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Offshore Structural Steel Plates for Extreme Low Temperature Service with Excellent HAZ Toughness†

ICHIMIYA Katsuyuki[*1] FUJIWARA Takaki[*2] SUZUKI Shinichi[*3]

Abstract:

Higher strength and toughness are required for offshore steel plates used for natural gas and petroleum resources development, as installation areas of structures move into arctic areas. The main property of offshore structure steel is the crack tip opening displacement (CTOD) property of weld joint, and the demand for satisfying −40°C of CTOD test temperature specification has increased. For the improvement of heat affected zone (HAZ) toughness, coarse austenite grain is suppressed by the pinning effect of TiN and oxysulfides, and low-C, -carbon equivalent (Ceq), -Si, -P, -Nb are adopted to decrease the martensite-austenite (M-A) constituents. Furthermore, by Ca inclusion which has the pinning effect of grain coarsening and ability to nucleate ferrite grain, finer bainite HAZ microstructure and excellent HAZ toughness ara achieved, and yield point (YP) 420 MPa class high strength steel was developed.

1. Introduction

In recent years, rising energy demand has spurred more active development of offshore petroleum and gas fields, and construction quantity of offshore structures for use in drilling and production has increased. Because the areas being developed are continuing to expand from the moderate regions of the past into cold districts and icy waters, the requirements placed on steel materials now include not only higher strength and heavier thickness, but also low temperature toughness[1–5]. Particularly due to the enormous impact in the unlikely event of an accident involving an offshore structure, the crack tip opening displacement (CTOD) property of weld joint, which is based on fracture mechanics, is also required in addition to the Charpy impact test[6, 7]. In general, the temperature in the requirement specification for the CTOD property is −10°C, but in recent years, there has also been a heightened need for the −40°C low temperature specification.

The welding processes used with offshore structural steels are multi-pass welding, such as submerged arc welding (SAW) and multi-pass flux-cored wire arc welding (FCAW). The heat affected zone (HAZ) in multi-pass welding is affected by a complex repeated heat cycle. In particular, the microstructures that reduce the CTOD property with poor toughness are the coarse grain HAZ (CGHAZ), which is heated to near the melting point of the steel, and the inter-critically reheated CGHAZ (ICCGHAZ), in which reheating is performed in the dual-phase region of ferrite (α) and austenite (γ) when the CGHAZ is subjected to the welding heat cycle in the next welding pass. These two microstructure are called the local brittle zone (LBZ)[8–11]. Especially in the ICCGHAZ, carbon concentrates in the γ that forms by reverse transformation when the material is reheated to the dual-phase region temperature, and upper bainite, which contains martensite-austenite constituents (M-A) and displays poor toughness, is formed in the subsequent cooling process. This has a large adverse effect on the CTOD property. Although it is necessary to increase the carbon equivalent (Ceq) by adding alloying elements to the steel composition in order to meet the needs for

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

*2 Staff Assistant Manager,
Plate & Forging Sec., Products Design & Quality Control for Steel Products Dept.,
West Japan Works (Kurashiki),
JFE Steel

*3 Staff Deputy General Manager,
London Office,
JFE Steel

Table 1 Target properties for the developed steel

		Steel plate			Weld joint			
		Tensile properties*1		Charpy impact properties*1	Welding method	Heat input	Charpy impact properties	CTOD properties
Grade	Thickness (mm)	YS (MPa)	TS (MPa)	vE-60 (J)		(kJ/mm)	vE-60 (J)	CTOD value at −40°C (mm)
YP420	76.2	420−540	517−640	≧48	FCAW SAW	0.7 5.0	≧48	≧0.30

*1T. P.: T-Direction
YS: Yield strength, TS: Tensile strength, vE: Absorbed energy, CTOD: Crack-tip opening displacement
FCAW: Flux-cored wire arc welding, SAW: Submerged arc welding

higher strength and heavier thickness steel materials, on the other hand, from the viewpoint of weld joint performance, this increases the amount of M-A, causing a remarkable deterioration in the CTOD property. For this reason, it is difficult to satisfy both base metal strength and the joint CTOD property. Moreover, it is particularly difficult to satisfy both requirements with higher strength/lower temperature specifications.

To overcome this challenge, JFE Steel developed an offshore structural steel for extreme low temperature service with excellent HAZ toughness by adding a technology that utilizes Ca inclusions to a technology for improving HAZ toughness by using advanced microalloying control.

This paper introduces the features of the developed yield point (YP) 420 MPa class steel for CTOD −40°C service, together with the performance of steel plates and weld joints of the developed steel.

2. Composition Design and Manufacturing Technology of Developed Steel

2.1 Performance Targets

Table 1 shows the performance targets of the developed steel. The developed steel conforms to S420 and S460 of the EN10225 (EN: European Norm) standard, MDS-120 Y30/Y35 of the NORSOK (norsk sokkels konkuranseposisjon) standard, and 2 W Grade 60 steel of the API (American Petroleum Institute) standard. The plate thickness is 76.2 mm, and the CTOD specification temperature is −40°C.

2.2 Improvement of CTOD Property of Weld Joint

The concept of improving the HAZ toughness of the developed steel is shown in **Fig. 1**. As mentioned previously, the CGHAZ is a region where the steel is heated to just below its melting point of the steel by welding, and as a result, γ grains undergo coarsening. Dispersion of particles that suppress grain coarsening is effective for improving the toughness of the CGHAZ. Precipitates which are stable at high temperature, namely, TiN[1, 12, 13] and oxysulfides[14–16], have a long history of use for this purpose. However, in order to suppress grain growth, it is necessary to disperse a larger number of finer particles, as expressed by the Zener Equation[17] ($R = \alpha \cdot r/f$, R: Grain diameter, α: Constant, r: Radius of precipitate particle, f: Volume fraction). In TiN control, while strictly controlling the amounts of added Ti and N and the Ti/N ratio, the thermal history is also optimized in the production process, and improvement of the toughness of the CGHAZ is realized by securing the most effective distribution condition.

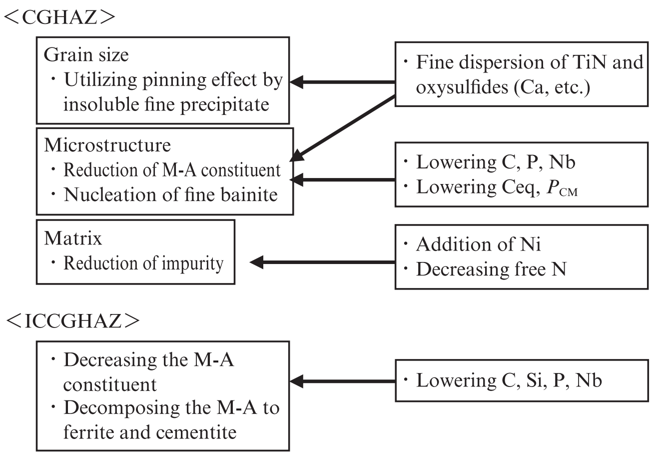
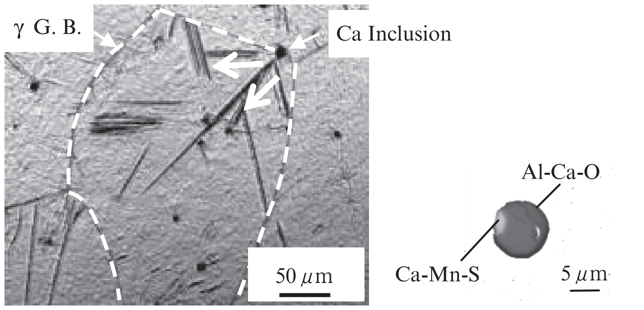


Fig. 1 Concept of improving heat affected zone (HAZ) toughness

In addition to the TiN control technology, in the developed steel, refinement of the HAZ microstructure was performed by newly promoting the intragranular bainite transformation to satisfy the requirements for low temperature toughness of weld joint. JFE Steel has developed and realized practical application of steels for large heat input welding by utilizing the function of Ca inclusions as nuclei for the α transformation in order to improve HAZ toughness in large heat input welding joints in the shipbuilding and construction fields. These steels use Ca inclusions in control of the HAZ microstructure, which comprises mainly α microstructure[18]. However, it was newly found that the same inclusions



(a) Surface relief observed by laser microscope (b) Bainite nucleation site

Fig. 2 Observation of transformation behavior

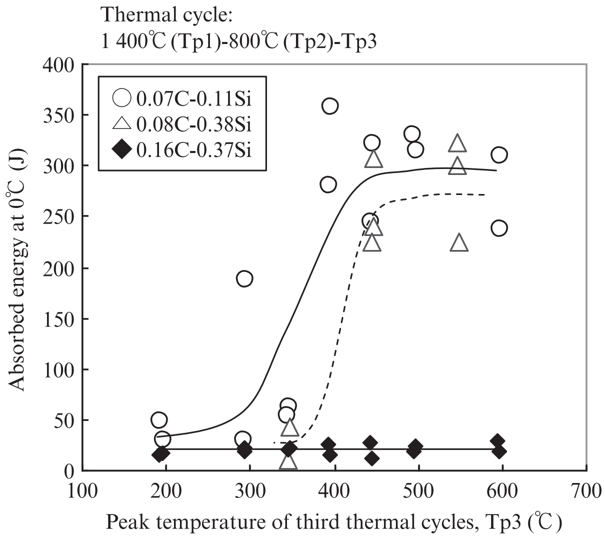


Fig. 3 Effect of C and Si contents on ICCGHAZ toughness in simulated heat affected zone (HAZ)

are also effective in refinement of small heat input welding HAZ microstructure of high strength steels. The HAZ microstructure consists mainly of bainite. This finding was applied in the developed steel. It is thought that Ca inclusions have both a pinning function and a transformation nucleation site function. That is, while suppressing grain boundary migration by dispersion in the steel, Ca inclusions also serve as nucleation sites for the bainite transformation, even in the cooling process in small heat input welding, and thereby contribute to refinement and high toughness of the HAZ microstructure. An example of this is shown in **Fig. 2**. A heat pattern that simulated small heat input welding was applied by using a laser microscope, and the effect of the Ca inclusions in the cooling process was investigated. The observed Ca inclusions were mainly oxysulfides composed of Mn, Al, etc. As can be seen in the figure, the Ca-based inclusions also function as bainite transformation nucleation sites, while continuing to suppress grain boundary migration by a pinning effect. The amount of addition of these Ca-based inclusions and the manufacturing conditions are controlled precisely so as to obtain the optimum composition and morphology in actual manufacturing.

The ICCGHAZ, which is the other LBZ, is the region where the CGHAZ that formed in the 1st pass is heated in the ($\alpha+\gamma$) dual-phase region between the Ac_1 and Ac_3 points in the next pass. Because the austenite that is formed by the reverse transformation process has a large solute carbon content, carbon is distributed from the ferrite phase to the austenite phase, where it concentrates. Continued cooling in this state causes the carbon-enriched austenite to form brittle upper bainite with a high M-A content, and this reduces toughness. The key points for improving the toughness of this microstructure are refinement of the CGHAZ, which was the prior microstructure, and reduction of the amount of M-A[19]. In order to suppress M-A formation, in addition to the importance of low C and a low Ceq, which have the largest effects, low Si, low P, and low Nb are also effective[2, 3]. **Figure 3** shows the effects of the C and Si contents on the toughness of the ICCGHAZ in the third reheating cycle. Toughness is improved, even under reheating to approximately 400°C, by reducing the contents of C and Si. This is because Si is almost insoluble in cementite, and reducing the Si content promotes the formation of cementite and facilitates decomposition of M-A[20]. This effect is considered to reduce the size of the LBZ in the HAZ in multi-pass welding, resulting in improved toughness.

In addition, reduction of impurity elements such as P, N, etc. and proper addition of Ni are effective for improving the toughness of the matrix. Ni is an element which makes it possible to increase strength while suppressing the negative effect on toughness. Therefore, the proper amount of Ni is added, considering the balance with other alloying elements.

3. Features of Developed Steel

3.1 Chemical Composition and Manufacturing Process

The chemical composition of the developed steel is shown in **Table 2**. To decrease M-A, the C and Si contents are reduced, and the optimum amount of Ni is added in comparison with the conventional YP420 class steel. On the other hand, Ceq is increased in order to secure strength. To improve HAZ toughness, TiN particles are controlled, and to form Ca inclusions, which are effective for the control of the HAZ microstructure, the amount of Ca addition is controlled, together with the amounts of addition of other complexing elements.

Figure 4 shows the manufacturing process. In the manufacture of the base material, in addition to using JFE Steel's online accelerated cooling device (*Super*-OLAC™), which makes it possible to realize a cooling

Table 2 Chemical compositions of developed steel plate

	Thickness (mm)	C	Si	Mn	P	S	Al	Others	Ceq*1	P_{CM}*2
Developed	76.2	0.06	0.10	1.55	0.005	0.001	0.029	Cu, Ni, Nb, Ti, Ca, etc	0.43	0.18
Conventional	101.6	0.08	0.14	1.57	0.005	0.001	0.032	Cu, Ni, Nb, Ti, etc	0.42	0.19

*1Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15, *2P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B

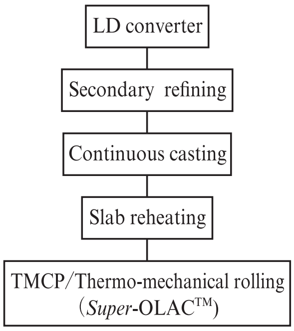


Fig. 4 Manufacturing process

rate equivalent to the theoretical limit, precise control is applied from heating of the slab material to the rolling temperature, rolling reduction, cooling start temperature, and cooling end temperature, making it possible to realize the target properties.

3.2 Mechanical Properties of Base Material

Photo 1 shows the microstructure of the base material. A microstructure consisting mainly of fine ferrite has been obtained. **Table 3** shows the results of a tensile test and Charpy impact test of the base material. The target properties shown in Table 1 were amply satisfied in both tests.

3.3 Strain Aging Property

Because offshore structural steels are generally used in steel pipe structures, large strain is applied to the material surface during manufacturing. Since toughness deterioration during the subsequent aging process becomes a problem, that property was evaluated. Pre-strain of 5% or 8% was applied, and aging heat treatment was performed by heating the materials to 250°C and holding at that temperature for 1 h.

Table 4 shows the results of the strain aged Charpy impact test. An adequate toughness value is obtained at −60°C, and the ductile-brittle fracture surface transition temperature (vTrs) also shows excellent toughness at −86°C or lower, even at 8% strain.

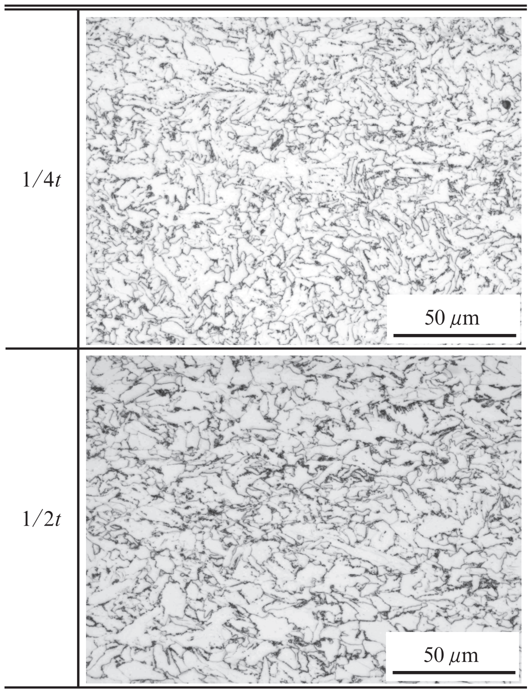


Photo 1 Optical micrographs of developed steel

Table 3 Mechanical properties of developed steel plate

Thickness	PWHT	Position	Direction	Tensile test			Charpy impact test	
				YS (MPa)	TS (MPa)	EL (%)	vE −60˚C (Ave.)	vTrs (˚C)
76.2	—	1/4*t*	L	465	552	29	342	−99
			T	467	543	30	366	−97
		1/2*t*	L	445	548	25	316	−69
			T	437	535	27	167	−68
	580˚C×4 h	1/4*t*	L	463	542	30	324	−88
			T	452	532	30	316	−92
		1/2*t*	L	438	539	28	311	−69
			T	420	521	30	221	−90

YS: Yield strength, TS: Tensile strength
El: Elongation, vE: Absorbed energy, vTrs: Ductile brittle transition temperature

Table 4 Strain aged Charpy impact properties of developed steel plate

Thickness	Position	Direction	strain (%)	Charpy impact test	
				vE −60˚C (Ave.)	vTrs (˚C)
76.2	Surface	L	5	283	−102
			8	271	−86
		T	5	305	−98
			8	267	−94

vE: Absorbed energy, vTrs: Ductile brittle transition temperature

Table 5 Drop-weight test results of developed steel plate

Thickness (mm)	Test piece type	PWHT	Location	Direction	T_{NDT} (˚C)
76.2	P-3	—	Surface	T	< −80
		580˚C×4 h			< −80

T_{NDT}: Nil-ductility transition temperature

3.4 NRL Drop Weight Property

An NRL drop weight test of the developed steel was performed in accordance with ASTM E208 (ASTM Standards). The test specimen shape was the P-3 type. Specimens were taken from the plate surface in the transverse (T) direction, and the nil-ductility transition temperature (T_{NDT}) was obtained. The drop weight energy was 400 J. The test results are shown in **Table 5**. The T_{NDT} temperature is −80°C or lower, showing an excellent property.

3.5 CTOD of Base Material

A CTOD test of the developed steel plate was performed based on BS7448 Part 1 (British Standards). **Figure 5** shows the results. Satisfactory values were obtained at the test temperature of −40°C, under conditions both with and without post weld heat treatment (PWHT).

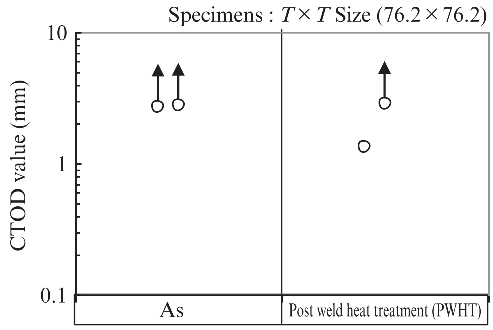
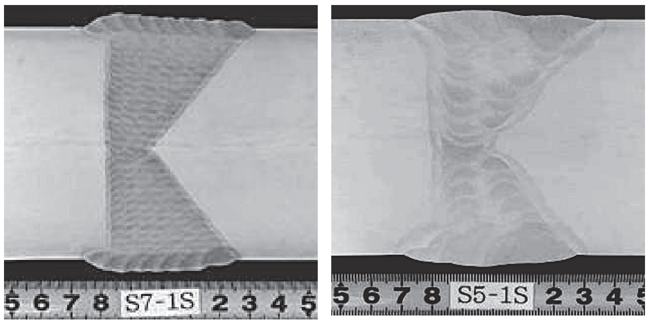


Fig. 5 Crack tip opening displacement (CTOD) test results of developed steel plate

4. Properties of Weld Joints

4.1 Welding Conditions

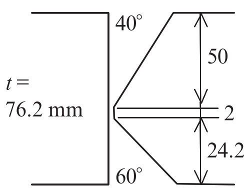
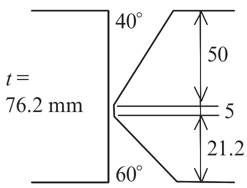
The welding conditions used with the developed steel plate are shown in **Table 6**. Weld joints were prepared by multi-layer gas metal arc welding (GMAW) with the welding heat input of 0.7 kJ/mm and by multi-layer submerged arc welding (SAW) with 5.0 kJ/mm. **Photo 2**



(a) 0.7 kJ/mm GMAW (b) 5.0 kJ/mm SAW

Photo 2 Macrostructures of weld joint

Table 6 Welding conditions

Thickness (mm)	Welding method	Groove shape	Preheat temperature (˚C)	Interpass temperature (˚C)	Heat input (kJ/mm)
76.2	GMAW		125−135	110−130	0.7
	SAW		125−135	130−200	5.0

GMAW: Gas metal arc welding, SAW: Submerged arc welding

Table 7 Mechanical properties of weld joint

Thickness (mm)	Welding method	Heat input (kJ/mm)	PWHT	Tensile test	Charpy impact test					
				TS(MPa)	Position	Test temp. (°C)	Absorbed energy, average (J)			
							WM	FL	FL + 2 mm	FL + 5 mm
76.2	GMAW	0.7	—	606	Sub-surface	−60	150	202	253	269
				607	Root		128	199	159	113
	SAW	5.0	—	571	Sub-surface		142	144	302	331
				574	Root		157	255	357	252
			580°C×4 h	552	Sub-surface		159	202	317	261
				552	Root		218	226	299	304

GMAW: Gas metal arc welding, SAW: Submerged arc welding, PWHT: Post weld heat treatment
TS: Tensile strength, WM: Weld metal, FL: Fusion line

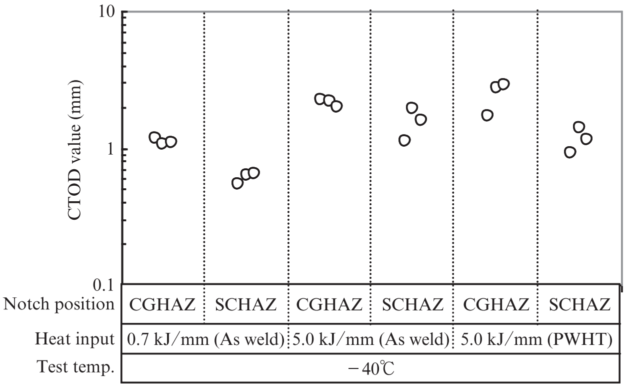


Fig. 6 Crack tip opening displacement (CTOD) test results of weld joint

shows the macrostructures of the weld joints.

4.2 Mechanical Properties of Weld Joints

The results of a tensile test and Charpy impact test of the weld joints are shown in **Table 7**. The tensile strength of the joints and the joint Charpy values both amply satisfied the targets.

4.3 CTOD Property of Weld Joints

Figure 6 shows the results of CTOD tests of the weld joints. The CGHAZ and sub-critically reheated HAZ (SCHAZ) were evaluated at the test temperature of −40°C based on BS7448 Part 2. The targets were amply satisfied in all cases, and it was found that the joints display high resistance to brittle fracture.

5. Conclusion

A CTOD −40°C YP420 MPa class steel plate with a thickness of 76.2 mm was developed as an offshore structural steel. Excellent base metal and weld joint performance could be obtained by applying Ca inclusions to HAZ microstructure control in order to improve HAZ toughness.

Active development of energy resources is also foreseen in the future, and JFE Steel will continue to develop steel materials that contribute to those efforts.

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