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The body can be viewed from the next page.

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1 Introduction

In recent years, with increased activity in petroleum energy development and resources, the locations of offshore structures have continued to expand into arctic and deep water areas. In addition to higher strength and increased thickness, the steel plates which are used in arctic offshore structures must satisfy CTOD value requirements at a low temperature of −40°C, compared with the conventional CTOD value requirements at −10°C, to ensure adequate fracture toughness, and must also meet an extremely strict nil-ductility transition temperature requirement of TNDT ≦ −85°C in the drop weight test to secure properties to prevent brittle crack propagation. In the present work, the authors developed a 75 mm thick YP420 MPa class steel for offshore structures which possesses excellent low temperature toughness, satisfying requirements even stricter than these conventional ones, and evaluated the characteristics of the base metal and welded joints of the new material.

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2 Target Properties of Steel Plate to be Developed

The target values in the development reported here are shown in **Table 1**. The fundamental properties were based on the low temperature specification of 2 W Gr. 60 steel[1] in the API standard. Although the required CTOD value of the heat affected zone (HAZ) of welds is specified as 0.25 mm or more for Gr. 50 steel with a thickness of 75 mm or under, no specification is given for Gr. 60 steel in the API RP2Z rule[2]. For this reason, here, the required value was calculated in proportion to the yield strength of the plate,[3] and was set at a target value of 0.30 mm. As the required value for the weld metal, a target value of 0.43 mm was adopted, based on

Table 1 Target values in mechanical properties and fracture toughness for steel plate developed

Steel plate						Welded joint				
YS (MPa)	TS (MPa)	El (%)	Charpy impact properties		NRL TNDT (°C)	Welding method	Heat input (kJ/mm)	V Charpy absorbed energy (J)	CTOD value at −40°C (mm)	
			Absorbed energy (J)	50% FATT (°C)					CGHAZ SCHAZ	Weld metal
414~586	≧517	≧22	vE_{-60} ≧41	≦−100	≦−85	SAW	5.0	vE_{-60} ≧41	≧0.30	≧0.43

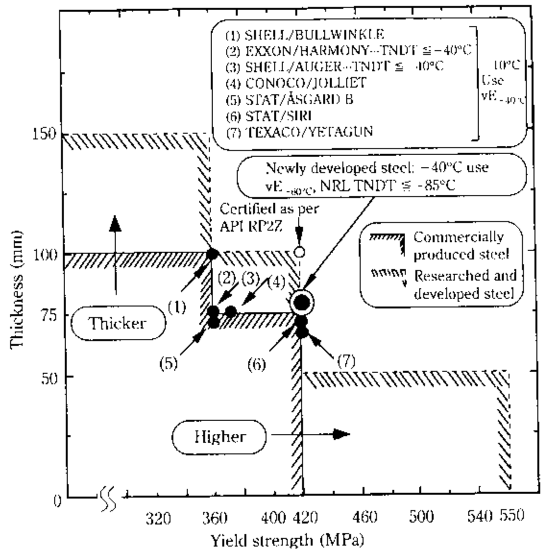


Fig. 1 Commercial availability and R&D works for offshore steels

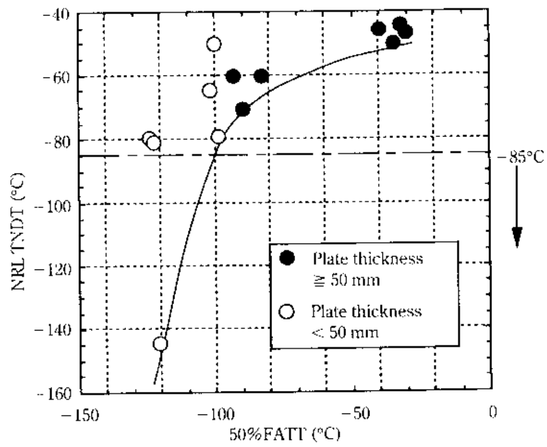


Fig. 2 Relation between 50%FATT and NRL TNDT

the requierd value of the HAZ + 0.13 mm, as stipulated in the API RP2Z rule. In the past, the CTOD temperature requirement has generally been −10°C. However, considering use in the Sakhalin offshore oil fields, where development is now being promoted, this value was set at −40°C. To ensure that adequate crack arrestability is possible even under conditions where the operating stress due to welding residual stress and stress concentrations exceeds the yield stress in the CAT curve of the fracture analysis diagram (FAD) proposed by Pellini et al.,[4] the target TNDT temperature was set at −85°C, using the design temperature "−40°C = TNDT + 45°C".

Figure 1 shows the positioning of the newly developed steel relative to the offshore structures manufactured by Kawasaki Steel in the past and the range of commercially available steels. With conventional steels, the Charpy test temperature is −40°C and the NRL TNDT is ≦ −40°C. However, as a distinctive feature of the newly developed steel, even though the new steel falls within the conventional production range terms of plate thickness and yield stress, an unprecedented level of low temperature toughness is required, namely, a Charpy test temperature value of −60°C and an NRL TNDT is ≦ −85°C. The relationship between the Charpy fracture appearance transition temperature (50%FATT) and NRL TNDT of the base metal is shown in **Fig. 2**. To satisfy the target temperature of −85°C in the TNDT drop-weight test, it is necessary to set the target for the 50%FATT at approximately −100°C.

3 Chemical Composition and Production Process

Table 2 shows the fundamental concept of the composition design and production process for securing the target toughness mentioned in Chapter 2. In this development, the basic process used by Kawasaki Steel to produce steels for offshore structures up to the present was optimized.

Specifically, this included lowering the Ceq and Pcm, lowering the contents of C, N, Si, and P, REM-Ti treatment, and controlling the Ti/N ratio[5–7]. To secure strength, controlled rolling and the MACS (multipurpose accelerated cooling system) process were applied. The contents of P and S were reduced to minimize the number of non-metallic inclusions, which can become the origin for brittle cracks, and to improve the anisotropy of the material properties of the plates. Due to the thickness (75 mm) of the product, there were limits to the effectiveness of rolling as a means of refining the microstructure. Therefore, particularly to secure toughness at the mid-thickness position, low reheating temperature was applied to the slabs used as plate material in order to prevent coarsening of the austenite grains

Table 2 Metallurgical measures for improving HAZ toughness at low temperatures

Item	Improvement of HAZ toughness	
	Metallurgy	Measure
Grain size	Utilizing pinning effect by fine precipitate TiN and REM (O, S)	REM-Ti treatment
Microstructure	Decreasing the M-A constituent + Fine ferrite-pearlite structure or lower bainite structure	Lowering Ceq and Pcm (MACS process)
Matrix	Decreasing free N and sol. Ti	Lowering C, N, Si and P together with controlling of Ti/N ratio and adequate Ni addition
	Minimizing the detrimental effect of precipitation hardening on toughness	Restricting Nb and V contents
	Toughening	Adequate Ni addition

during reheating. However, when low reheating temperature was performed, the hardenability of the plates was reduced, and it became difficult to form a ferrite-bainite microstructure with satisfactory strength and toughness. Therefore, the use of accelerated cooling after rolling, together with the addition of elements which are effective in improving hardenability, was studied.

The alloying elements which increase hardenability include C, Si, Mn, Cu, Ni, Cr, Mo, V, B, and others, as is known from their DI values, but it was feared that C, Si, Cr, Mo, and B would cause deterioration of the HAZ toughness. On the other hand, Ni is an element which increases the toughness of the base metal matrix and improves hardenability without impairing the toughness of the HAZ, but from the viewpoint of production costs, the amount of Ni addition must be minimized. However, in order to meet the extremely high toughness requirement in this development, an increase in the amount of Ni addition was considered necessary. The effect of the Ni content on strength and toughness is shown in **Fig. 3**, which indicates that both strength and toughness improve at Ni contents of up to 1.5%. Although strength depends on the increase in hardenability, if the amount of Ni addition is too large, the material becomes excessively hard, and its toughness deteriorates. Accordingly, the Ni content should be designed with an upper limit of 1.5%. **Figure 4** shows the relationship between the CTOD value of the HAZ and the Ni content of the plate. Ni content of approximately 1% is necessary in order to achieve the targeted CTOD value of 0.30 mm or more in

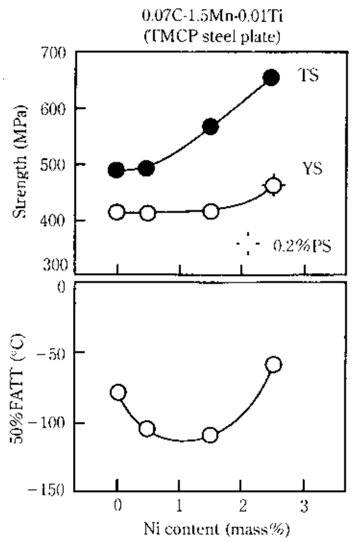


Fig. 3 Effect of Ni content on strength and toughness of TMCP steel plate

the HAZ at −40°C, therefore the target contents of Ni was set at 1.1%.

Table 3 shows the chemical composition of the newly developed steel plates. The composition is low C, low S-Cu-Nb with 1.1%Ni addition to secure high toughness, as discussed above. Because the Pcm is under 0.20%, it is considered possible to perform welding without preheating. **Figure 5** shows the manufacturing process used

Table 3 Chemical composition of steel plate developed

(mass%)

C	Si	Mn	P	S	Cu	Ni	Nb	Al	N	Ceq*1	Pcm*2	Note
0.07	0.10	1.55	0.005	0.001	0.29	1.09	0.015	0.028	0.0039	0.42	0.18	REM-Ti treated

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

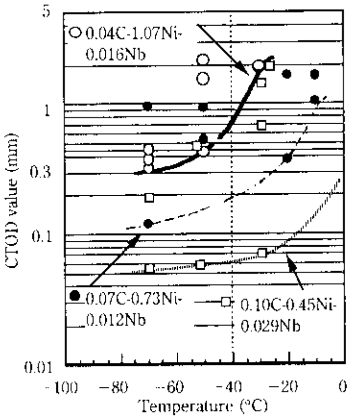


Fig. 4 Effect of Ni content on CTOD value at HAZ of SAW welded joints (H.I. 5.0 kJ/mm, Notch location: CGHAZ)

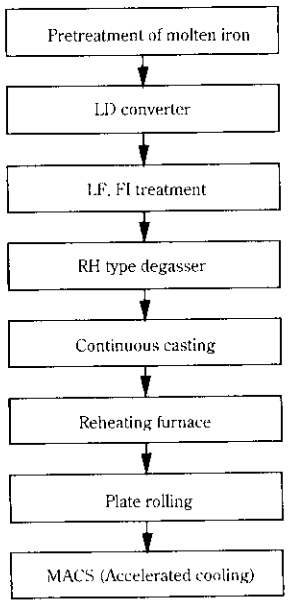


Fig. 5 Manufacturing process of steel plate developed

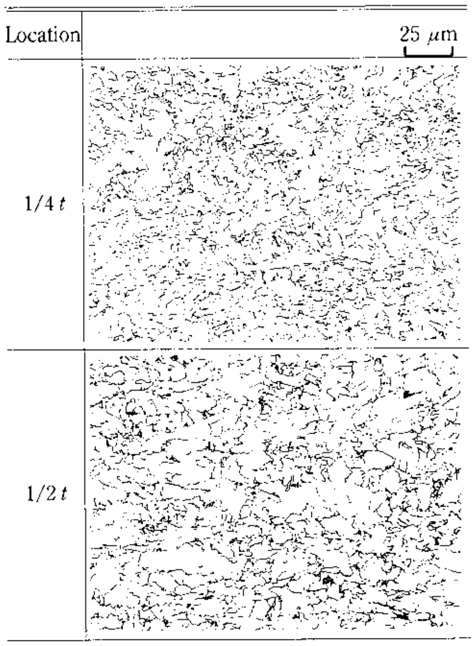


Photo 1 Microstructure of steel plate developed

with the new plates. In the steelmaking process, P and S were reduced, and REM-Ti treatment was performed. To secure an adequate reduction ratio for compressing the porosities at the center of the slab during rolling, slabs with the maximum continuous casting thickness of 310 mm were used. In the plate rolling process, low temperature reheating was performed, followed by controlled rolling, mainly in the non-recrystallized austenite region, accelerated cooling.

4 Properties of Plates

4.1 Fundamental Properties of Base Metal

Photo 1 shows the optical microstructure of the base metal. Both the 1/4 position and the mid-thickness position have a bainite microstructure which includes fine acicular ferrite. Although the microstructure at the mid-thickness position is somewhat coarse in comparison with that at the 1/4 thickness position, an adequately fine microstructure was obtained. **Table 4** shows the results of a tensile test and 2 mm V notch Charpy impact test. In both cases, the results, including those at the mid-thickness position, satisfied the target values for strength and toughness shown in Table 1. The Charpy FATT temperature was −135°C at the 1/4 thickness, satisfying the target of under −100°C, and was −95°C even at the mid-thickness position, indicating that satisfactory toughness had been obtained in the base metal. In addition, the reduction of area in the through-thickness direction being 61% or more, the material possesses

Table 4 Mechanical properties of steel plate developed

Location	Direction	Tensile properties YS (MPa)	TS (MPa)	El (%)	Charpy impact properties Absorbed energy (J) −60°C	−80°C	−100°C	50% FATT (°C)	Preheat temp. without cracking (°C)
Subsurface	T	—	—	—	324	305	258	−135	≦25
1/4*t*	L	446	529	35	—	—	—	—	
	T	451	541	34	400	405	324	−135	
	Z	—	519	61*1	—	—	—	—	
1/2*t*	L	425	520	34	—	—	—	—	
	T	432	522	33	193	156	122	−95	
	Z	—	524	62*1	—	—	—	—	

*1 Reduction of area (%)

Table 5 Drop-weight test results of steel plate developed

Test piece type	Location	Direction	TNDT (°C)
P-2	Surface	L	−120
	1/2*t*	L	− 90

good resistance to lamellar tearing.

4.2 Drop-Weight Test Properties

A drop-weight test of the newly developed steel was performed as specified in ASTM E208 with the results shown in **Table 5**. The TNDT results at the surface and the mid-thickness position were −120°C and −90°C, respectively, amply satisfying the extremely strict requirement for properties to prevent crack propagation, as shown by the target of TNDT ≦ −85°C in Table 1.

4.3 Fracture Toughness of Base Metal

4.3.1 Properities to prevent brittle fracture initiation

Properties to prevent brittle fracture initiation in the base metal were investigated by a three point bend CTOD test (assuming in a specimen thickness of *B*, *B* × *B* size).[3] As shown in **Fig. 6**, the CTOD value was greater than 1.55 mm at −40°C and a satisfactory value of more than 1.37 mm was obtained even at −80°C.

4.3.2 Properties to prevent crack propagation

Properties to prevent crack propagation in the base metal were investigated by the ESSO test. **Figure 7** shows the temperature dependence of the crack arrest property, Kca. The Kca value satisfied the requirement for the WES 3003 A[8] grade when the working stress at a service temperature of −40°C is 1/2 of the yield stress, and thus showed to satisfactory properties to prevent crack propagation.

4.4 Properties after Strain Aging

Changes in the toughness of the plate subsurface area

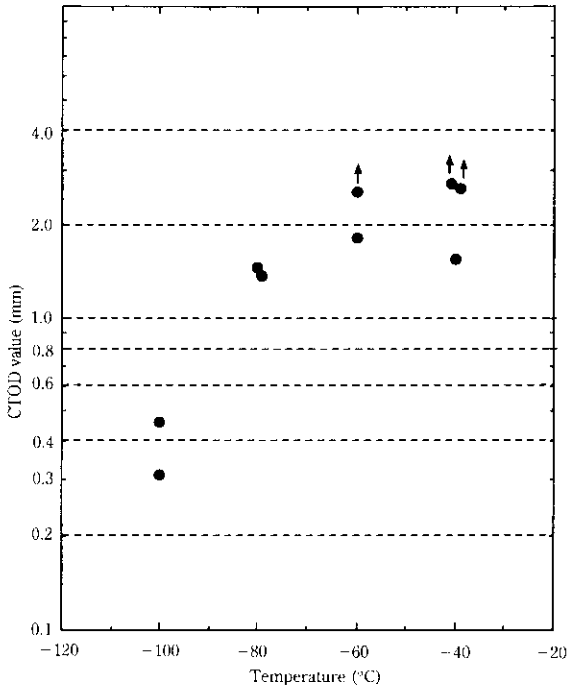


Fig. 6 CTOD test results for steel plate developed

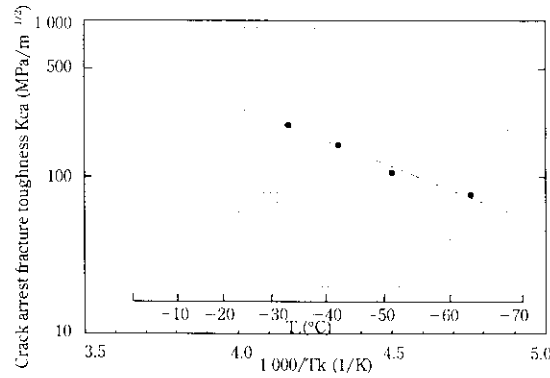


Fig. 7 Results of temperature gradient type of ESSO test for crack arrest fracture toughness for steel plate developed

Table 6 Effect of strain aging on Charpy impact properties for steel plate developed

Strain and aging[*1]	Charpy impact properties[*2]			
	Absorbed energy (J)			50% FATT (°C)
	−60°C	−80°C	−100°C	
No	324	305	258	−135
5% + aging	310	291	231	−125
10% + aging	298	244	206	−105

[*1] Aging : 250°C × 1 h
[*2] Specimen location and direction : subsurface, transverse

were investigated by the Charpy impact test after applying a maximum tensile strain of 10% and aging at 250°C for 1 h. **Table 6** shows the test results. When 5% strain was applied, the increase in the 50% FATT due to strain aging was extremely small, at a maximum of 10°C. Satisfactory results were also obtained at 10% strain, the 50% FATT showing a value or −105°C.

4.5 Weldability

Sensitivity to weld cracking at low temperatures was investigated by the oblique Y-groove, weld cracking test, as specified in JIS Z3158. As shown previously in Table 4, the temperature for preventing surface, cross-section, and root cracks is 25°C or under, and it is therefore considered possible to perform welding without preheating in actual work.

5 Properties of Welded Joints

5.1 Welding Conditions

Table 7 shows the welding conditions applied with the new steel plates. Multi-pass submerged arc welding was performed with a K-groove and a heat input of 5.0 kJ/mm.

5.2 Fundamental Properties of Welded Joints

Table 8 shows the results of a tensile test of welded joints and a Charpy impact test at various notch positions on welded joints at the 1/4 thickness position. The tensile strength of the joints adequately satisfied the target values for the base metal in Table 1. The Charpy absorbed energy of the joints was 255 J or more at −60°C, even with the notch position on the fusion line (position which includes 50% weld metal and 50%HAZ), and the 50%FATT was −90°C, showing a satisfactory Charpy property in the joints.

5.3 CTOD Property of Weld Joints

A CTOD test of the welded joints was conducted using samples of the same $B \times B$ size as with the base metal. The test and evaluation were performed based on ASTM E1290 and API RP2Z. **Figure 8** shows the test results. The minimum CTOD values at −40°C were 1.39 in the CGHAZ, 2.22 mm in the SCHAZ, and 2.35 or more in the W. M., amply satisfying the respective target values of 0.30 mm or more for the CGHAZ and SCHAZ and 0.43 mm or more for the W. M. Satisfactory results were also obtained at −60°C, with the CGHAZ showing values over 0.38 mm and even the W. M. showing values over 0.52 mm. After the test, each specimen was sectioned to confirm that all the fatigue crack tips

Table 7 Welding conditions

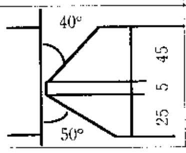
Welding method	Wire × Flux	Groove shape (mm)	Electrode	Current (A)	Voltage (V)	Speed (mm/min)	Heat input (kJ/mm)	Preheat temp. (°C)	Interpass temp. (°C)
Multipass SAW	KW30T (modified) × KB100		L T	550 550	30 32	410	5.0	min. 250	min. 250

Table 8 Mechanical properties of welded joints of steel plate developed

Welding method	Heat input (kJ/mm)	Tensile test		V-Charpy impact test							
		TS (MPa)	Location of rupture	Thickwise location	Testing temperature (°C)	Absorbed energy (J)					
						WM	FL	HAZ1	HAZ3	HAZ5	HAZ7
Multipass SAW	5.0	543	HAZ	1/4 t	−60	214	255	381	335	315	329
		546	HAZ		−80	194	217	284	283	269	306
					50%FATT (°C)	−85	−90	−135	−155	−130	−95

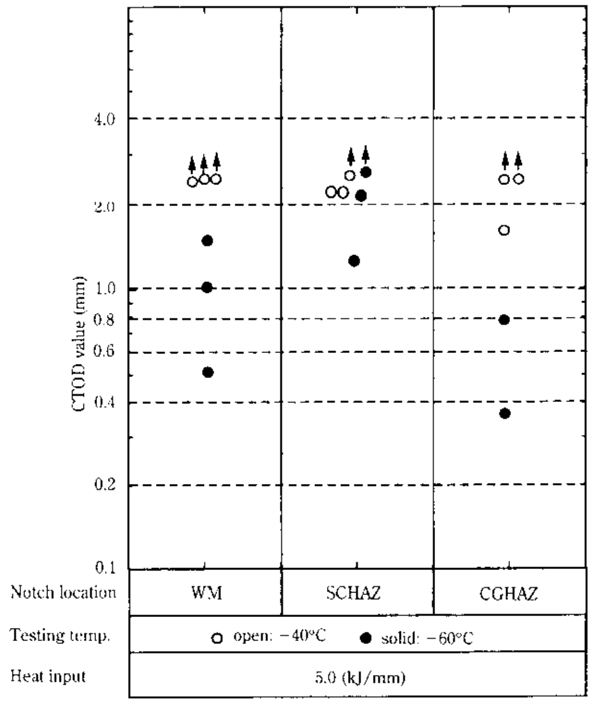


Fig. 8 CTOD test results for SAW welded joints of steel plate developed

included the coarse-grained HAZ over at least 23% of the specimen thickness to satisfy the API RP2Z rule.

6 Conclusion

High toughness YP 420 MPa steel plates 75 mm in thickness were developed for arctic offshore structures by adopting a low C-low S-Cr-Nb-1.1%Ni composition and applying the MACS (multipurpose accelerated cooling system) process. The new plates satisfy an extremely strict low temperature toughness specification which requires a CTOD value of 0.30 mm or more in welded joints at a design temperature of −40°C and a drop-weight test TNDT of −85°C or under. The following conclusions were obtained based on the results of an investigation of the characteristics of the base metal and submerged arc welded joints.

(1) Extremely good results were obtained for the toughness of the base metal, which showed an FATT of −95°C at the mid-thickness position in the T-direction, and L-direction CTOD values of 1.55 mm or more at −40°C and 1.37 mm or more even at −80°C.

(2) The drop-weight test TNDT amply satisfied the target value of −85°C or under with vaules of −120°C at the surface and −90°C at the mid-thickness position, indicating that satisfactory properties to prevent brittle crack propagation had been obtained.

(3) The CTOD value of the heat affected zone in SAW joints welded with a K-groove and a heat input of 5.0 kJ/mm was 1.60 mm or more in the CGHAZ and 2.22 mm or more in the SCHAZ at −40°C, achieving the target value of 0.30 mm or more.
The weld metal, with a CTOD of 2.35 mm or more, also amply satisfied the target value of 0.43 mm or more. Satisfactory values were obtained even at −60°C, with the results for the CGHAZ, SCHAZ, and W. M. exceeding 0.38 mm, 1.20 mm, and 0.52 mm, respectively, confirming that the new plates possess satisfactory resistance to the initiation and propagation of brittle fracture in arctic offshore environments.

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