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Steel Plates with Excellent HAZ Toughness for Offshore Structures†

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Abstract:

JFE Steel has developed high strength steel plates for offshore structures, which meet the low temperature specification. The range of products has expanded corresponding to the rising demand for the steel used for the offshore structure arising form robust oil resource development in recent years. Excellent properties of the plates and their welded joints are obtained by micro-alloying technology, and latest controlled rolling and accelerated cooling technology using Super-OLAC™ (On-Line Accelerated Cooling). High strength steel plates which are designed for excellent weldability thorough the low weld cracking parameter P_{CM} value have been developed by Super-OLAC™ for up to 550 MPa class in yield stress, up to 101.6 mm in thickness with 420 MPa class in yield strees, and satisfying −40°C of crack tip opening displacement (CTOD) temperature specificetion for offshore structure. They have achieved already a lot of actual application results.

1. Introduction

Recent years have seen robust development of petroleum resources accompanying rising global energy demand. Construction of large-scale offshore structures has increased in response to these trends, and the range of installation is progressively expanding into arctic and deepwater areas. In addition to high strength and heavy thickness, the low temperature crack tip opening displacement (CTOD) specification for safety evaluation by fracture mechanics and other properties are required in steel plates for these structures. JFE Steel has developed steel plates with high strength and heavy thickness for offshore structures which meet these severe requirements for steel plates and has an extensive record of application in actual projects. **Table 1** shows examples of steel plates for offshore structures developed by JFE Steel. At present, it is possible to meet yield point (YP) requirements up to 690 MPa class. Among these plates, YP 550 MPa and lower class steels can be manufactured by either the thermo-mechanical control process (TMCP) utilizing controlled rolling and controlled cooling or direct quenching and tempering (DQ-T). These products meet the performance requirements of all relevant specifications, and manufacturing qualifications have already been obtained in all cases. In the future, JFE Steel plans to further expand this product line by developing larger thickness and higher performance products.

Among steel plates manufactured utilizing the TMCP or DQ-T processes by JFE Steel, the properties of the base material are secured in heavy thickness plates, and

Table 1 Available strength and thickness of steel plates for offshore structures

YP Class (MPa)	Charpy Temp. (°C)	CTOD Test Temp. (°C)	Thickness (mm)
355	−40	−10	up to 101.6
420	−40	−10	up to 101.6
	−60	−40	up to 75
500	−40	—	up to 108
550	−40	—	up to 108
620	−40	—	up to 108
690	−40	—	up to 108

YP: Yield point CTOD: Crack tip opening displacement

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both welded joint toughness and the CTOD property are satisfied while using a low weld cracking composition (P_{CM}) design with excellent weldability, by using advanced material quality design and steelmaking technology in combination with leading-edge plate manufacturing technology. In particular, one key manufacturing technology is JFE Steel's *Super*-OLAC™ (On-line Accelerated Cooling)[1)] equipment, which is an advanced accelerated cooling system that features a high cooling capacity and uniform cooling performance.

This paper introduces the various properties of steel plates and welded joints of TMCP and DQ-T type heavy thickness, high strength steel plates developed by JFE Steel for use in offshore structures.

2. Composition Design and Manufacturing Processes

2.1 Targets in Development of Steel Plates

The target properties of the steel plates for offshore structures introduced in this paper are shown in **Table 2**. Steel A conforms to 2W Grade 50 steel under API standards (API: The American Petroleum Institute), Steels B and C conform to API 2W Grade 60 steel and its low temperature specification, and Steel D conforms to YP 500 MPa steel (NV E500) under DNV standards (DNV: Det Norske Veritas). In the case of Steel C, a CTOD test temperature of −40°C was adopted considering use in cold regions, which have become increasingly important for petroleum development in recent years.

2.2 Improved CTOD Property of Welded Joints

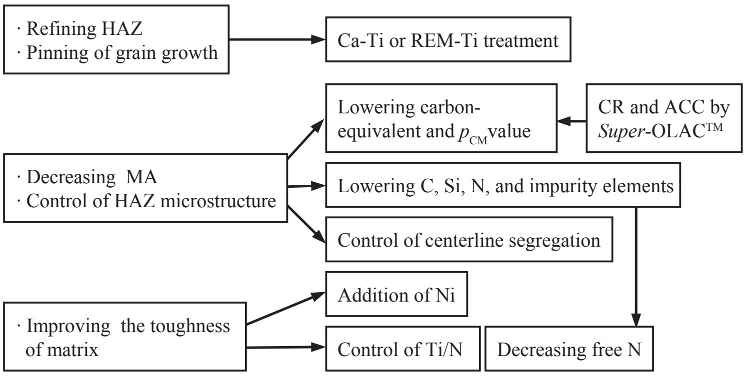
Among the performance requirements for steel plates for offshore structures, one important property is the toughness of the heat affected zone (HAZ) in multilayer welding. The causes of reduced weld toughness and CTOD properties are considered to be the coarse-grained region that forms around the fusion line as a result of welding heat, and the local brittle zone (LBZ) formed by the heat cycle in multi-pass welding.

The important microstructures for suppressing formation of the LBZ are the coarse grain HAZ (CGHAZ) and the inter-critically reheated CGHAZ (ICCGHAZ). The concept of improving the toughness of the HAZ in multilayer welding is shown in **Fig. 1**. The CGHAZ is an area which is exposed to temperatures of 1 350°C or higher by welding heat and undergoes grain coarsening as a result. Coarsening of austenite grains is suppressed by the pinning effects of TiN and oxysulfides, which are formed by Ca-Ti treatment or rare earth element (REM)-

Table 2 Target properties of the steel plates and welded joints

Steel	Thickness (mm)	Mother plate			Welded joint			
		YS (MPa)	TS (MPa)	Chapy absorbed energy (J)	Welding method	Heat input (kJ/mm)	Chapy absorbed energy (J)	CTOD value (mm)
A	101.6	345–483	≥448	${}_vE_{-40°C}$≥41	SAW	1.5–4.5	${}_vE_{-40°C}$≥41	≥0.38 at −10°C
B	101.6	414–586	≥517	${}_vE_{-40°C}$≥48	GMAW SAW	0.8 3.0–4.5	${}_vE_{-40°C}$≥48	≥0.30 at −10°C
C	75	414–586	≥517	${}_vE_{-60°C}$≥48	SAW	5.0	${}_vE_{-60°C}$≥48	≥0.30 at −40°C
D	50	≥500	610–770	${}_vE_{-50°C}$≥33	SAW	3.5	${}_vE_{-50°C}$≥37	—

YS: Yield strength TS: Tensile strength ${}_vE$: Absorbed energy CTOD: Crack tip opening displacement
SAW: Submerged arc welding GMAW: Gas metal arc welding



MA: Martensite-austenite constituent REM: Rare earth elements
CR: Controlled rolling ACC: Accelerated cooling

Fig. 1 Concept of improving heat-affected zone (HAZ) toughness

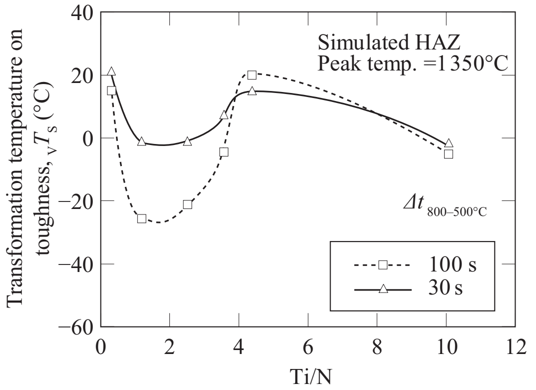


Fig. 2 Effect of Ti/N ratio on heat-affected zone (HAZ) toughness in simulated HAZ

Ti treatment[2–4], together with optimization of the material microstructure by nonmetallic inclusion control. The relationship of the Ti/N ratio and notch toughness of a simulated HAZ under a heat cycle is shown in **Fig. 2**. Since an optimum value exists in the Ti/N ratio, the contents of Ti and N are strictly controlled[5,6].

The ICCGHAZ is formed by recheating CGHAZ, which is formed by prior welding pass, to the dual-phase region between the Ac_1 point and Ac_3 point by the welding heat of succeeding passes. In reheating to the dual-phase region, carbon concentrates in reverse-transformed austenite, and then martensite-austenite constituent (MA): the brittle phase is formed during cooling process in ICCGHAZ. As a result, toughness is remarkably reduced[7]. A low C, low C_{eq} (carbon equivalent), low P_{CM}, low P, low Si, low N composition design was adopted to suppress the formation of MA, and excellent strength was realized in heavy thickness plates by applying the leading-edge *Super*-OLAC™ (On-line Accelerated Cooling) equipment.

Figure 3 shows the relationship between the Ni content and the base material strength and CTOD property of the welded joint. In general, increasing the amount of added alloying elements in order to obtain strength decreases toughness and the CTOD property of the welded joints. However, because Ni addition contributes to improvement of base material strength while securing the CTOD property, both the CTOD property of the welded joints and the base material properties can be satisfied by adding the optimum amount of Ni, corresponding to the CTOD temperature requirement.

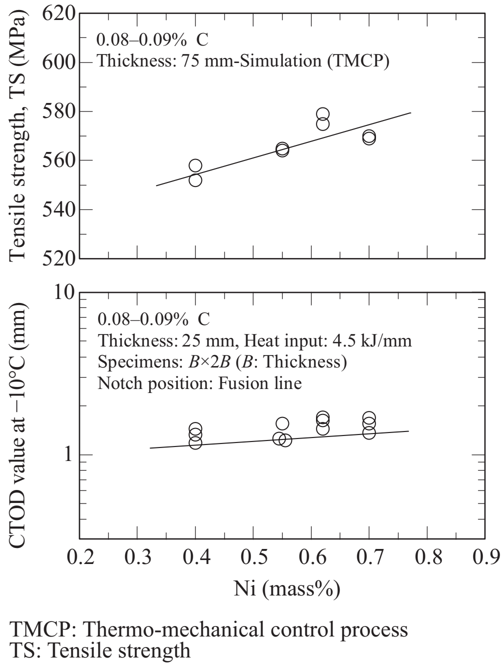


Fig. 3 Effect of Ni content on strength of steel plates and crack tip opening (CTOD) property of welded joint

3. Properties of Steel Plates

3.1 Chemical Composition and Manufacturing Process

Table 3 shows the chemical compositions of the respective steel plates. Carbon contents are reduced to 0.08% or less, and low P_{CM} of 0.20% or less are adopted to achieve excellent weldability. In the steelmaking process, N and the impurity elements P and S are reduced, and Ca-Ti or REM-Ti treatment is performed as necessary, and slabs with a thickness of 310 mm or 250 mm are produced by continuous casting. In plate rolling, accelerating cooling using the *Super*-OLAC™ is performed after controlled rolling. Heavy reduction rolling is also applied in order to compress porosities in the slab center and control the microstructure of the steel plate. With Steel D, which is a YP 500 MPa class steel, tempering is performed after direct quenching by accelerated cooling in order to secure the proper strength and toughness.

Table 3 Chemical composition of steel plates

(mass%)

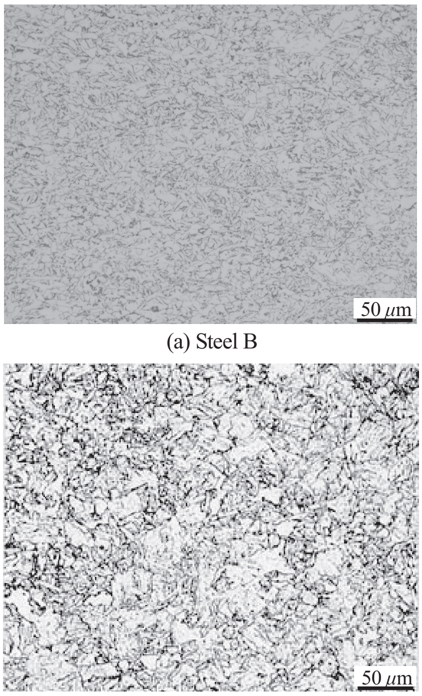
Steel	Thickness	C	Si	Mn	P	S	Al	others	C_{eq}	P_{CM}
A	101.6 mm	0.07	0.13	1.49	0.005	0.001	0.029	Cu, Ni, Nb, Ti, etc.	0.35	0.16
B	101.6 mm	0.08	0.14	1.57	0.005	0.001	0.032	Cu, Ni Nb, Ti, etc.	0.42	0.19
C	75 mm	0.07	0.10	1.55	0.005	0.001	0.028	Cu, Ni, Nb, Ti, etc.	0.42	0.18
D	50 mm	0.07	0.20	1.32	0.007	0.001	0.040	Cu, Ni, Cr, Mo, V, etc.	0.42	0.19

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

3.2 Mechanical Properties of Base Materials

Examples of the microstructures of the base steel plates are shown in **Photo 1**. Steel B has a bainitic main microstructure containing fine acicular ferrite, and substantially the same microstructure is also obtained in Steels A and C. Steel D comprises a single phase microstructure of fine bainite.

The results of tensile tests and Charpy impact tests of the base materials are shown in **Table 4**. All plates satisfy the target values for strength and toughness including the middle thickness shown in Table 1. With Steel B having a thickness of 101.6 mm, strength and toughness after post weld heat treatment (PWHT) also satisfy the target values.



(a) Steel B

(b) Steel D

Photo 1 Microstructure of steel plates

3.3 CTOD Property of Base Materials

The fracture toughness characteristics of the base steel plates were evaluated by the 3-point bending CTOD test. **Table 5** shows the test results. All the steels showed enough CTOD values at the required temperatures.

3.4 Strain Aging Property

The Charpy impact test was performed after aging treatment at 250°C for 1 hour under a maximum prestrain of 10%. **Table 6** shows the test results. Although toughness shows a decreasing tendency due to strain aging treatment, the toughness of steels satisfies each

Table 5 Crack tip opening displacement (CTOD) test results of steel plates

Steel	Thickness	PWHT	Position	Test temp. (°C)	CTOD value (mm)
A	101.6 mm	—	T	−10	≥2.86, ≥2.43
B	101.6 mm	580°C ×4 h	L	−10	2.51, ≥2.56
			T	−10	≥2.58, ≥2.65
C	75 mm	—	L	−40	≥2.72, ≥2.62, 1.55

Specimen: $B \times B$ (B: Thickness) PWHT: Post weld heat treatment
L: Longitudinal T: Transverse

Table 4 Mechanical properties of steel plates

Steel	Thickness	PWHT	Position	Direction	Tensile test			Charpy impact test			
					YS (MPa)	TS (MPa)	El (%)	Absorbed energy, average (J) −40°C	−50°C	−60°C	${}_vT_s$(°C)
A	101.6 mm	—	1/4t	L	432	527	32*1	—	—	—	—
				T	438	542	31*1	441	—	440	−85
			1/2t	L	377	502	32*1	—	—	—	—
				T	382	506	32*1	405	—	211	−80
B	101.6 mm	580°C ×4 h	1/4t	L	436	532	33*1	434	—	427	−90
				T	452	544	33*1	436	—	440	−100
			1/2t	L	422	524	29*1	336	—	240	−70
				T	426	539	32*1	157	—	172	−65
C	75 mm	—	1/4t	L	446	529	35*1	—	—	—	—
				T	451	541	34*1	—	—	400	−135
			1/2t	L	425	520	34*1	—	—	—	—
				T	432	522	33*1	—	—	193	−95
D	50 mm	—	1/4t	L	569	659	29*2	291*3	278	—	−71
				T	567	660	28*2	247*3	238	—	−67
			1/2t	L	564	658	30*2	239*3	234	—	−69
				T	574	664	28*2	228*3	213	—	−62

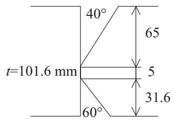
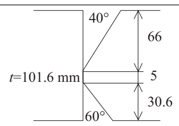
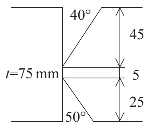
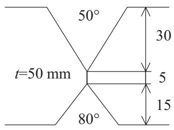
*1Specimen: φ12.5 mm, Gage length=50 mm *2Specimen: φ14 mm, Gage length=50 mm *3Testing temperature: −35°C
PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation
${}_vT_s$: Transformation temperature on toughness L: Longitudinal T: Transverse

Table 6 Strain aged Charpy impact properties of steel plates

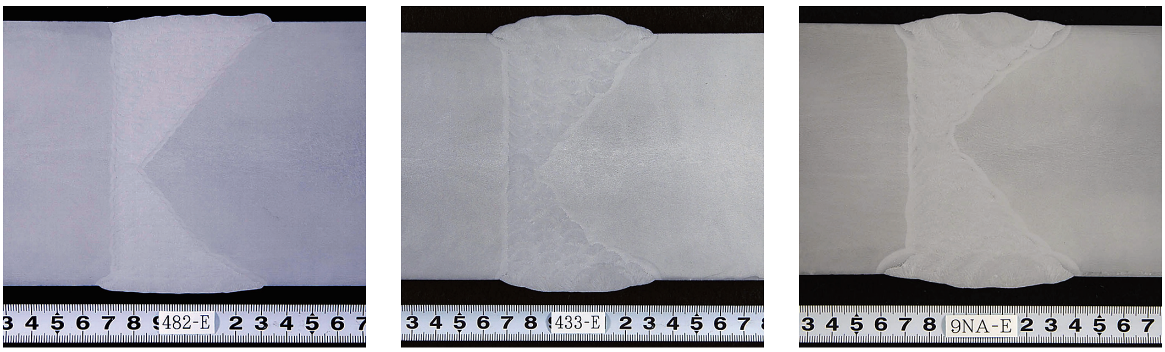
Steel	Thickness	Position	Direction	Strain	Charpy absorbed energy, average (J)			$_{v}T_{s}$ (°C)
					−40°C	−50°C	−60°C	
A	101.6 mm	Surface	T	0% 5%	426 254	— —	273 18	−88 −47
B	101.6 mm	Surface	T	0% 5% 8%	397 137 83	— — —	339 111 44	<−100 −70 −50
C	75 mm	Surface	T	0% 5% 10%	— — —	— — —	324 310 298	−135 −125 −105
D	50 mm	1/4*t*	L	0% 5%	291*1 241*1	278 194	— —	−71 −64

Aging: 250°C×1 h *1Testing temperature: −35°C L: Longitudinal T: Transverse
$_{v}T_{s}$: Transformation temperature on toughness

Table 7 Welding condition

Steel	Thickness	Welding method	Consumable	Groove shape	Heat input (kJ/mm)
A	101.6 mm	SAW	KW-30T/ KB100		1.5 3.0 4.5
B	101.6 mm	GMAW	DWA-55LSR*1		0.8
		SAW	US-36J*1 / PFH-55LT*1		3.0 4.5
C	75 mm	SAW	KW30T (modified) / KB100		5.0
D	50 mm	SAW	US-56B*1 / PFH-80AK*1		3.8

*1Supplied by Kobe Steel, Ltd.
SAW: Submerged arc welding GMAW: Gas metal arc welding



(a) GMAW, Heat input = 0.8 kJ/mm (b) SAW, Heat input = 3.0 kJ/mm (c) SAW, Heat input = 4.5 kJ/mm

SAW: Submerged arc welding GMAW: Gas metal arc welding

Photo 2 Macrostructure of Steel B welded joint

Table 8 Mechanical properties of welded joints

Steel	Thickness	Welding method	Heat input (kJ/mm)	Tensile test		Charpy impact test						
				Tensile strenght (MPa)	Location of rupture	Position	Test temp.	Absorbed energy, average (J)				
								WM	FL	FL +1 mm	FL +2 mm	SCHAZ
A	101.6 mm	SAW	1.5	572	WM	1/4t	−40°C −60°C	291 250	462 434	— —	— —	306 139
			3.0	579	WM	1/4t	−40°C −60°C	197 172	397 187	— —	— —	351 278
			4.5	549	WM	1/4t	−40°C −60°C	249 162	416 416	— —	— —	399 361
B	101.6 mm	GMAW	0.8	593 591	HAZ HAZ	1/4t	−40°C −60°C	156 133	478 489	— —	278 257	274 249
		SAW	3.0	595 594	HAZ HAZ	1/4t	−40°C −60°C	238 193	397 322	— —	434 325	306 269
			4.5	596 595	HAZ HAZ	1/4t	−40°C −60°C	252 248	451 440	— —	428 406	399 346
C	75 mm	SAW	5.0	543 546	HAZ HAZ	1/4t	−60°C −80°C	214 194	255 217	381 284	— —	— —
D	50 mm	SAW	3.8	682 684	HAZ HAZ	1/4t	−35°C −50°C	194 147	230 156	245 151	— —	— —

WM: Weld metal FL: Fusion line SCHAZ: Sub-critically HAZ HAZ: Heat-affected zone
SAW: Submerged arc welding GMAW: Gas metal arc welding

target property. In particular, Steel B and Steel C showed extremely good strain aging properties at the required temperature of $_{V}T_{S}$: −50°C with 8% strain for Steel B and $_{V}T_{S}$: −105°C under 10% strain with Steel C.

4. Properties of Welded Joints

4.1 Welding Conditions

The welding conditions applied with the respective steel plates are shown in **Table 7**. Welded joints were produced by multilayer gas metal arc welding (GMAW) with the welding heat input of 0.8 kJ/mm and by multilayer submerged arc welding (SAW) with heat inputs of 1.5–5.0 kJ/mm. In the case of Steels A and B, performance evaluations were performed with joints produced using 3 welding heat input levels. **Photo 2** shows the macrostructures of the welded joints of Steel B at each heat input.

4.2 Mechanical Properties of Welded Joints

The results of tensile tests and Charpy impact tests of the welded joints are shown in **Table 8**. Both of the tensile strength of the welded joints and Charpy absorbed energy of HAZ satisfy the target values of each steel plate.

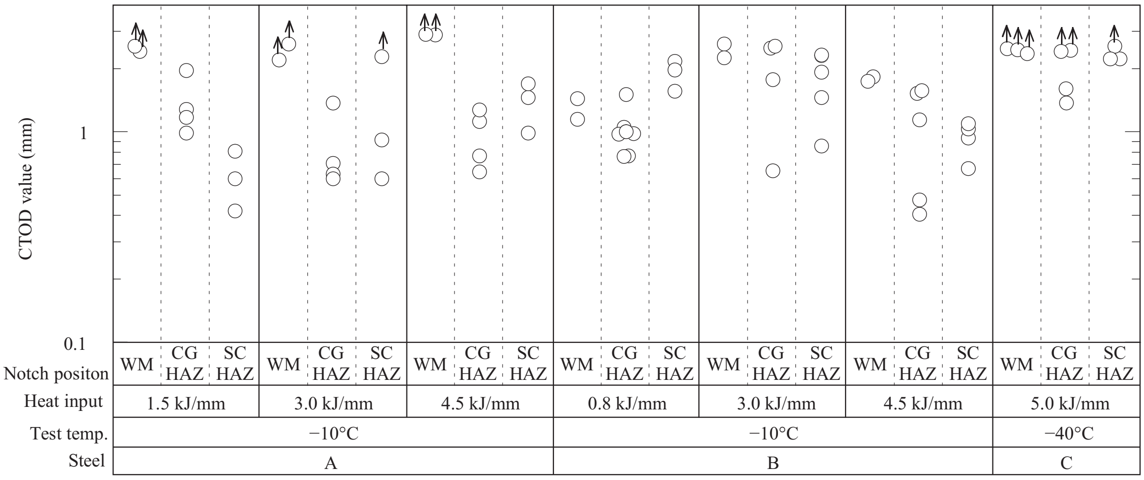
4.3 CTOD Properties of Welded Joints

The results of the CTOD test of the welded joints are shown in **Fig. 4**. CTOD tests and evaluations were performed with the notch position in the weld metal (WM), CGHAZ, and sub-critically HAZ (SCHAZ) were performed based on BS 7748 Part 2 (1997) and API RP 2Z[8]. The CTOD values of the CGHAZ with welding heat inputs up to 5.0 kJ/mm were Steel A: 0.60 mm or more at −10°C, Steel B: 0.40 mm at −10°C, and Steel C: 1.39 mm at −40°C. The CTOD values of the SCHAZ were Steel A: 0.42 mm or more, Steel B: 0.67 mm or more, and Steel C: 2.22 mm or more. Thus, the test results satisfied the targets in all cases, and the joints showed sufficiently high resistance to occurrence of brittle fracture. The proportions of the CGHAZ and SCHAZ in the crack tips of these test pieces all satisfied the provisions of API RP 2Z.

5. Conclusion

As high performance steel plates for offshore structures, the properties of a heavy thickness YP 420 MPa steel plate with thicknesses up to 101.6 mm, a low temperature specification material with a CTOD temperature of −40°C considering use in cold regions, and a high strength YP 500 MPa steel plate were introduced. These steel plates were developed by using a combination of advanced composition design and plate manufacturing technologies, beginning with JFE Steel's *Super*-OLAC™ accelerated cooling device. In all cases, the materials possess satisfactory base material and welded joint performance.

As the development of petroleum resources continues to expand into arctic and deepwater regions, it can be predicted that the need for high performance steel



Specimen: *B*×*B* (*B*: Thickness)
WM: Weld metal CGHAZ: Coarse grain HAZ SCHAZ: Sub-critically HAZ HAZ: Heat-affected zone

Fig. 4 Crack tip opening displacement (CTOD) test results of welded joint

plates for offshore structures will also continue to increase. In the future, application of the developed steels described in this report to various types of offshore structures is expected.

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