JFE TECHNICAL REPORT
No. 20 (Mar. 2015)

Development of YP460 N/mm^2 Class Heavy Thick Plate with Excellent Brittle Crack Arrestability for Mega Container Carriers†

HASE Kazukuni[*1] HANDA Tsunehisa[*2] ETO Taiki[*3]

Abstract:

YP460 N/mm^2 class heavy thick plate with excellent crack arrestability for mega container carriers has been developed. Advanced alloy design and an optimized controlled rolling and cooling process using Super-OLAC^{TM} (On-Line Accelerated Cooling) are applied to obtain highly oriented textures parallel to the surface of the plate, which are effective to prevent brittle crack propagation. The crack arrest toughness (Kca at −10°C) of the developed steel is 16 800 N/mm$^{3/2}$, which is more than double that of the guidelines on brittle crack arrest design issued by Class NK. The large scale duplex ESSO test, assuming the structure of the hatch side coaming of container carriers, was also carried out, and the result revealed that the developed steel plate has very good performance to stop brittle crack propagation. The developed steel plate is supposed to be utilized to ensure the safety of mega container carriers against brittle fracture.

1. Introduction

Recently, the size of container carriers has increased as the container freight movement volumes between Asia and Europe expanded. Large container carriers more than 10 000 TEU (Twenty feet equivalent unit) are called "Mega Container Carriers." The largest container carrier, 18 000 TEU, was constructed in 2011 for transport efficiency improvement[1,2] and a larger sized container carrier is also planed to be constructed in a couple of years.

Steel plates applied for the upper hull structure of large container carrier, such as the hatch side coaming and upper deck, are becoming thicker and higher in strength in order to ensure the required structural strength due to the large cargo opening structure. YP390 and YP460 class steels more than 70 mm in thickness have been developed and put into practical use for the construction of mega container carriers[3–5].

Fracture toughness is required for these thick steels to ensure the safety of the hull structure and suppress brittle fracture, which leads to catastrophic sea accidents. Therefore, E grade steels are used for upper hull structures. It is very difficult to suppress crack initiation in weld joints perfectly, even though careful attention is paid to suppressing welding defects during the welding procedure. Therefore, thick plates with excellent crack arrestability must be used in the hatch side coaming and upper deck to suppress brittle crack propagation even when a crack initiates at the weld joint.

The crack arrestability of thick plate for hull structures is studied in an industry-academia collaboration committee, "Brittle Crack Arrest Design Committee of the Japan Welding Engineering Society"[6], and the results have been summarized and incorporated in Class NK "Guidelines on Brittle Crack Arrest Design" (Nippon Kaiji Kyokai, 2009)[7]. In the guideline, the minimum brittle crack arrest toughness, Kca, of the steel at −10°C is to be 6 000 N/mm$^{3/2}$ for plate thicknesses between 50 mm and 75 mm, and the block joint is to be

† Originally published in *JFE GIHO* No. 33 (Feb. 2014), p. 13–18

[*1] Dr. Eng.,
General Manager, Steel Products Res. Dept.,
Steel Res. Lab.,
JFE Steel

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

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

Copyright © 2015 JFE Steel Corporation. All Rights Reserved.

shifted more than 300 mm in order to stop the brittle crack propagation from the hatch side coaming to the upper deck and the upper deck to the hatch side coaming by the structural discontinuity effect.

The new Unified Requirement (UR) concerning crack arrest design was issued by International Association of Classification Societies (IACS) in January 2013.

Both the use of steel plate with excellent crack arrestability and structural discontinuities such as weld line shift between the hatch side coaming and upper deck, or crack arrest holes put in the block-to-block butt welds, are required when the YP460 steel between 50 mm and 100 mm in thickness is used for the construction of mega container carrier[8]. This UR is to be applied to container carriers contracted for construction on or after 1 January 2014[8].

Thus, heavy thick high strength steel with excellent crack arrestability has been desired in this field.

There are some methods reported in order to enhance the crack arrestability of steel plates. The most popular one is to improve the impact toughness of the plate by means of grain refinement[9–14].

JFE Steel has focused on the crystallographic texture, which has been mainly studied in automotive steel sheets, and developed a new technology to enhance crack arrestability by controlling the favored texture to prevent straight brittle crack propagation.

This paper describes the features of the developed YP460 steel plate, which is suitable for the hatch side coaming of mega container carriers.

2. Techniques for High Crack Arrestability

There are some methods which the enhance brittle crack arrest toughness (hereinafter, Kca), of steel plates[9–15]. Grain refinement is one of the most popular methods to improve Kca. It was also reported that plate with ultra-fine grains in the surface layer had excellent Kca through the formation of a shear lip during crack propagation. JFE Steel has focused on texture control as well as grain refinement in the rolling process to produce a new steel plate with excellent crack arrestability[4].

Handa et al. investigated the effect of plate toughness and crystallographic texture on the brittle crack arrest temperature (${}_{25}T_{\mathrm{K6000}}$), and derived a new parameter, the Y-index, as a function of vTrs of the plate and the (100) and (211) texture concentrations measured by X-ray analysis[16]. There is a good correlation between the Y-index and brittle crack arrest temperature, as shown in **Fig. 1**. They also clarified the fact that a steel plate with a highly orientated (211) and/or (100) texture parallel to the surface of the plate exhibits good arrestability by forming sub-cracks along with the cleavage plane.

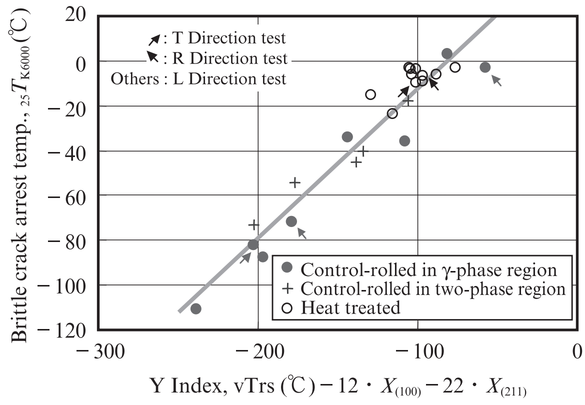


Fig. 1 Relationship between ${}_{25}T_{\mathrm{K6000}}$ and Yindex

Tsuyama et al. investigated the effect of texture on brittle crack arrest toughness[17]. Steel with a strong texture of the (100) plane or (211) plane in the middle part of the steel plate showed the split nail type fracture morphology, while the conventional steel plate showed the thumb nail type one. The stress intensity factor of the split nail type steel becomes smaller than the thumb nail type one as a brittle crack propagates. These results suggest that heavy thick steel plate with excellent crack arrest toughness can be developed by controlling texture.

Based on the above-mentioned original metallurgical approach, heavy thick YP460 steel plate with excellent Kca value has been developed. Both the alloy design and the production conditions were optimized to obtain specific textures suitable for improving brittle crack arrest toughness.

3. Properties of Steel Plates

3.1 Chemical Composition and Manufacturing Process

The chemical compositions of the developed steel plates are shown in **Table 1**. These steels have the carbon equivalent (Ceq) of 0.46 mass% to satisfy the specification of EH47 grade E steel, even in the case of heavy thick plate. The weldability of these steels is also good due to their low Pcm alloy design.

The plates of 70 mm and 85 mm in thickness are manufactured by the thermo-mechanical control process (TMCP process) with control of tensile strength, toughness and texture to satisfy the specification of EH47 E-grade steel and to obtain a high Kca value.

The mechanical properties of the base plate and weld joint and the crack arrestability of the plate are shown in this section.

3.2 Mechanical Properties of Developed Steel

The mechanical properties of the developed steel

Table 1 Chemical composition of steels developed

(mass%)

Thickness (mm)	C	Si	Mn	P	S	Others	Ceq*	P_{CM}**
70	0.06	0.15	1.91	0.005	0.002	Cu, Ni, Cr, Nb, Ti	0.46	0.19
85	0.06	0.15	1.89	0.006	0.002	Cu, Ni, Cr, Nb, Ti	0.46	0.19
Specification of EH47 (IACS UR W31)	As approved by each classification society						≦0.49	≦0.22

*Ceq=C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5
**P_{CM}=C+Si/30+(Mn+Cu+Cr)/20+Mo/15+V/10+Ni/60+5B

Table 2 Mechanical properties of steels developed

Steel	Thickness (mm)	Position	Tensile property				Charpy impact property	
			Direction	YP (N/mm²)	TS (N/mm²)	El (%)	Direction	vE_{-40} (J)
Developed	70	1/4*t*	C	497	591	26	L	332
		1/2*t*	C	490	585	24	L	294
	85	1/4*t*	C	486	587	26	L	344
		1/2*t*	C	477	586	21	L	334
Specification of EH47 (IACS UR W31)			C	≧460	570−720	≧17	L	≧53 (70 mm*t*) ≧64 (85 mm*t*)

YP: Yield point TS: Tensile strength
El: Elongation vE_{-40}: Absorbed energy

plates are shown in **Table 2**. The tensile properties of the plates satisfy the specification value of YP460 steel even at the middle part of the plates. The Charpy impact energies of the plates at −40°C are more than 290 J, which is enough to satisfy the specification value of YP460 E grade steel.

3.3 Microstructure

Typical microstructures of the developed steels are shown in **Photo 1**. The observed areas are the quarter and the middle part of the plates. All of the microstructure is classified as upper bainite. This means the developed steel has a uniform microstructure regardless of the plate thickness and position.

The Y-indexes of the steels were measured according to the equation in Fig. 1 in order to estimate the crack arrest toughness. The relative intensity ratios of ND//<100> and ND//<211> were obtained by pole figure measurement. The Y-index of both the 70 mm and 85 mm plates were −170, which means that these steels have good crack arrest toughness, as shown in Fig. 1

3.4 Brittle Crack Arrest Toughness

The standard ESSO test was conducted in accordance with "Test method for brittle crack arrest toughness (WES 2815) " in order to assess Kca of the developed steels and the conventional YP390 grade steel[4]. The sample was set with the stress loading direction parallel to the rolling direction. **Figure 2** shows the standard ESSO test results for the conventional YP390, texture

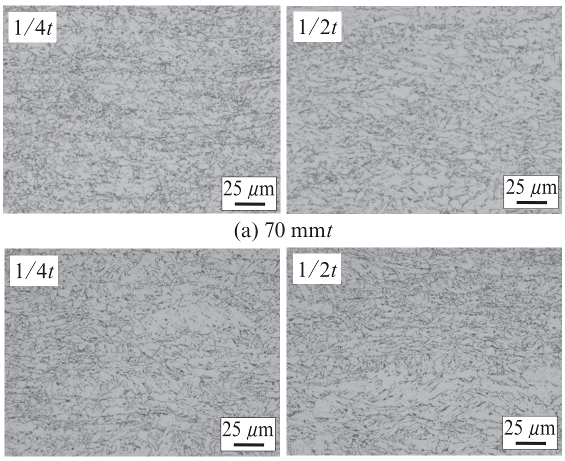


Photo 1 Microstructures of steels developed

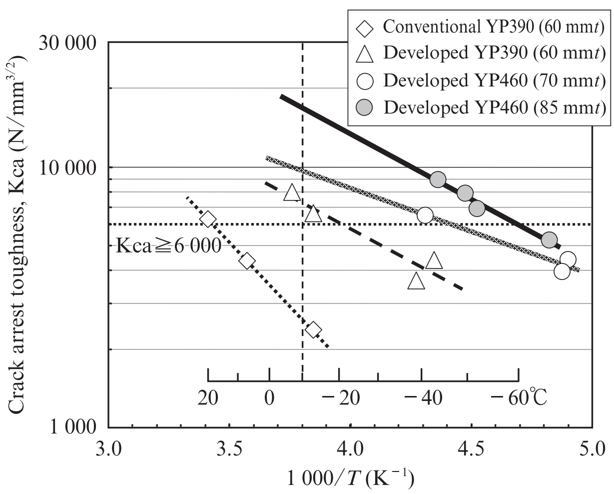


Fig. 2 Results of temperature gradient type ESSO test

controlled YP390 and the developed YP460 steels. The Kca value of the texture controlled YP390 is 7 300 N/mm$^{3/2}$, while that of the conventional one is 2 500 N/mm$^{3/2}$. As for the developed YP460 steels, the Kca values of the 70 mm and 85 mm plates exceed the prescribed Kca value, 6 000 N/mm$^{3/2}$. The Kca values of these steels were 16 800 N/mm$^{3/2}$ and 9 600 N/mm$^{3/2}$ for the 70 mm and 85 mm plates, respectively.

Photo 2 shows the fracture surface of the developed steel after the standard ESSO test. The split nail type fracture surface, which can largely decrease the stress intensity factor, is observed. This is because the texture is properly controlled to achieve high brittle crack toughness in the developed YP460 steels.

The large scale duplex ESSO test was conducted for the developed YP460 steel to verify that a brittle crack can arrest in the steel plate under the large scale condition. Test specimen is shown in **Fig. 3**. The specimen is composed of a brittle crack running plate and a test plate. The crack running plate has a large heat input weld joint by electrogas arc welding (EGW), so that a brittle crack initiated at the notch can propagate along the heat affected zone of the joint and go into the test plate. The test assumes the case that a brittle crack initiates at an upper deck and propagates into a hatch side coaming plate. The overview of the large scale duplex ESSO test is shown in **Fig. 4**. Test temperature of the specimen was −10°C, which is the hull design temperature. The large scale test clarified the fact that the effect of the unloading stress wave on the dynamic stress intensity factor of a crack penetrating into the test plate becomes negligible in the range of brittle crack propagation rates between 500 and 800 m/s when the specimen length is 6.8 m or more, or the distance between the loading points is more than 10 m. The behavior of long brittle crack propagation and arrest in this condition is

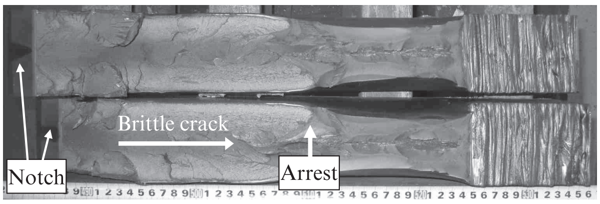


Photo 2 Example of fracture appearance of temperature gradient ESSO test specimen (Kca=7 880 N/mm$^{3/2}$, Temperature=−50°C)

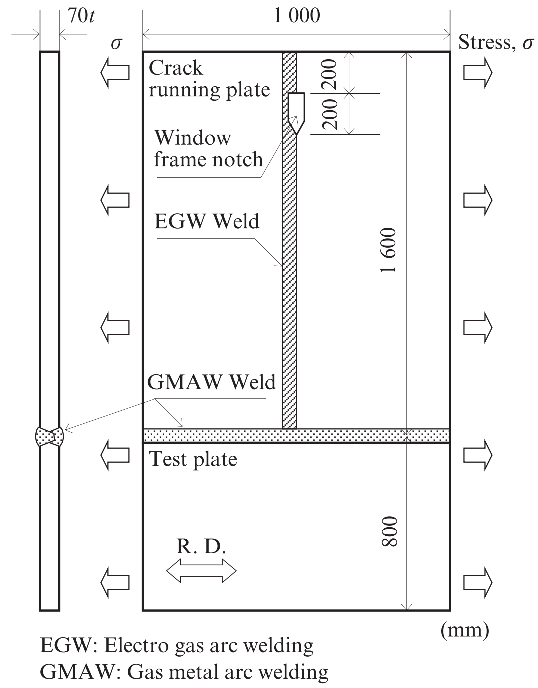


Fig. 3 Dimension of large scale duplex ESSO test specimen

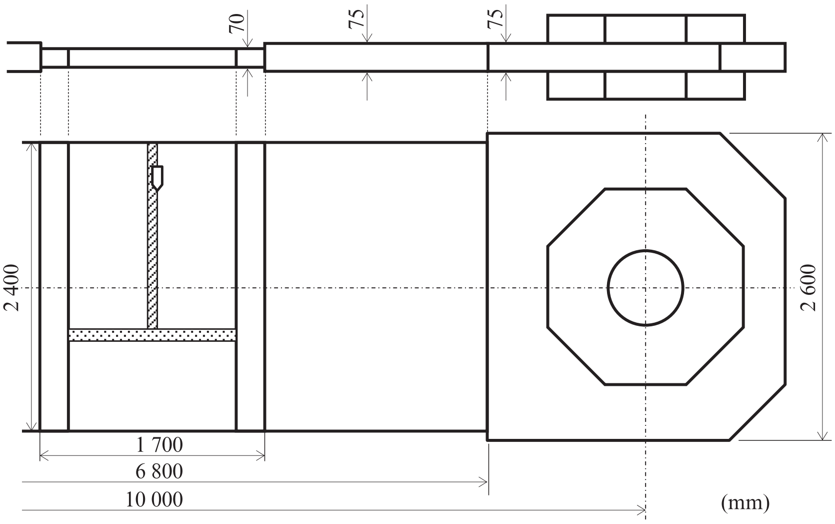


Fig. 4 Test procedure of large scale duplex ESSO test

Table 3 Results of large scale duplex ESSO tests

No.	Applied stress (N/mm^2)	Test temperature (°C)	Result	Crack length in test plate (mm)
1	257	−10	Arrest	23
2	282	−10	Arrest	29

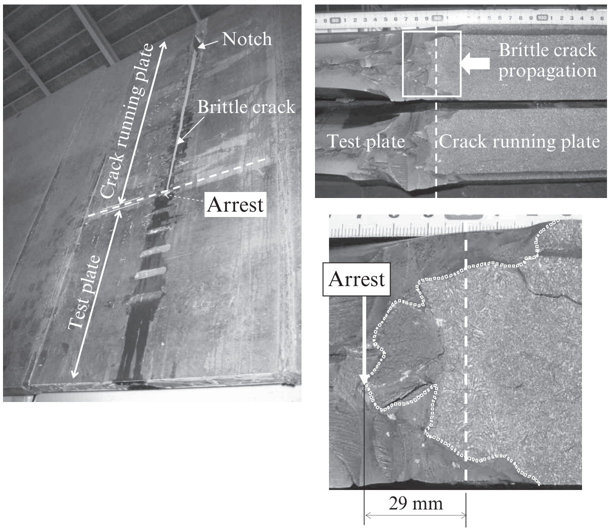


Photo 3 Fracture path and fracture appearance of large scale duplex ESSO test specimen

considered to be substantially the same as that in the actual condition[18,19]. Therefore, the distance between loading points in the test was set to 10 m, as shown in Fig. 4. The applied stress conditions were 257 N/mm^2 and 282 N/mm^2, which is the design stress of hull girder longitudinal bending of YP390 and YP460 steels. The test results are summarized in **Table 3**. The fracture path and fracture surface appearance of the specimen with loading stress of 282 N/mm^2 are shown in **Photo 3**. The brittle cracks that penetrated into the test plates were arrested with a slight propagation to the test plate under both applied stress conditions. The test results indicate that the developed steels exhibit excellent crack arrestability.

4. Weldability of Developed Steel

4.1 Crack Sensitivity

The weldability of the developed YP460 steel plate was investigated by both a short bead test and a y-groove type weld cracking test.

The short bead test was conducted in accordance with JIS Z 3101 (JIS: Japanese Industry Standard). The maximum Vickers hardness with various bead lengths is shown in **Fig. 5**. Although the hardness increases with decreasing bead length, the maximum hardness in the arc strike condition is still below HV350.

In Japanese Shipbuilding Quality Standard (JSQS),

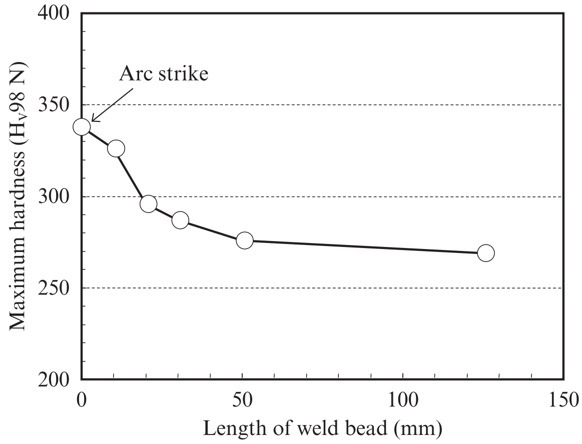


Fig. 5 Maximum hardness test results of the developed steel

Table 4 y groove weld cracking test results

Welding atmosphere	Preheating temperature	Crack ratio (%)		
		Surface crack	Cross section	Root crack
20°C, RH60%	25°C	0 0 0	0 0 0	0 0 0
0°C	0°C	0 0 0	0 0 0	0 0 0
−20°C	−20°C	0 0 0	0 0 0	0 0 0

*Welding consumable: LB-62UL (4.0 mmϕ) , Kobe Steel, Ltd.
*Welding condition 170 A-25 V-150 mm/min, 1.7 kJ/mm

pre-heating is required for TMCP type high tension steels with Ceq more than 0.36% when the ambient temperature is less than 5°C. The alloy design of the developed steel is a relatively high Ceq, more than 0.36%, to satisfy both the required tensile strength and arrestability. Therefore, a y-groove type weld cracking test was conducted in accordance with JIS Z 3158 to check the cold cracking susceptibility without pre-heating. The welding atmospheres were 20°C-RH60%, 0°C, and −20°C and the welding heat input was 17 kJ/cm. A summary of the test results is shown in **Table 4**. No cold cracking was observed even in the specimens tested at −20°C due to the low Pcm alloy design.

4.2 Multi-pass Weld Joint Properties

Multi-pass weld joints were made by gas metal arc welding (GMAW) using flux cored wire (FCW) to evaluate the weld joint properties. The welding conditions are shown in **Table 5**. Both the tensile test and the Charpy impact test of the joint were conducted in accordance with the rules for approval of materials for ships by ClassNK.

The results of the tensile test and Charpy impact test

Table 5 Welding conditions of multi-pass GMAW

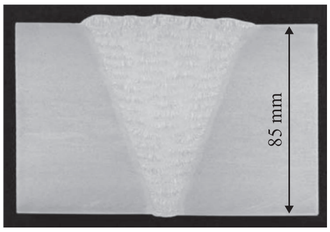
Welding consumable	DW-460 L (1.2 mmϕ) , Kobe Steel, Ltd. FBB-3 (Backing material) , Id
Welding condition	Groove angle: 40°, Gap: 5 mm 280 A, 35 V, 210 mm/min, 2.8 kJ/mm, 100% CO_2
Macrostructure	

Table 6 Tensile test results of weld joint

Prescription	Thickness (mm)	Width (mm)	TS (N/mm^2)	Fracture position
EH47 GMAW joint	85	30	598	Base plate
			602	Base plate
Specification of EH47 (IACS UR W31)			≧570	—

TS: Tensile strength GMAW: Gas metal arc welding

Table 7 Charpy impact test results of weld joint

Prescription	Thickness portion / Notch position	vE$_{-20}$ (J) Surface-1 mm	1/2t	Root-1 mm
EH47 GMAW joint	W. M.	153	143	105
	F. L.	282	236	171
	F. L.+2 mm	304	367	314
	F. L.+5 mm	334	342	327
Specification of EH47 (IACS UR W31)		≧64	≧64	≧64

vE$_{-20}$: Absorbed energy GMAW: Gas metal arc welding
W. M.: Weld metal F. L.: Fusion line

of the joint are shown in **Tables 6** and **7**, respectively. The developed steel satisfies all the specification values of EH47 grade steel.

5. Conclusions

YP460 (EH47 grade) heavy thick steel plate with excellent crack arrestability was developed. Very high crack arrest toughness (Kca) at −10°C was achieved by improving low temperature toughness and controlling texture through an advanced TMCP process. The summary of the developed steel is as follows. The developed steel makes it possible to ensure the safety of mega container carriers.

(1) The developed steel satisfies the specification of YP460 E grade. High crack arrestability and good weldability are also achieved by an advanced alloy design, and high Ceq and low Pcm are satisfied at the same time.

(2) The developed steel shows very high crack arrest toughness by controlling the texture through optimizing the chemical composition and the rolling and cooling conditions. The crack arrest toughness (Kca at −10°C) of the developed steel rolled to 70 mm and 85 mm in thickness is 16 800 N/mm$^{3/2}$ and 9 600 N/mm$^{3/2}$, respectively.

(3) Large scale duplex ESSO tests were conducted for the developed YP460 steel plate with the 70 mm thickness. A brittle crack that initiated at the crack running plate propagated along the weld line and arrested with a slight propagation to the test plate. This result demonstrates that the developed plate has excellent crack arrestability in the actual hull structure.

(4) The properties of multi-pass weld joints satisfy all the requirements of YP460 E grade steel. The weldability of the developed steel is equivalent to the conventional steel due to the low Pcm alloy design.

References

1) Nagatsuka, S. KANRIN. 2007, no. 11, p. 14. (Japanese)
2) http://www. ship-technology. com/projects/triple-e-class/
3) Morishige, H.; Tanaka, S.; Tanaka, Y.; Hirota, K. KANRIN. 2009, no. 24, p. 18. (Japanese)
4) Nishimura, K.; Handa, T.; Hashimoto, M. JFE Giho. 2007, no. 18, p. 18. (Japanese)
5) Ichimiya, K.; Sumi, H.; Hirai, R. JFE Technical Report. 2008, no. 11, p. 7.
6) Yamaguchi, Y.; Yajima, H.; Aihara, S.; Yoshinari, H.; Hirota, K.; Toyoda, M.; Kiyosue, T.; Tanaka, S.; Okabe, T.; Kageyama, K.; Funatsu, Y.; Handa, T.; Kawabata, T.; Tani, T. Proc. of the 21th International Offshore and Polar Engineering Conference. Beijing, Chaina, 2010-06-20–25, p. 80.
7) Nippon Kaiji Kyokai. "Guideline for Brittle Crack Arrest Design." 2009-09.
8) IACS. "Requirements for Use of Extremely Thick Steel Plates," UR S33, 2013-01.
9) Tada, M.; Yajima, H.; Deguchi, A.; Nito, H.; Katsuta, J. Journal of the Seibu Zosen Kai. 1989, vol. 69, p. 227. (Japanese)
10) Suzuki, S.; Muraoka, R.; Tani, S.; Wada, N. NKK Technical Report. 1999, no. 168, p. 78. (Japanese)
11) Tamura, E.; Minami, F. CAMP-ISIJ. 2008, vol. 21, p. 564.
12) Kaneko, M.; Tani, T. R&D Kobe Steel Engineering Report. 2011, vol. 61, no. 2, p. 2. (Japanese)
13) Kubo, S.; Kawabata, T.; Inami, A.; Maeda, T.; Hiramatsu, H.; Matsuda, H.; Michiba, K.; Nishiyama, G.; Kiyosue, T.; Matsuura, M.; Okamoto, K. Nihon Sempaku Kaiyou Kougakkai Kouen Rombunshuu. 2007, no. 5E, p. 139. (Japanese)
14) Sirahata, H.; Minagawa, M.; Inoue, T.; Otani, J.; Funatsu, Y. Materia. 2012, vol. 51, no. 2, p. 76. (Japanese)
15) Ishikawa, T.; Inoue, T.; Hagihara, I.; Imai, T. Nippon Steel Technical Report. 1999, no. 371, p. 107. (Japanese)
16) Handa, T.; Tagawa, T.; Minami, F. Tetsu-to-Hagané. 2012, vol. 98, no. 1, p. 32.
17) Tsuyama, S.; Takeuchi, Y.; Nishimura, K.; Handa, T. Quarterly Journal of The Japan Welding Society. 2012, vol. 30, no. 2, p. 188.
18) Handa, T.; Igi, S.; Endo, S.; Tsuyama, S.; Shiomi, H. Quarterly Journal of The Japan Welding Society. 2012, vol. 30, no. 3, p. 213.
19) Handa, T.; Igi, S.; Endo, S.; Tsuyama, S.; Shiomi, H. Science and Technology of Welding and Joining. 2013, vol. 18, no. 6, p. 478.

Copyright © 2015 JFE Steel Corporation. All Rights Reserved. Unauthorized reproduction prohibited.