Technical Report

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High Strength TMCP Steel Plate for Offshore Structure with Excellent HAZ Toughness at Welded Joints

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Abstract

The steel plate for offshore structures is required to have excellent low-temperature HAZ toughness because of more severe environmental conditions such as deeper sea and frigid oceanic conditions. Therefore, the steel plate with excellent HAZ toughness for offshore structures has been developed. As a important point in the development of the steel is the refinement of the effective grain size of the HAZ microstructure, strengthening of formation of IGF has been tried on Ti-O steel. Addition of Mn to Ti-O steel, an important element for Ti-O steel for IGF formation, was increased intentionally. Consequently, IGF has increased as compared with conventional Ti-O steel, FSP size has decreased, and HAZ toughness has been improved. The developed steel has excellent CTOD properties at −20°C, thus the developed steel can be applied to offshore structures in frigid sea.

1. Introduction

The steel plates used for offshore structures (hereinafter referred to as offshore structure material) are required to have excellent low-temperature toughness not only for the base metal but also for the welded joints from the viewpoint of preventing brittle fractures. In particular, in many cases, the low-temperature toughness of Charpy not only impacts properties but also Crack Tip Opening Displacement (CTOD) properties governed by local embrittling phase are required, and therefore, compatibility of high toughness and high strength through refining of microstructure of heat affected zone (HAZ) and reduction and suppression of formation of embrittling phase has become one of the subjects of the offshore structure material.

Till now, Nippon Steel & Sumitomo Metal Corporation has guaranteed the welded joints CTOD properties of such steels as Ti-N steel, Ti-O steel, Mg-O steel, Cu-precipitated steel and so on, and based on technologies relevant to such steels, a steel with yield strength (YS) of 355 MPa or more has been developed and put into actual use.[1, 2] Technologies to improve the toughness of HAZ by utilizing refined particles like this way is collectively termed as HTUFF™ (High HAZ Toughness Technology with Fine Microstructure Imparted by Fine Particles) by Nippon Steel & Sumitomo Metal. Conventionally, CTOD properties of welded joints at −10°C was generally demanded; however in recent years, offshore structures have come to be constructed on icy waters as well as on the waters of the Arctic Circle. As there were projects among them, such as the Sakhalin Project, which demanded ultralow welded joint CTOD properties at −35°C or below. Therefore, Nippon Steel & Sumitomo Metal has completed the development of YP355 MPa steel and YP420 MPa steel and applied them to actual use.[3, 4] Furthermore, to cope with the growing demand for energy, enhancing strength of steel material was promoted by the increase in size of offshore structures and weight saving; therefore, as the increase in marine exploitation under more severe oceanic environment in cold district was foreseen, demand was growing for steel materials having welded joint CTOD properties at −20°C in addition to the steel material with CTOD properties at −10°C, which had been conventionally demanded as standard until then. To cope with the demand, development of steel material aimed at welded joint CTOD properties at −20°C was planned.

To improve HAZ toughness, it is important to take into consideration the followings; ① to lower HAZ hardness, ② to reduce brit-

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tle phase and, ③ to refine effective grain size in HAZ. Among them in particular, ③ is considered to be most effective means for offshore structure material as compatible improvement of strength and HAZ toughness can be realized without sacrificing strength like with other methods. Ti-O steel has excellent HAZ toughness, and it was intended for Ti oxides; to be refined and made to disperse densely in steel by the deoxidization control in steel-making process, to become the nuclei site in intra-granular transformation in HAZ, to promote formation of IGF (Intra-Granular Ferrite). Consequently, to suppress the formation of competing coarse-transformed microstructure of FSP (Ferrite Side Plate), which is harmful to HAZ toughness and to refine the effective grain size. Therefore, Ti-O steel alone is capable of securing excellent HAZ toughness; however, to secure welded joint CTOD properties at −20°C in a stable manner, further refining of effective grain size in HAZ was tried. Upon studying the subject, attention was directed to the finding that the effective mechanism that develops the formation of IGF from Ti oxides existing in Ti-O steel is the behavior of Ti oxides absorbing Mn in austenite matrix and forming a Mn-depleted zones around it during cooling of HAZ.[5, 6] To fully utilize the characteristic IGF-forming nature of Ti-O steel, effective exploitation of Mn contributing to formation of IGF greatly in Ti-O steel was employed to further promote formation of IGF, and New HTUFF steel was successfully developed wherein further refining of effective grain size was realized.

This means that in Ti-O steel, Mn contributes to the achievement of further refining of effective grain size in HAZ[7] by using, as already known, ① the effect of promoting intra-granular transformation by forming a Mn-depleted zones around a fine Ti oxide inside of a prior austenite grain in HAZ microstructure and ② by compositely utilizing the suppressing effect of Mn on formation of coarse FSP, which is harmful to HAZ toughness with the Mn concentrated on the prior austenite grain boundaries in HAZ microstructure by utilizing the characteristics of Mn that tends to be concentrated on grain boundaries. Such technology is termed as "Effective Manganese Using" (EMU) in Nippon Steel & Sumitomo Metal. Mn is a useful element for improving the strength and toughness of base material steel and has been clarified that with the use of EMU technology, namely the combined use of Mn and Ti-O steel, highly effective functions can be obtained in HAZ toughness. This article reports the results of the development and the actual production. Further, the mechanism of EMU and so on is carried in the Nippon Steel & Sumitomo Metal Technical Report.[8)]

2. Target of Development

Table 1 shows the chemical compositions and prescribed mechanical properties of base material and welded joints of API2W Gr.60[9)] and EN10225 S420[10)] to which TMCP (thermo-mechanical controlled process) steel is applied as for offshore structure steel. Both of them are 50 kg/mm^2 class steel materials of YS 420 MPa class, which are applied to offshore structures in many projects in recent years. In case welded joint CTOD properties are required for

Table 1 Chemical compositions and mechanical requirements of TMCP steel for offshore structure

① Chemical compositions

Spec.		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	Ti	Al	N	B	Ca	C_{eq}	P_{CM}
		(mass%)																	
API2W Gr.60	Min.	–	0.05	1.15	–	–	–	–	–	–	–	*	0.003	0.02	–	–	–	–	–
	Max.	0.16	0.50	1.65	0.03	0.010	0.35	1.0	0.25	0.15	0.03		0.02	0.06	0.012	0.0005	–	0.45	0.25
EN10225 S420	Min.	–	0.15	–	–	–	–	–	–	–	–	–	–	0.015	–	–	–	–	-
	Max.	0.14	0.55	1.65	0.020	0.007	0.30	0.70	0.25	0.25	0.040	0.080	0.025	0.055	0.010	0.0005	0.005	0.42	0.22

*Vanadium shall not be intentionally added without the specific approval of the purchaser.

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

② Mechanical properties of base material

② -1 Tensile test

Spec.	Thickness (t) (mm)	Yield strength (YS) (MPa)	Tensile strength (TS) (MPa)	Elongation (%)	YS/TS ratio (%)
API2W Gr.60	≦ 25	414/621	≧ 517	≧ 22 (GL = 50 mm) ≧ 16 (GL = 200 mm)	–
	25 < t ≦ 100	414/586			
EN10225 S420	≦ 16	≧ 420	500/660	≧ 19 (GL = 5.65 $\sqrt{S}$)	≦ 93
	16 < t ≦ 40	≧ 400			≦ 90
	40 < t ≦ 63	≧ 390	480/640		
	63 < t ≦ 100	≧ 380			

②-2 Charpy V-notch impact test

Spec.	Thickness (t) (mm)	Test temperature (°C)	Location of specimen	Energy (J)
API2W Gr.60	≦ 100	−40	Mid-thick.	≧ 41/48 (min./ave.)
EN10225 S420	≦ 40	−40	Sub-surface	≧ 42/60 (min./ave.)
	40 < t ≦ 100	−40	Sub-surface and mid-thick.	

②-3 Through thickness tensile test

Spec.	Thickness (t) (mm)	Tensile strength (MPa)	Reduction of area (%)
API2W Gr.60	19 ≦ t ≦ 100	–	≧ 30 (min.)
EN10225 S420	25 ≦ t ≦ 40	≧ 400	≧ 25/35 (min./ave.)
	40 < t ≦ 100	≧ 384	

③ **Fracture toughness of welded joints**

Spec.	Charpy test				CTOD		
	Test Temperature (°C)	Location of specimen	Notch location	Energy (J)	Test temperature (°C)	Notch location	Critical CTOD (δ) (mm)
API2W Gr.60	Transition full curve	Quarter-thick. Root	Coarse grain HAZ (CGHAZ) Sub-critical HAZ (SCHAZ)	–	−10	Coarse grain HAZ (CGHAZ) Etched HAZ boundary (Eached HAZ)	(≧ 0.38)
EN10225 S420	−40	Cap Mid-thick. Root	Weld Metal (WM) Fusion Line (FL) FL+2mm (HAZ) FL+5mm (HAZ)	≧ 29/42 (min./ave.)	−10	Weld Metal Grain coarsend HAZ (GCHAZ) Subcritical/Intercritical HAZ boundary (SC/ICHAZ)	– (≧ 0.25)

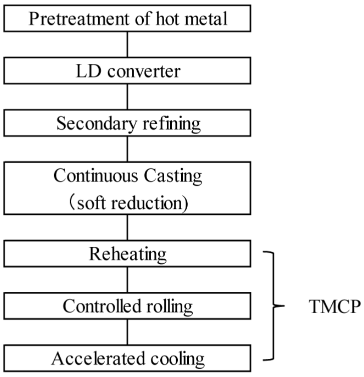


Fig. 1 Manufacturing process

the steel of these standards; conventionally, the specification value at −10°C is guaranteed. However, as temperatures of the environments of offshore structures are going down in recent years and as customers' demand for guaranteeing welded joint CTOD at −20°C were growing, guarantee of welded joint CTOD at −20°C was targeted.

3. Mechanical Properties of Developed Steel

3.1 Chemical compositions and production process

Although various methods are conceivable for securing welded joint CTOD properties at −20°C, the development was based on the application of New HTUFF steel wherein EMU technology of effectively utilizing Mn in Ti-O steel was extensively used. Further, it is needless to mention of the importance of steel making technologies of from refining to solidification which cover deoxidization, nonmetallic inclusion control, center segregation control and so on. However, it is also required to effectively use the micro-alloying technology for the TMCP technology to yield its maximum effect in plate rolling process. Therefore, achievement of higher strength and higher toughness of base material was attempted by, in addition to effectively using Nb and Ti, strictly controlling the various conditions of the process from heating to cooling without unnecessarily increasing chemical compositions, carbon equivalent (C_{eq}), and weld cracking sensitivity compositions (P_{CM}).

Figure 1 shows the manufacturing process, and **Table 2** shows typical chemical compositions. In the casting process, purity of high degree is secured as a matter of fact, and furthermore, soft reduction is applied by split rolls as countermeasures for center segregation. Production conditions of TMCP from heating to accelerated cooling were optimized and strictly controlled. In the heating process, the heating temperature was controlled to optimized temperature so that the added Nb sufficiently solid-dissolves and coarsening of heated austenite grain is suppressed by Ti(C,N).

Table 2 Typical chemical compositions of New HTUFF steel

(mass%)						Others	(mass%)
C	Si	Mn	P	S	Al		P_{CM}
0.07	0.17	1.93	0.004	0.003	0.001	Cu,Ni,Nb,Ti	0.19

Table 3 Measures of improving HAZ toughness

Measures	Purpose
Ti-killed and fix the nitrogen	Improving matrix toughness and nucleation IGF
Low silicon	Decreasing local brittle zone (MA)
Low carbon	Decreasing HAZ hardness
Low aluminum	Enhancing nucleation IGF and decreasing local brittele zone (MA)
Control the TiN balance	Suppressing TiC embrittlement
Low impurity elements	Improving matrix toughness and decreasing local brittle zone
Low P_{CM}	Improving matrix and HAZ toughness
Effective manganese using	Suppressing formation of harmful microstructure (FSP)

Table 3 shows measures for improving HAZ toughness. Although to secure the welded joint CTOD properties at −20°C, refining of HAZ microstructure is considered to be important, however, in this development, the following were attempted by applying New HTUFF steel wherein EMU is thoroughly exploited: ① to refine effective grain in the microstructure in the neighborhood of the welding fusion line to the extent finer than the grain size of conventional steel, ② to decrease Si content and to eliminate use of Al to reduce MA (Martensite-Austenite constituent), and ③ to optimize Ti-N composition balance based on chemistry stoichiometry to avoid embrittlement by TiC.

4. Examples of Application to Steel Plate for Offshore Structure

4.1 Mechanical properties of base material

Development of New HTUFF steel conforming to welded joint CTOD properties at −20°C was completed in 2013 and after the completion of the development, the steel was applied to guarantee the welded joint CTOD properties at −10°C and production started. In **Fig. 2**, results of the tensile test, in **Fig. 3**, results of Charpy impact test of the base material and, in **Fig. 4**, the result of through thickness tensile test are respectively shown. Conformity to prescribed mechanical properties of strength, base material toughness and through thickness tensile properties (reduction of area: RAz)

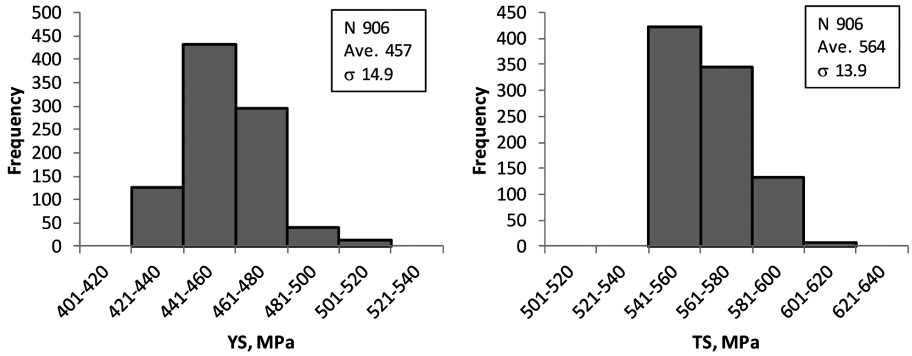


Fig. 2 Mechanical properties of base material (tensile test) (60 ≦ t ≦ 100 mm)

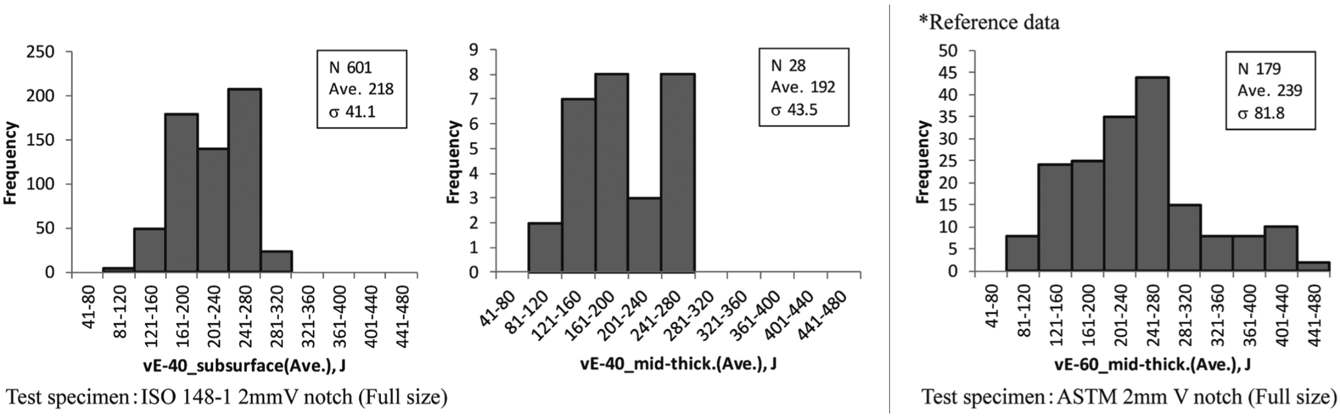


Fig. 3 Mechanical properties of base material (Charpy impact test) (60 ≦ t ≦ 100 mm)

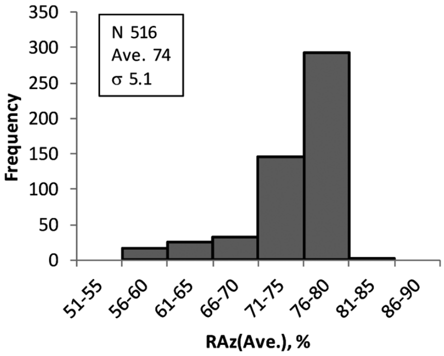


Fig. 4 Mechanical properties of base material (through thickness tensile test) (60 ≦ t ≦ 100 mm)

was confirmed. With respect to base material toughness, the following were found: ① The base material exhibits excellent subsurface impact value of about 220 J and 190 J in the mid-thickness of the plate at the conventionally requested test temperature of −40°C and further, ② Excellent results were also obtained at the test temperature of −60°C. **Figure 5** shows the microstructure of a plate of 100 mm in thickness. Owing to optimization of TMCP conditions and strict control thereof, the entire thick steel plate of 100 mm in thickness consists of a fine ferrite–bainite microstructure and thereby, excellent mechanical properties of base material could be obtained.

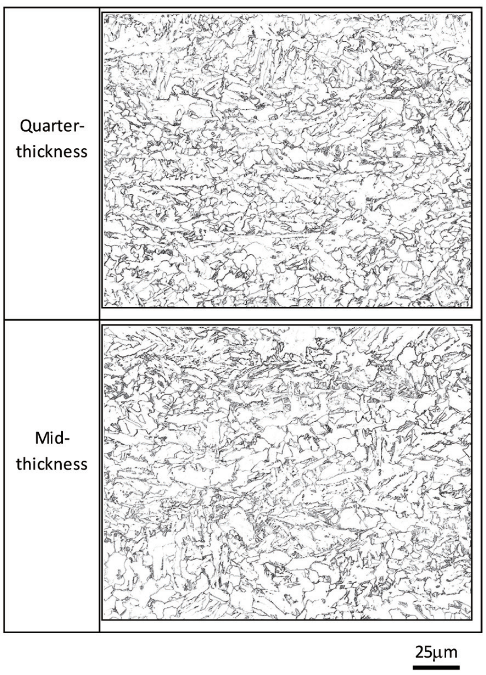
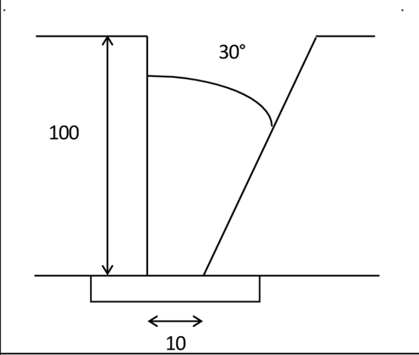
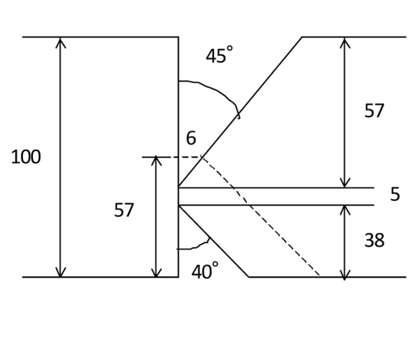


Fig. 5 Microstructures of base material (t = 100 mm)

4.2 Mechanical properties of welded joint

Mechanical properties of welded joints were assessed, using steel plates of 100 mm thickness. Welding conditions are as shown in **Fig. 6**, which conform to API RP 2Z [11] applied to offshore struc-

Welding method	SAW / multipass welding		FCAW / multipass welding
Groove profile (Unit:mm)			
Welding wire	Y-D (4.8ϕ)*1		SF-50L(1.2ϕ)*1
Flux	NB-55L*1		-
Shielding gas	-		80%Ar-20%CO_2
Current (A)	750	650	280
Voltage (V)	32	28	26
Speed (mm/s)	320	360	380
Heat input (kJ/mm)	4.5	3.0	0.8

*1 Nippon Steel & Sumikin Welding Co., Ltd.

Fig. 6 Welding conditions

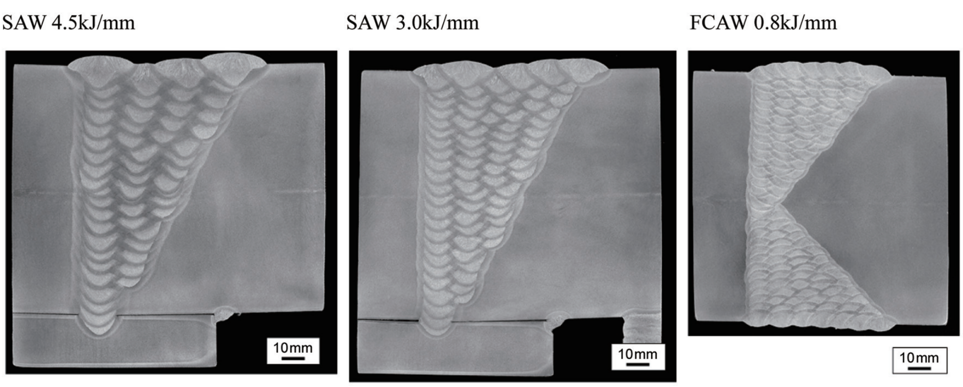


Fig. 7 Macrostructures of welded joints

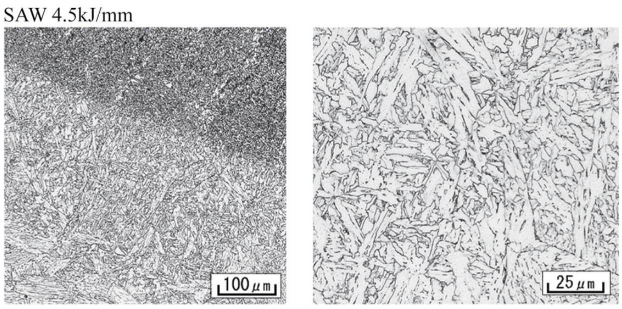


Fig. 8 Microstructures of welded joint

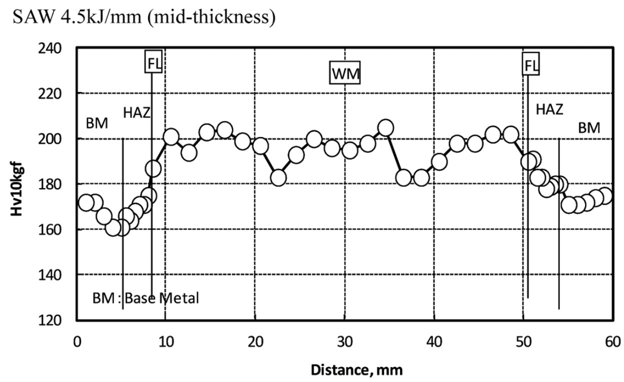


Fig. 9 Hardness distribution accross the welded joints

tures. Actually welded following joints were prepared and mechanical properties after welding was assessed: ① Flux Cored Arc Welding (FCAW) with heat input (HI)=0.8 kJ/mm, ② Submerged Arc Welding (SAW) with HI=3.0 kJ/mm and ③ SAW with HI=4.5 kJ/mm. **Figure 7** shows the macrostructures of the welded joints and **Fig. 8** shows the microstructures of the SAW-welded joint with HI=4.5 J/mm. The targeted microstructure in which a fine IGF is formed within a coarse austenite grain, characteristic to New HTUFF steel, was confirmed. **Figure 9** shows hardness distribution across the weld joint. It is known that drop in hardness in HAZ is

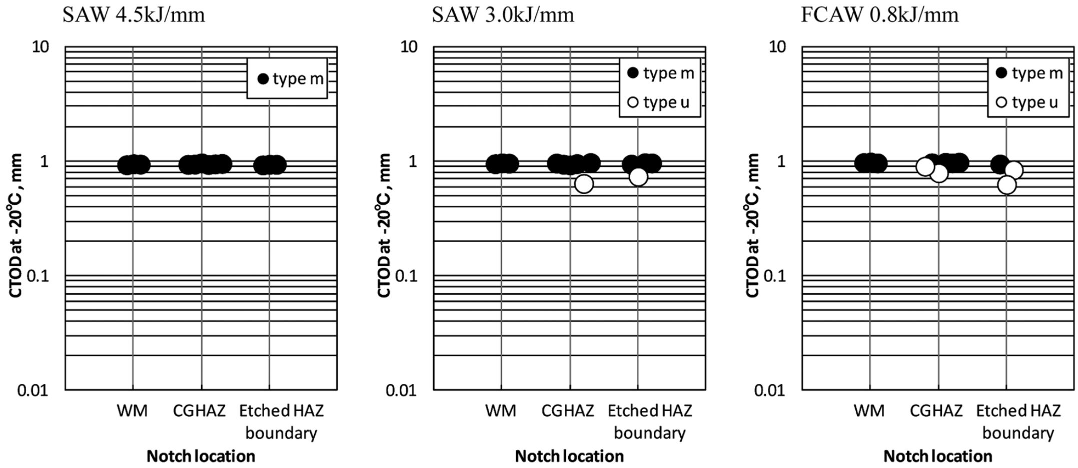


Fig. 10 CTOD test results of welded joints

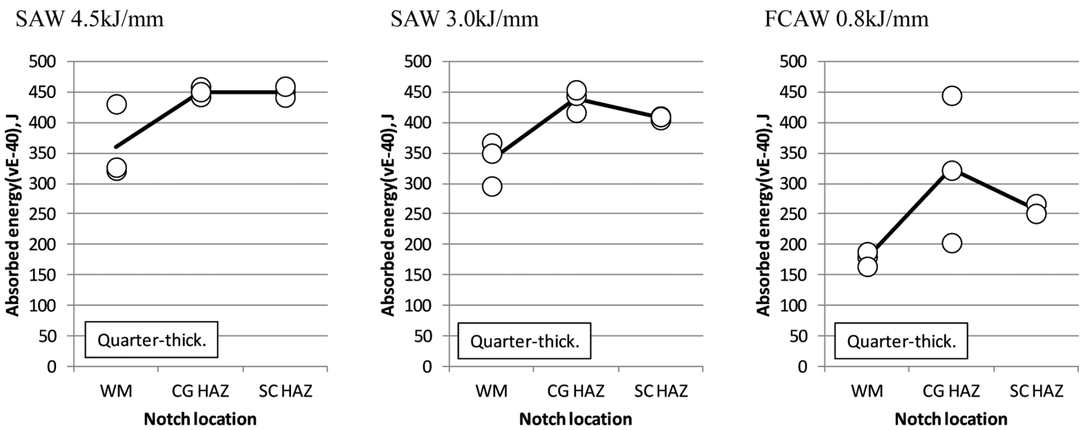


Fig. 11 Charpy impact test results of welded joints

small and the weld metal (WM) hardness exceeds well the hardness of base material.

Figure 10 shows CTOD test results of welded joints conducted at the test temperature of −20°C. Notch locations conform to API RP 2Z [11] and notches are located at Coarse Grain HAZ (CGHAZ), Etched HAZ boundary, which appears when the weld joint section is etched with an appropriate etching agent and weld metal part whose welded joint is assessed. For all heat input levels at all notch locations, highly excellent CTOD properties far exceeding the aimed value (δ=0.38 mm) even at the test temperature of −20°C was obtained. **Figure 11** shows the results of weld joint Charpy impact test at −40°C. Under any welding conditions, excellent low temperature characteristics sufficiently satisfying the prescribed value was exhibited.

4.3 Weldability

Weldability of New HTUFF steel was also studied by Controlled Thermal Severity (CTS) test [10] and y-groove weldability test.[12] Partly due to the subject steel plate being a low P_{CM} steel, cracking did not occur in all tests under the condition of free of preheating and excellent weldability was exhibited (**Tables 4**, **5**).

Table 4 CTS weldability test results

Preheat temperature (°C)	Hardness HV load: 5kgf			Crack evaluation
	Min.	Max.	Ave.	
25	277	317	293	No cracking
50	271	301	288	No cracking
75	261	311	288	No cracking

SMAW : 1.0 kJ/mm

5. Conclusion

Steel of YS 420 MPa class of 100 mm in thickness guaranteed for welded joint CTOD properties at −20°C was successfully developed by applying EMU technology together with full exploitation of TMCP technology and micro-alloying technology and the production of the subject steel material already started and excellent mechanical properties of base material and welded joints are exhibited.

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Table 5 y-groove weldability test results

Preheat temperature (°C)	Surface craking ratio (%)						Section craking ratio (%)						Root craking ratio (%)					
	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

SMAW: 1.7 kJ/mm
Atmosphere: 28°C, 71% humidity

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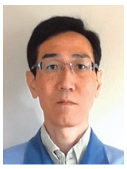
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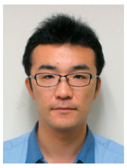
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