellent joint properties after large-heat-input welding. This material culminates from improvements in the "JFE EWEL®" technology[3,4] for enhancing the toughness of the HAZ affected by large-heat-input welding via high-level microalloying control.

This paper describes the features of the YP460 MPa-class steel and the performance of the plates and welded joints of this steel.

---

† Originally published in *JFE GIHO* No. 18 (Nov. 2007), p. 13–17


[*1] Senior Researcher Deputy Manager,
Bar & Wire Res. Dept.,
Steel Res. Lab.,
JFE Steel


[*2] Senior Researcher Deputy Manager,
Joining & Strength Res. Dept.,
Steel Res. Lab.,
JFE Steel


[*3] Staff Manager,
Plate & Forging Sec., Products Design & Quality Control for Steel Products Dept.,
West Japan Works,
JFE Steel

Table 1 Target values in mechanical properties and C_{eq} for developed steel plate

		Steel plate						Welded joint	
		Tensile properties*1				Charpy impact properties*2	C_{eq}*3 (%)	Tensile properties*2	Charpy impact properties
Grade	Thickness (mm)	YS (MPa)	TS (MPa)	El (%)		$_vE_{-40}$		TS (MPa)*4	$_vE_{-20}$ (J)
YP460	60	≧460	570–720	*5		*5	≦0.42	≧570	*5
EH40	$50 < t \leqq 70$	≧390	510–650	≧20		≧46	≦0.40	≧510	≧41

*1T.P.: T-direction *2T.P.: L-direction *3C_{eq}=C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15 *4T.P.: NK U2A *5Equivalent to EH40
YS: Yield strength TS: Tensile strength El: Elongation $_vE$: Absorbed energy

2. Target Performance

Table 1 shows the target properties of the YP 460 MPa-class steel, as compared to the Class NK EH40 (KE40) standard. Welded joints were prepared by large-heat-input one-pass EGW, and evaluated. With the exception of tensile strength, the target properties were equivalent to those of EH40.

3. Techniques for the Microalloying Design and Manufacturing of the Newly Developed Steel

3.1 Outline of JFE EWEL[3,4]

JFE Steel's JFE EWEL technology was applied for the microalloying design of the newly developed steel. The technical elements of the JFE EWEL technology will be described below.

3.1.1 Grain size control of HAZ

In order to minimize the coarse-grain HAZ region during large-heat-input welding, it is necessary to suppress the austenite grain growth at high temperatures. Though nitrides and oxides, materials stable at high temperatures, are generally used to suppress the austenite grain growth[5–9], JFE Steel used TiN.

The Ti and N contents, Ti/N ratio, and amounts of added microalloys are controlled by thermodynamic calculations conducted by Thermo-Calc and experimental examinations. This has enabled JFE to raise the temperature of the dissolution of TiN in a solid solution state to not less than 1 450°C, and to finely disperse the TiN.

3.1.2 Intragranular structure control and technique for increasing the matrix toughness

The intragranular structure is refined by using BN and Ca-based inclusions as nucleation sites in the prior austenite grains in the austenite-to-ferrite transformation. BN is effective in reducing the solute N (a detractor of HAZ toughness) and increasing the toughness of the matrix. And because part of the B added to steel exists as solute B, the formation of coarse grain-boundary ferrite from the prior austenite grain boundaries can suppressed, leading to a further increase in toughness.

3.2 Technique for Reducing Martensite-Austenite Constituents

To ensure the strength of YP460 MPa-class steels in the base metal and in the joints obtained by large-heat-input welding, there is a need to increase the amounts of added alloying elements. As shown in **Fig. 1**, however, the synthetic HAZ toughness deteriorates with increases in the carbon equivalent (C_{eq}) and Nb contents. This is because the microstructure changes from one consisting mainly of ferrite to one consisting mainly of upper bainite containing M-A (martensite-austenite) constituents, that is, constituents with adverse effects on toughness. The toughness can be increased by refining the structure, and the structure can be refined by refining the austenite grains. At present, however, it is very difficult to refine an intragranular bainite structure uniformly. This is because the toughness is compromised by the weakest structure (coarse structure). JFE Steel has there-

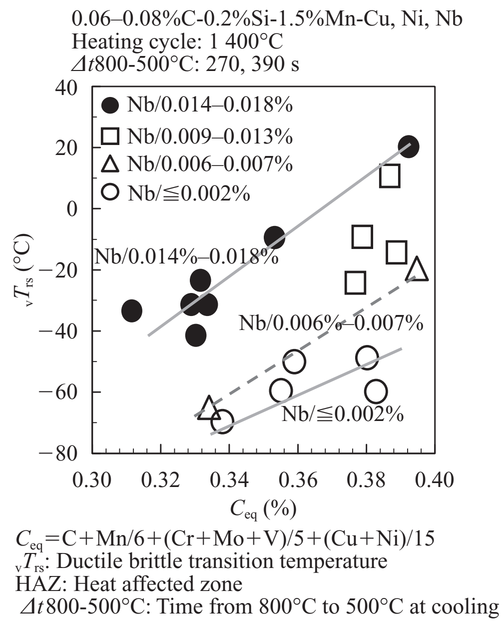


Fig. 1 Effect of C_{eq} and Nb contents on synthetic HAZ toughness

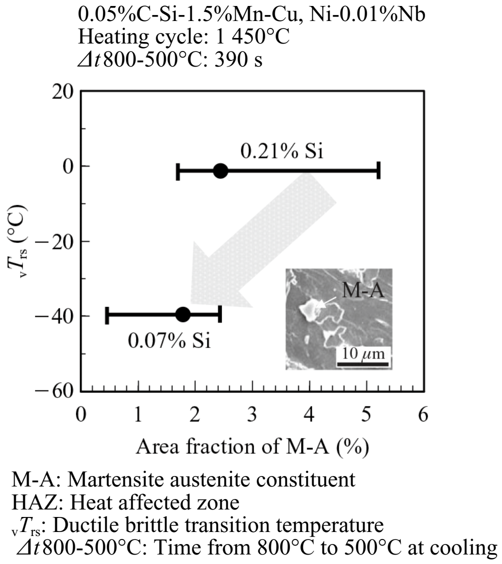


Fig. 2 Effect of Si contents on synthetic HAZ toughness

fore worked to improve the toughness by searching for ways to reduce the amounts of M-A constituents[10].

M-A constituents are generated mainly in a microsegregation in which Mn and the like are enriched in the cooling process after large-heat-input welding. This microsegregation occurs when components are enriched in a dendrite arm during continuous casting. An examination revealed the effectiveness of reducing the levels of Si, Nb, and P, in addition to reducing the C content. **Figure 2** shows the relationship between the Si content and the area fraction of M-A. The area fraction of M-A was determined by photographing ten fields of view at a magnification of 2 000× and measuring the area fraction in each field of view. The maximum area fraction of M-A changes greatly due to differences in the Si content. This is because, as described above, the M-A constituents are unevenly distributed in a microsegregation. The M-A decomposition behavior in the temper effect generated by subsequent passes during multi-pass welding is construed to be an effect of Si on M-A reduction[11]. This might be accounted for by the relation between the Si content and cementite: a decline in the Si content leads to an increase in precipitation of cementite, because Si scarcely dissolves in cementite in a solid solution state. On the other hand, there are scarcely any reports about one-pass welding. In the heat cycle of the present one-pass large-heat-input welding of YP460 MPa-class steels, however, we have found that a decrease in the Si content is clearly very effective in reducing the M-A constituents.

3.3 Technique for Manufacturing High-Strength, High-Toughness Heavy-Wall Materials

The prescribed base material properties must be met after performing a microalloying design in which the HAZ toughness is duly considered. YP460 MPa-class steel plates must provide an impact value at −40°C in the Charpy impact test. The general practice until now, in almost all cases, has been to subject YP460 MPa-class steel plates to re-heating quenching-tempering treatment or direct quenching (or low-temperature cooling stop)-tempering treatment. In the newly developed steel, however, high strength and high toughness are achieved by the TMCP process.

In the manufacturing of the base metal, the target properties are realized by precisely controlling the slab heating temperature, the rolling temperature, the rolling reduction, the start cooling temperature, and the stop cooling temperature, while using an online cooling device (*Super*-OLAC) to attain cooling rates equivalent to the theoretical limits.

4. Properties of the Newly Developed Steel

4.1 Mechanical Properties of Base Metal

Table 2 shows the chemical composition of the newly developed steel. In order to lower the M-A constituents, the carbon content is lowered to 0.05% and the Si content is lowered to 0.07%, compared to the levels present in conventional steel EH40 for large-heat-input welding. In order to ensure strength, on the other hand, the carbon equivalent is increased to 0.39% and an appropriate amount of Nb is added.

Table 3 shows the tensile test results and Charpy impact test results of the newly developed steel plate. For the base material properties, target properties of both strength and elongation are met. The absorbed energy at –40°C is not less than 250 J and the base metal has a sufficient value as an E-grade steel.

4.2 Weldability

The Japan Shipbuilding Quality Standard (JSQS)

Table 2 Chemical compositions of developed steel plate

	Thickness (mm)	Chemical composition (mass%)						
		C	Si	Mn	Nb	Ti	Others	C_{eq}*
YP460	60	0.05	0.07	1.55	0.01	0.01	Cu, Ni, Ca, B, etc.	0.39
EH40	80	0.08	0.22	1.54	—	0.01	Ca, B, etc.	0.36

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

Table 3 Mechanical properties of developed steel plate

YP (MPa)	TS (MPa)	El (%)	$_vE_{-40}$ (J)
508	654	21	282

YP: Yield point TS: Tensile strength
El: Elongation $_vE$: Absorbed energy

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
60	0°C-60%	0	LB-62UL (4 mmϕ) (Kobe Steel, Ltd.)	170	25	15	0	0	0
							0	0	0
							0	0	0
	20°C-60%	25					0	0	0
							0	0	0
							0	0	0

specifies that TMCP type high-tensile steels with a C_{eq} content in excess of 0.36% must be preheated when the atmospheric temperature is not more than 5°C. In this newly developed steel, the authors adjusted the C_{eq} to 0.39%, in order to ensure strength. We therefore checked the weldability.

A y-groove cracking test was conducted with a heat input of 17 kJ/cm in accordance with JIS Z 3158 at steel plate temperatures of 0°C and 25°C, in a temperature- and humidity-controlled room adjusted to two conditions: room temperature 0˚C/humidity 60%, room temperature 20°C/humidity 60%. The test welding conditions and test results are shown in **Table 4**. No cracking occurred under either condition. The newly developed steel plate was thus confirmed to have excellent weldability.

4.3 NRL Drop-Weight Properties

The NRL drop-weight test was conducted for the newly developed steel in accordance with ASTM E208 (ASTM Standards). A test piece shape of the P-3 type was adopted. Test pieces were taken from the surface of a steel plate in the L (longitudinal) direction and the T_{NDT} temperature (nil-ductility transition temperature) was determined. A drop-weight energy of 400 J was used. The test results are shown in **Table 5**. The T_{NDT} temperature was –75°C. The newly developed steel plate was thus confirmed to have excellent properties.

Table 5 Drop-weight test results of steel plate developed

Thickness (mm)	Test piece type	Location	Direction	T_{NDT} (°C)
60	P-3	Surface	Longitudinal	−75

T_{NDT}: Nil-ductility transition temperature

4.4 Line-Heating Properties

Straightening work by gas flame heating is indispensable for ensuring dimensional accuracy after welding in shipbuilding operations. For the line-heating conditions for TMCP high-tensile steels, JSQS specifies that at carbon equivalents exceeding 0.38%, a steel plate heated to a surface temperature of not more than 900°C should be water cooled at not more than 900°C after air cooling. At carbon equivalents exceeding not more than 0.38%, on the other hand, the standard prescribes water cooling or air cooling immediately after heating. Steps must also be taken to confirm that the mechanical properties do not deteriorate even after the line-heating. In this case, the carbon equivalent is 0.39%.Water cooling was performed twice after heating to 900°C: once immediately after heating and once from 500°C. The tensile test of the full-thickness base metal and the Charpy impact test of a surface layer portion were conducted. The test results are shown in **Table 6**. Both the base metal strength and the Charpy impact properties met the target properties, and the tests confirmed that adequate base metal properties were maintained after line heating.

4.5 Properties of Large-heat-input Welded Joints

In order to evaluate joints obtained by large-heat-input welding, one-pass EGW welded joints were prepared under the conditions shown in **Table 7**. **Photo 1** shows an example of a macrostructure and an example of a microstructure near a fusion line. The tensile

Table 6 Mechanical properties of the steel plates after line-heating treatment

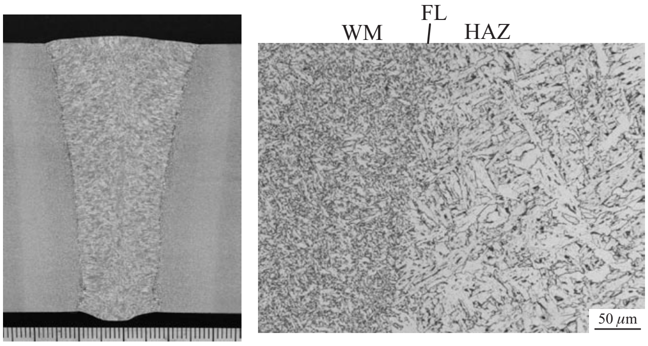
Thickness (mm)	Maximum heating temperature (°C)	Cooling conditions	YP* (MPa)	TS* (MPa)	El* (%)	${}_vE_{-40}$ (J)
60	900	Immediate WQ	524	650	20	218
		WQ from 500°C	539	650	19	181

*T.P.: NKU1
WQ: Water quench YS: Yield strength TS: Tensile strength El: Elongation ${}_vE$: Absorbed energy

Table 7 Welding conditions for EGW welded joint

Thickness (mm)	Welding method	Welding consumable	Pass	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)
60	EGW	Developed wire (1.6 mmϕ) KL-4 (Kobe Steel, Ltd.)	1	390	42	2.7	364

EGW: Electrogas arc welding



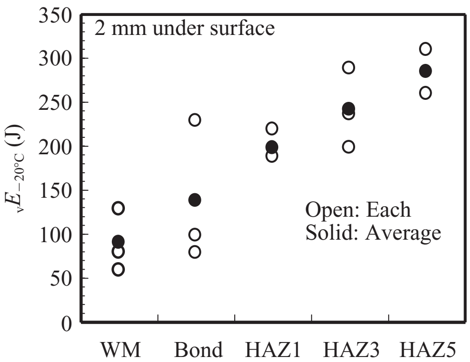
WM: Weld metal FL: Fusion line HAZ: Heat affected zone

Photo 1 Macrostructure and microstructure at fusion line of EGW welded joint

Table 8 Tensile test results of EGW welded joint

TS (MPa)	Fracture positions
586	Base metal
584	Base metal

T.P.: NKU2A
EGW: Electrogas arc welding TS: Tensile strength



$_vE$: Absorbed energy
WM: Weld metal HAZ: Heat affected zone

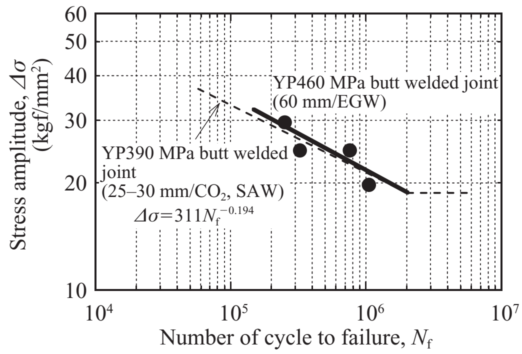
Fig. 3 Charpy impact properties of EGW welded joint

strength of the welded joints is shown in **Table 8**. A tensile strength of 570 MPa is sufficiently met. The results of the Charpy impact test are shown in **Fig. 3**. A sufficiently high absorbed energy is obtained in all of the notch positions. The CTOD test results are shown in **Table 9**. The welded joints exhibited sufficiently high resistance to brittle fracture propagation at –10°C. The fatigue test results are shown in **Fig. 4**. The fatigue strength of base metals increases with increasing strength, whereas

Table 9 CTOD test results for EGW welded joint of developed steel plate

Thickness (mm)	Test temperature (°C)	Notch location	δ (mm)	Fracture mode
60	−10	Bond	0.705	u
			0.728	u
			0.403	u

CTOD: Crack tip opening displacement
EGW: Electrogas arc welding



EGW: Electrogas arc welding SAW: Submerged arc welding

Fig. 4 *S*-*N* diagram of EGW welded joint

that of the welded joints usually remains constant and does not depend on the strength of the base metal[12]. The present results also reveal this phenomenon. The newly developed steel exhibits fatigue properties comparable to those of conventional YP390 MPa-class steels[13].

5. Conclusion

JFE Steel developed a YP460 MPa-class steel for large-heat-input welding by applying its JFE EWEL technology for improved HAZ toughness. The authors believe that this newly developed steel can help improve efficiency in the construction of large container ships, improve fuel consumption, and reduce environmental burdens.

The present steel was developed in collaboration with IHI Marine United Inc., IHI Corp., and Welding Company, Kobe Steel Ltd. Detailed examinations on the application of this steel plate to actual ships are now being carried out, including fracture experiments with a full-scale structural model. According to tests on the brittle crack arrestability of the newly developed steel, the Kca (crack arrest toughness) value at –10°C is not more than 6 000 N/mm$^{3/2}$. The steel also has excellent properties in this respect.

References

1) Sakaguchi, K.; Toyoda, M.; Inukai, Y. IHI Engineering Reviw. 2007, vol. 40, no. 2, p. 49–53.
2) Nagatsuka, S. Kanrin. 2007, no. 11, p. 12–16.
3) Suzuki, S.; Ichimiya, K.; Akita, T. JFE Giho. 2005, no. 5, p. 24–29.
4) Suzuki, S.; Oi, K.; Ichimiya, K.; Kitani, Y.; Murakami, Y. Materia. 2004, vol. 43, no. 3, p. 232–234.
5) Kanazawa, S.; Nakashima, A.; Okamoto, K.; Kanaya, K. Tetsu-to-Hagané. 1975, vol. 61, no. 11, p. 2589–2603.
6) Kasamatsu, Y.; Takashima, S.; Hosoya, R. Tetsu-to-Hagané. 1979, vol. 65, no. 8, p. 1232–1241.
7) Nakanishi, M.; Komizo, Y.; Seta, I. J. of Jpn. Welding Soc. 1983, vol. 52, no. 2, p. 117–124.
8) Deshimaru, S.; Hirai, M.; Amano, K.; Ueda, S.; Uemura, H.; Tsubota, K. Kawasaki Steel Giho. 1986, vol. 18, no. 4, p. 295–300.
9) Kojima, A.; Kiyose, A.; Minagawa, M.; Hirano, A.; Yoshii, K.; Nakashima, T.; Hoshino, M.; Ueshima, Y. CAMP-ISIJ. 2003, vol. 16, p. 360–363.
10) Kawabata, F.; Amano, K.; Toyoda, M.; Minami, F.; Proc. 10th Int. Conf. OMAE, 1991, vol. 3, p. 73–80.
11) Tanigawa, O.; Ishii, H.; Itakura, N,; Amano, K.; Nakano, Y,; Kawabata, F. Kawasaki Steel Giho. 1986, vol. 18, no. 4, p. 295–300.
12) Watanabe, O.; Matsumot, S.; Nakano, Y.; Saito, Y. Quarterly Journal of the Japan Welding Society. 1995, vol. 13, no. 3, p. 438–443.
13) Kitada, H. doctoral thesis, University of Tokyo. 1990.