JFE TECHNICAL REPORT
No. 26 (Mar. 2021)

YP500 N/mm^2 Class High Strength Steel Plates for Offshore Structures with Excellent CTOD Properties at Welded Joints

TERAZAWA Yusuke[*1] TANAKA Toshitaka[*2] SUZUKI Shinichi[*3]

Abstract:

Increase of the size of offshore structure proceeds steadily, and the strength and plate thickness required for steel plates have increased. In addition, the demand for specifications with welded joint CTOD properties has also increased for the construction in cold regions. Therefore, it is necessary to achieve both high strength of the base plate and excellent HAZ toughness. JFE Steel has developed steel plates with excellent welded joint CTOD property through elaborate HAZ microstructure control utilizing microalloying technology. This developed steel has both high strength of base plate and excellent welded joint CTOD properties by applying advanced thermo-mechanical control process and making island martensite, which is an embrittlement microstructure in HAZ, harmless. In this paper, YP500 N/mm^2 class steel plate of 75 mm in thickness with excellent CTOD properties is introduced.

1. Introduction

Construction of offshore structures for development of marine oil fields and gas fields is forecast to become even more active in the future as a result of increased world energy demand due to the growth of the emerging economies. To meet this strong energy demand, upscaling of offshore structures and expansion of construction areas into cold regions is progressing, and accompanying these trends, the strength, plate thickness and low temperature toughness required in steel materials is also increasing [1–5]. As a feature of steel plates for offshore structures, not only Charpy impact testing, but also welded joint CTOD (crack-tip opening displacement) properties are increasingly required for strict safety guarantees [6, 7]. Up to the present, JFE Steel has developed steel plates for offshore structures up to the yield stress YS420 N/mm^2 strength class and joint CTOD specification temperatures of −10 to −40°C. These products already have an extensive record of application.

This report introduces a YS500 N/mm^2 class steel plate with a thickness of 75 mm that satisfies the CTOD −10°C specification, which was newly developed in order to respond to demand for higher strength steel plates with joint CTOD specifications.

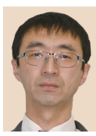
2. Microstructure Control Technology of Developed Steel

2.1 Target Properties

Table 1 shows the target properties of the developed steel. The steel conforms to M-120 Y40, Y45, Y50 and Y55 in the Norsk sokkels konkuranseposisjon (NORSOK) standard, and has a maximum plate thickness of 75 mm and a CTOD specification temperature of −10°C.

† Originally published in *JFE GIHO* No. 46 (Aug. 2020), p. 50−56

*1 Senior Researcher Deputy Manager,
Steel Products Research Dept.,
Steel Res. Lab.,
JFE Steel



*2 Staff Deputy General Manager,
Plate Sec.,
Products Design & Quality Control for Steel Products Dept.,
West Japan Works (Fukuyama),
JFE Steel

*3 Staff Deputy General Manager,
Plate Business Planning Dept.,
JFE Steel

Table 1 Target properties for the developed steel

		Steel plate			Welded joint			
		Tensile properties*		Charpy absorbed energy*	Welding method	Heat input (kJ/mm)	Charpy absorbed energy	CTOD properties
Class	Thickness (mm)	YS (N/mm^2)	TS (N/mm^2)	vE_{-40} (J)			vE_{-40} (J)	CTOD value at −10°C (mm)
YP500	75	500-580	600-700	≧60	FCAW SAW	0.7 3.5	≧60	≧0.25

* Test piece: Transverse direction
YS: Yield strength, TS: Tensile strength,
FCAW: Flux-cored wire arc welding, SAW: Submerged arc welding

2.2 Improvement of CTOD Properties of Welded Joints

Multilayer welding methods such as submerged arc welding (SAW) and flux-cored arc welding (FCAW) are applied in welding of steel plates of offshore structures, and as a result, various types of heat affected zones (HAZs) are formed because the weld is affected by multiple, different heat histories, corresponding to the distance from the weld bead. These HAZs include the coarse grain HAZ (CGHAZ) adjacent to the weld line, where the temperature rises to nearly the melting point of the steel, and the inter-critically reheated CGHAZ (ICCGHAZ), which is formed by the reheating of CGHAZ in the dual-phase region of ferrite and austenite by the welding in the next pass. These two HAZs are known to be locally-embrittled microstructures with low toughness [8–11], and are a cause of deterioration of the CTOD properties of welded joints. In particular, CTOD properties are remarkably deteriorated in the ICCGHAZ owing to enrichment of carbon in the austenite phase during heating in the dual-phase region, and formation of a large amount of island martensite (martensite-austenite (MA) constituent), which is an embrittled microstructure, in the following cooling process. In addition, the amount of island martensite in the ICCGHAZ also increases because a high carbon equivalent (*C*eq) is necessary when manufacturing high strength, high thickness steel plates, which makes it extremely difficult to satisfy both high strength in the base metal and the CTOD properties of welded joints. In order to solve this problem, JFE Steel uses the thermo-mechanical control process (TMCP) utilizing advanced controlled rolling and controlled cooling, and a HAZ microstructure control technology by microalloying. **Figure 1** shows the concept for improving the HAZ toughness of the developed steel.

First, in production of the base material, *C*eq is minimized by increasing the strength of the base metal by the high speed cooling technology of the state-of-the-art *Super*-OLAC™-A on-line accelerated cooling device, which is able to realize a cooling rate equivalent to the theoretical limit.

Next, the HAZ microstructure control technology will be described. Both the CGHAZ and the ICCGHAZ are regions where γ grains undergo coarsening due to heating to just below the melting point by welding heat. To improve the toughness of these zones,

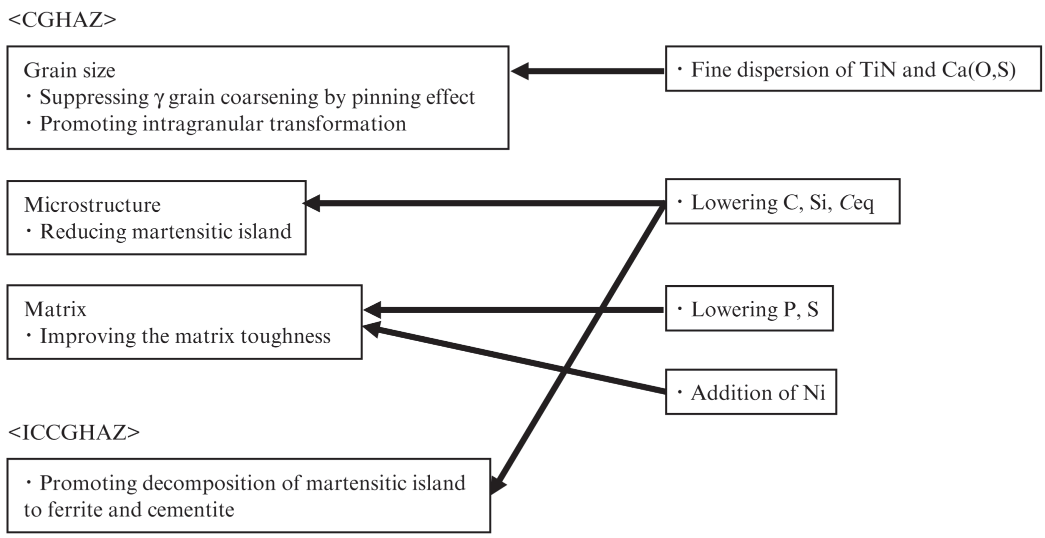


Fig. 1 Concept for improving HAZ toughness

coarsening of the γ grain is suppressed by a pinning effect achieved by dispersing fine particles of TiN [1, 12, 13] and Ca(O,S) [5], which remain stable up to high temperatures. In addition, these particles also refine the final microstructure by becoming nuclei for the acicular ferrite transformation in the cooling process, and thus have the effect of improving toughness.

The negative effect of the island martensite in the ICCGHAZ is eliminated by the following technique. First, the amount of island martensite that forms in the ICCGHAZ is reduced by adopting a low C, low Si, low *C*eq composition design [2, 3]. The low Si composition is also effective for promoting decomposition of the island martensite caused by the temperature rise in the welding passes after formation of the ICCGHAZ [14]. **Figure 2** shows the relationship between the amount of Si addition and the SEM images of (top) samples with simulated ICCGHAZ microstructures formed by SAW welding with a heat input of 3.5 kJ/mm using a heat cycle testing device, and (bottom) samples with simulated tempered-ICCGHAZ microstructures obtained by further heating to 600°C to simulate the temperature rise in the welding pass after formation of the ICCGHAZ. The SEM images in Fig. 2 were obtained by removing cementite by a two-step etching process consisting of etching in 3% nital, followed by electrolytic polishing (electropolishing) with an aqueous solution prepared by dissolving 200 g of sodium hydroxide and 40 g of picric acid in 800 ml of water. Since the cementite is substantially removed, virtually all of the microstructure that appears as white is the island martensite microstructure. From these images, it can be understood that the decomposition reaction of island martensite into ferrite and cementite is promoted and the amount of island martensite finally remaining in the steel is reduced when the added Si content is decreased from 0.36 mass% (left) to 0.18 mass% (right), and this effect is particularly strong when heating is applied after the formation of the ICCGHAZ, as seen in the tempered-ICCGHAZ at the lower right in Fig. 2.

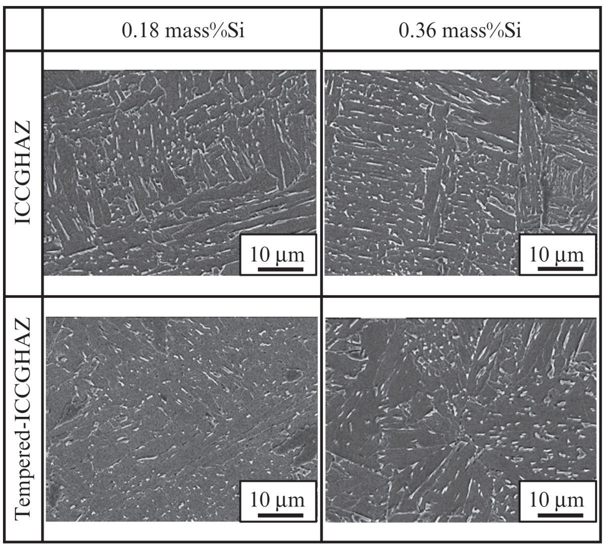


Fig. 2 Effect of Si content on microstructure of simulated ICCGHAZ

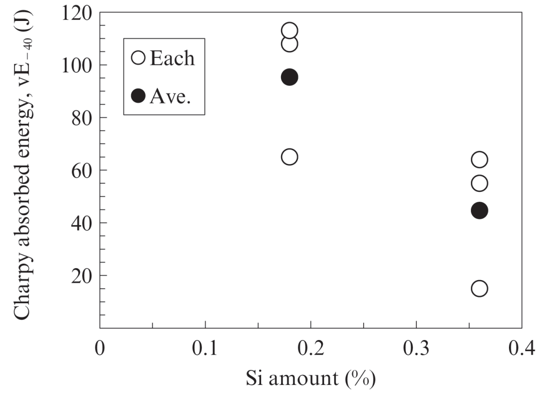


Fig. 3 Relationship between Charpy absorbed energy of simulated tempered-ICCGHAZ and Si amount

Figure 3 shows the relationship between the added Si content and the results of the Charpy impact test of the simulated tempered-ICCGHAZ. As the added Si content is decreased, Charpy absorbed energy increases. This improvement in the Charpy impact property is thought to be due to a reduction in the amount of island martensite.

The toughness of the matrix is also improved by reducing P, S and other impurity elements which have an embrittling effect on the microstructure of the steel, and optimizing the amount of added Ni, which has a toughness improvement effect.

3. Properties of Developed Steel

3.1 Chemical Composition and Manufacturing Process

Table 2 shows the chemical composition of the developed steel. A low C, low Si, low *C*eq composition design was adopted to improve joint CTOD properties, and as noted above, addition of Ni was optimized to improve toughness. Ti and Ca were added to refine the HAZ microstructure, and at the same time, the content of other elements were optimized so as to control the shape of the precipitates formed by Ti and Ca.

Table 2 Chemical composition of developed steel plate

C	Si	Mn	P	S	Al	Others	*C*eq*
0.07	0.18	1.58	0.004	0.002	0.035	Cu, Ni, Mo, Nb, Ti, Ca, etc.	0.46

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

LD Converter

Secondary refining

Continuous casting

Slab reheating

TMCP/Thermo-mechanical controlled rolling
(*Super*-OLAC^{TM}-A)

Fig. 4 Manufacturing process

Figure 4 shows the manufacturing process. The target properties were realized by precisely controlling slab casting conditions, as well as the slab reheating temperature, the hot rolling temperature and reduction, and the cooling start temperature and cooling finish temperature in hot rolling.

3.2 Mechanical Properties of Base Metal

Figure 5 shows the microstructure of the base plate. A fine bainite microstructure was obtained to the plate 1/2 t position. **Table 3** shows the results of a tensile test and Charpy impact test of the base plate. All test results fully satisfied the target properties shown in Table 1, regardless of whether post weld heat treatment (PWHT) was applied or not. In addition, the ductile-brittle fracture surface transition temperature (vTrs) also showed excellent values with respect to the specification temperature.

3.3 Strain Aging Property

The strain aging property was evaluated by a strain aged Charpy test. Prestrain was set at 5, 8 or 10%, and aging treatment was conducted by holding the samples at 250°C for 1 h. **Table 4** shows the results of the strain aged Charpy impact test. Even with 10% prestrain, the steel displayed satisfactory absorbed energy, and vTrs was also excellent, at −79°C.

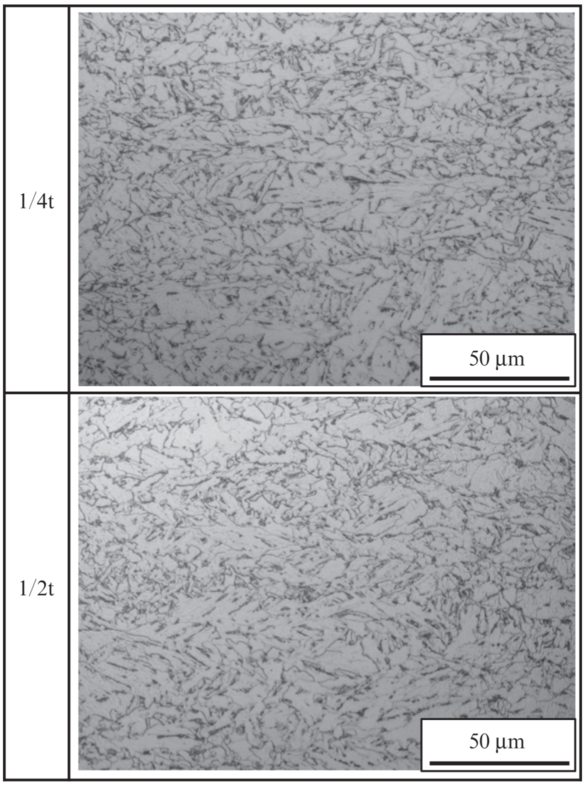


Fig. 5 Optical micrographs of base plate

Table 4 Results of strain aged Charpy impact test forbase plate

Thickness (mm)	Position	Direction	Pre-strain	Charpy impact test	
			(%)	vE$_{-40}$ (J)	vTrs (°C)
75	Surface	T	5	216	−85
			8	164	−82
			10	189	−79

3.4 NRL Drop Weight Property

A NRL drop weight test conforming to ASTM E208 in the ASTM standards was conducted using a sample with the P-3 type test piece geometry taken from the surface of the steel plate, and the nil-ductility transition temperature (NDTT) was obtained. The drop weight energy was 400 J. The test results are shown in **Table 5**. NDTT was lower than −80°C, showing an excellent drop weight property.

Table 3 Results of tensile test and Charpy impact test for base plate

Thickness (mm)	PWHT	Position	Direction	Tensile test			Charpy impact test	
				YS (N/mm^2)	TS (N/mm^2)	El (%)	vE$_{-40}$ (J)	vTrs (°C)
75	—	1/4t	T	565	627	26	289	<−100
		1/2t		533	633	21	216	−73
	580°C −4 hr	1/4t		559	625	27	284	<−100
		1/2t		543	625	23	152	−81

3.5 CTOD Properties of Base Plate

Figure 6 shows the results of the CTOD test of the base plate conducted at the test temperature of −10°C in accordance with ISO 12135. Satisfactory results were obtained, regardless of whether PWHT was performed or not.

4. Properties of Welded Joints

4.1 Welding Conditions

Table 6 shows the welding conditions used in preparing the welded joints for the joint tests. The welded joints were prepared by multilayer FCAW with the heat input of 0.7 kJ/mm, and by multilayer SAW with the heat input of 3.5 kJ/mm. **Figure 7** shows the macrostructures of the welded joints.

4.2 Mechanical Properties of Welded Joints

Table 7 shows the results of the tensile test and Charpy impact test of the welded joints. The welded joints fully satisfied the targets for both tensile proper-

Table 5 Results of drop weight test for base plate

Thickness (mm)	PWHT	Position	Direction	NDTT (°C)
75	—	Surface	T	< −80
	580°C −4 hr			< −80

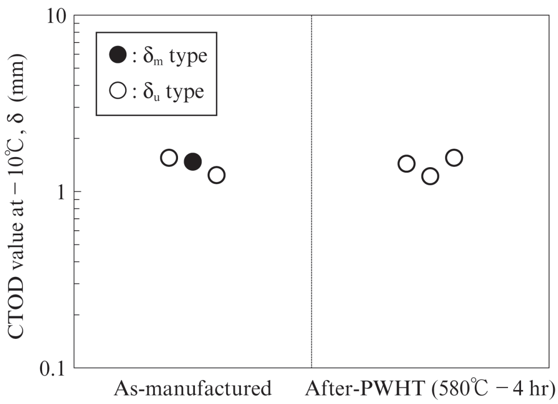


Fig. 6 Results of CTOD test for base plate

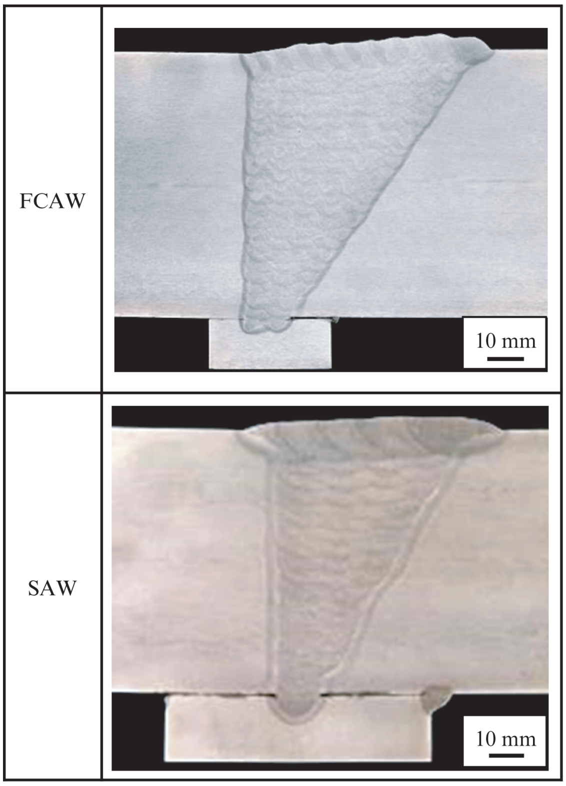


Fig. 7 Macrostructures of welded joint

Table 6 Welding conditions

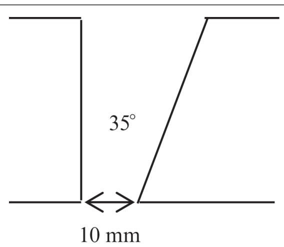
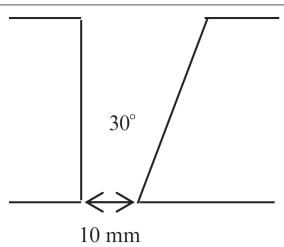
Thickness (mm)	Welding method	Welding consumable	Groove shape	Preheat temperature (°C)	Interpass temperature (°C)	Heat input (kJ/mm)
75	FCAW	MX-A62L (1.2 mmϕ), (Kobe steel, Ltd.)		150	> 150	0.7
	SAW	US-2N (4.0 mmϕ), PFH-55LT (Kobe steel, Ltd.)		130	> 140	3.5

Table 7 Results of tensile test and Charpy impact test for welded joint

Thickness (mm)	Welding method	Heat input (kJ/mm)	PWHT	Tensile test TS (N/mm^2)	Charpy impact test Position	vE$_{-40}$ (J) W.M.	F.L.	F.L. + 2 mm	F.L. + 5 mm
75	FCAW	0.7	—	655	Sub-surface	175	226	229	252
					Root	172	325	118	142
	SAW	3.5	—	629	Sub-surface	161	177	247	241
					Root	119	213	268	274
			580°C −4 hr	626	Sub-surface	174	202	279	265
					Root	82	164	234	258

W. M.: Weld metal, F. L.: Fusion line

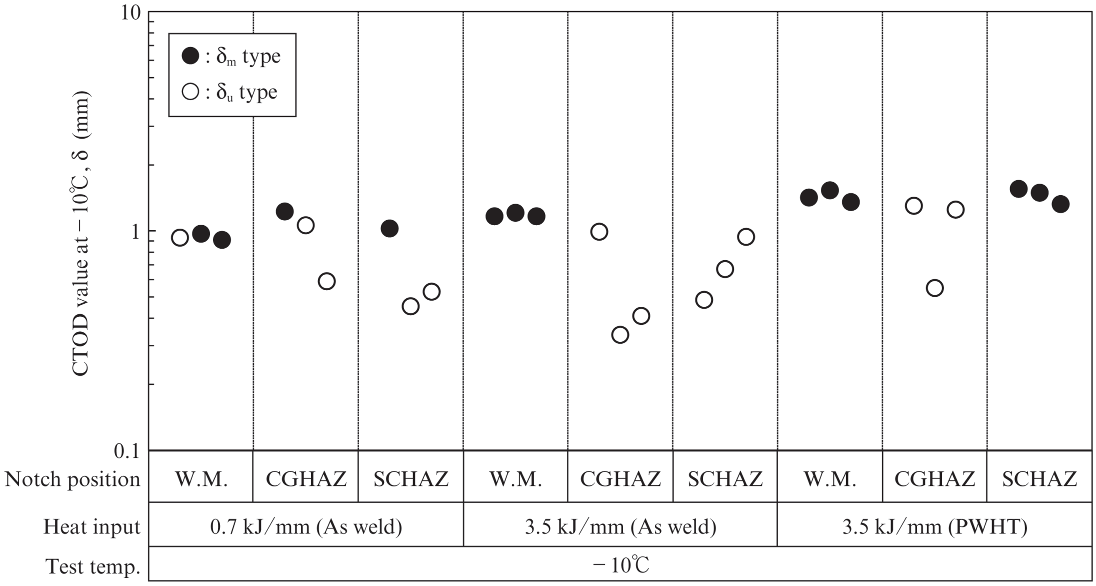


Fig. 8 Results of CTOD test for welded joint

ties and Charpy properties under all test conditions.

4.3 CTOD Properties of Welded Joints

Figure 8 shows the results of the CTOD test of the welded joints. The test was conducted in accordance with ISO 15653 at the test temperature of −10°C. The CTOD values satisfied the targets at all test positions (WM (weld metal) CGHAZ, and subcritically reheated HAZ (SCHAZ)) under all test conditions, confirming that the welded joints show excellent brittle crack initiation resistance.

5. Conclusion

A new YS500 N/mm^2 class steel plate with a thickness of 75 mm which satisfies the CTOD −10°C specification was developed as a steel plate for offshore structures used in deep-water energy resource development. Although this is a high strength steel plate of YP500 N/mm^2 class, satisfactory welded joint CTOD properties were achieved by utilizing advanced composition design and a combination of plate manufacturing technologies, beginning with the *Super*-OLAC-A on-line accelerated cooling device.

Because active development of marine energy resources is also forecast for the future, application of the developed steel in various offshore structures is expected.

References

1) Tanigawa, O.; Ishii, H.; Itakura, N.; Amano, K.; Nakano, Y.; Kawabata, F. 420 MPa and 500 MPa Yield Strength Steel Plates with High HAZ Toughness Produced by TMCP for Offshore Structures. Kawasaki Steel Technical report. 1993, no. 29, p. 54–63.
2) Yuga, M.; Hashimoto, M.; Suzuki, S. Steel Plates with Excellent HAZ Toughness for Offshore Structures. JFE Technical report. 2013, no. 18, p. 43–49.
3) Ichimiya, K.; Yuga., M.; Hase, K.; Endo, S.; Hirata, K.; Matsunaga, N.; Suzuki, S. Steel Plates With Excellent HAZ Toughness for Offshore Structure, Proceedings of OMAE2013, International Conference. ASME. MAT2013–10617.
4) Hisata M.; Kawabata., F.; Itakura, N.; Orita, T.; Yamamoto, O.; Kudo, J. A 75 mm Thick 420 MPa YS Steel Plate With Superior Toughness for Offshore Structures. Proceedings of OMAE99,

International Conference. ASME. MAT-2099.
5) Ichimiya, K.; Fujiwara, T.; Suzuki, S. Offshore Structural Steel Plates for Extreme Low Temperature Service with Excellent HAZ Toughness. JFE Technical report. 2015, no. 20, p. 20–25.
6) Arimochi, K; Isaka, K. Approaches to LBZ Free Technologies. Proc. 10th int. Conf. OMAE. 1991, p. 213.
7) Terada, Y.; Chijiiwa, R.; Tamehiro, H.; Kawasaki, H.; Tanaka, K. Development of high-toughness age-hardenable copper-bearing steel plate for offshore structures. CAMP-ISIJ. 1991, vol. 4, S1884.
8) Sato, M.; Yamato, K. On the Microstructure and Toughness of HAZ in as Rolled or Normalized 50 and 60kg/mm^2 High Strength Steel. Journal of JWS. 1981, vol. 50, p. 11–19.
9) Hotta, T.; Sakai, T.; Yamato, K.; Imai, T.; Kakimoto, E. Kouchouryokukou no yousetsunetsueikyoubu no sosei ni tsuite (dai 1pou). Journal of JWS. 1966, vol. 35, p. 847.
10) Koso, M.; Miura, M.; Ohmori, Y. Microstructure and toughness of weld heat-affected zone in 785MNm-2 HSLA steel. Met. Technol. 1981, vol. 8, p. 482.
11) Machida, S.; Miyata, T.; Toyosada, M.; Hagiwara, Y. Study of Methods for CTOD Testing of Weldments. ASTM Symposium on Fatigue and Fracture Testing of Weldments. 1988.
12) Kanazawa, S.; Nakajima, A.; Okamoto, K.; Kanatani, K. Improved Toughness of Weld Fussion Zone by Fine TiN Particles and Development of a Steel for Large Heat Input Welding. Tetsu-toHagané. 1975, vol. 61, no. 11, p. 2589–2603.
13) Kasamatsu, Y.; Takashima, S.; Hosoya, T. Effect of Titanium and Nitrogen on Toughness of Heat-Affected Zone of Steel Plate with Tensile Strength of 50kg/mm^2 in High Heat Input Welding. Tetsu-to-Hagané. 1979, vol. 65, no. 8, p. 1232–1241.
14) Kawabata, F.; Amano, K; Toyoda, M.; Minami, F. Tempering Effect by Succeeding Weld Passes on Multi-Layered HAZ Toughness. Proc. 10th int. Conf. OMAE. 1991, vol. 3, p. 73–80.