Development and realization of large scale LNG storage tank applying 7% Nickel steel plate

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1. BACKGROUND AND AIMS

Figure 1 Appearance of 180Ml class LNG tank

Increase of natural gas demand led the increase of constructions of Liquefied Natural Gas (LNG) storage tanks worldwide. The inner tank material for above ground LNG storage tanks has mostly been made of 9%Ni steel plate over the last 50 years as it has excellent mechanical properties under the cryogenic temperature of -160deg.C. During this period, the LNG storage tanks made of 9%Ni steel plate have safely been operated. Meanwhile, technologies of steel making, welding, design, construction and inspection of 9%Ni steel plate have been improved significantly and enable us to achieve enlarging volumetric capacity of the tank to 2-3 times（Figure 1）.

As the global LNG demand remains high, construction of LNG storage tanks is expected to continue to increase in the future. 9%Ni steel plate[1-5] has generally been used as an inner tank component of aboveground LNG storage tanks for the last half century. It is well known that excellent cryogenic fracture toughness of high nickel alloy steel plates are attributed to the retained austenite and the refinement microstructure obtained by nickel content and heat treatment process. The newly developed 7%Ni-TMCP steel plate[6-7] adopts a Thermo-Mechanical Control Process (TMCP) to succeed in obtaining the refinement microstructure and the retained austenite which bring equivalent fracture resistance to equivalent to the conventional 9%Ni steel plate[6] with a 2% nickel content reduction. Reduction of the nickel content significantly contributes to saving natural resources as well as to mitigating anticipated rising construction cost due to significant fluctuations in nickel price.

In this paper, metallurgical basis of 7%Ni-TMCP steel plate is re-considered in view points of improving toughness of both base metal and welded joints. This paper also reports the results of large scale fracture toughness tests conducted for assessing the safety performance of the LNG storage tank made of 7%Ni-TMCP steel plate and comparing with the study results made on the conventional 9%Ni steel plate, including the studies on the large capacities LNG storage tanks with heavy thickness plates. Additionally fracture toughness test results of repair welding, physical constants, fatigue properties and so on are reported in order to apply new material developed to actual LNG storage tanks.

Through these series of co-operative research and development, Osaka Gas decided in 2011 to construct a new 230,000m^3 LNG storage tank applying 7%Ni-TMCP steel plate in Senboku terminal 1.

2. METALLURGICAL BASIS OF 7%NI-TMCP STEEL PLATE

In order to ensure the safe operation of LNG storage tanks, resistance to brittle fracture should be considered both in arrest of propagating cracks in the base plate and in brittle crack initiation especially in the heat affected zone (HAZ) as shown in Figure 2.

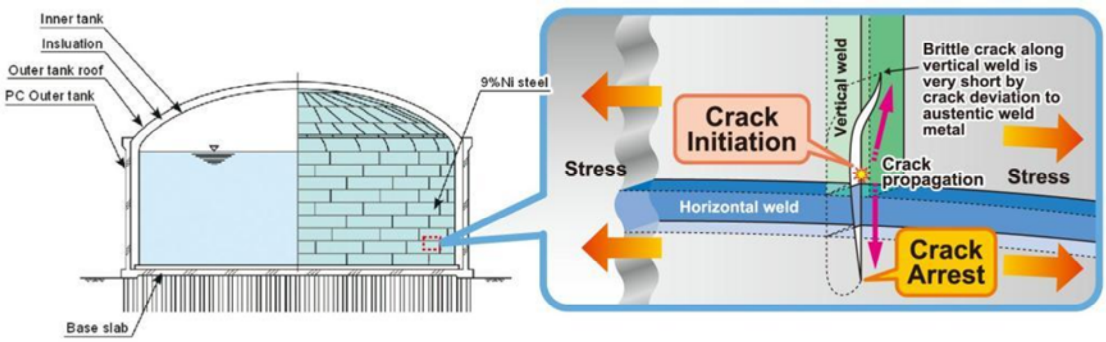


Figure 2 Requisite properties for material of LNG tank

2.1 Mechanism of Improving Arrestability of Base Metal

TMCP with large reduction just above A_{r3} is known as an effective process for enhancement of toughness due to refinement of microstructure[6)-7),10)]. The TMCP with an addition of intermediate heat treatment could achieve finer microstructure for 7%Ni steel plate production (Figure 3).

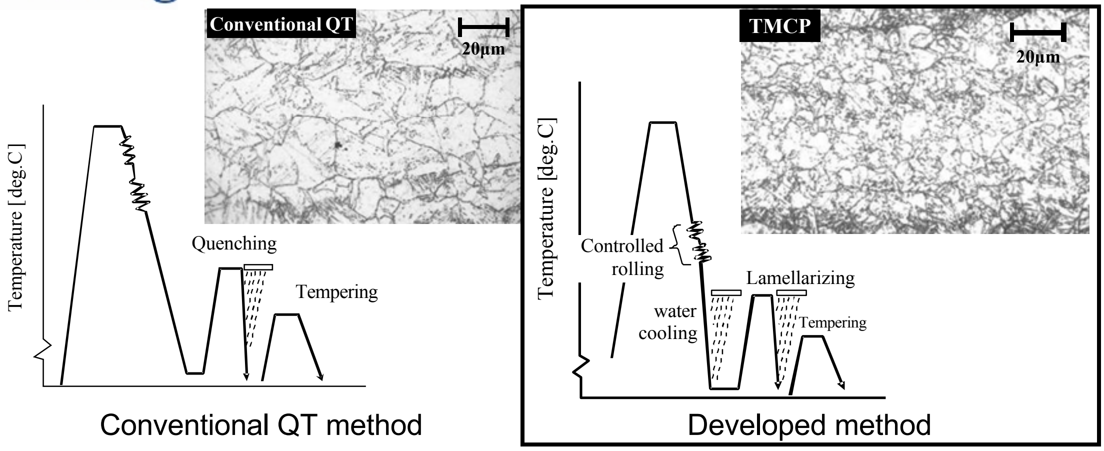


Figure 3 Generals of production process and typical microstructure

Retained austenite is also known to contribute for improving toughness of high nickel steels. As nickel depresses M_s transformation temperature and serves to stabilize austenite thermally, the decrease of nickel generally reduces retained austenite fraction. However, it is clearly shown that 7%Ni-TMCP steel plates achieve higher retained austenite volume than that of quenched and tempered 9%Ni steel plate (Figure 4)

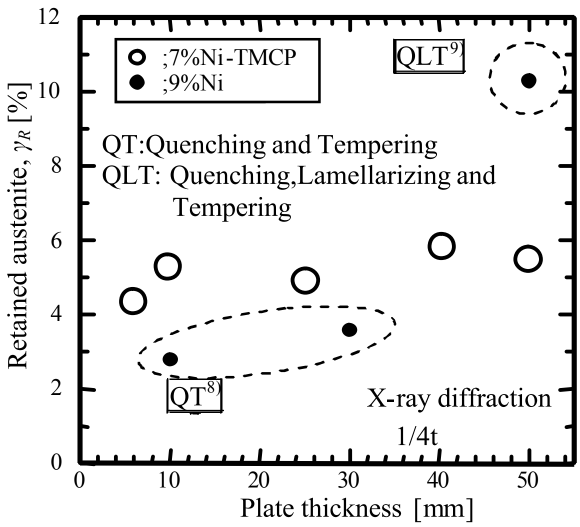


Figure 4 Evaluation result of retained austenite

Finer microstructure and more retained austenite results in improving arrestability of 7%Ni-TMCP steel plates. This property is evaluated as follows.

Dynamic Tear (DT) tests compliant with ASTM E604[11] were performed for estimation of brittle crack arrest toughness[12]. The DT absorbed energy at -196 deg. C shows more than 1900J (Table 1). Shear area of fracture surface is more than 95%. These results indicate excellent resistance to brittle crack propagation.

Table 1 DT test results

Thick. [mm]	Temp. [deg.C]	Absorbed energy [J]	Shear area [%]
25	-196	2407	95
		2355	97
		2615	100
40		2693	100
		2510	100
		2823	100
50		2433	100
		1968	100
		2510	100

Furthermore, Duplex ESSO tests (Figure 5) were performed under the applied load of 393 MPa at -196 deg.C to directly evaluate the arrest toughness. Results of 25 mm, 40 mm and

50mm thick plate specimens showed “No-Go” as summarized in Table 2. Figure 6 shows fracture surface of Duplex ESSO test for 50mm thickness, as an example.

Table 2 Duplex ESSO test results

Thick. [mm]	Aimed temp. [deg.C]	Applied stress [MPa]	Arrested crack length [mm]	Temp. at Arrested point [deg.C]	Judgment*
25	-165	393	150.9	-177	No-Go
40		393	153.7	-167	No-Go
		393	152.0	-170	No-Go
50		393	160.0	-172	No-Go
		393	155.0	-169	No-Go
25	-196	393	150.8	-196	No-Go
40		393	151.6	-196	No-Go
50		393	174.0	-194	No-Go
		393	189.0	-196	No-Go

*No-Go ; Crack propagation was arrested at test plate within t (plate thick.)

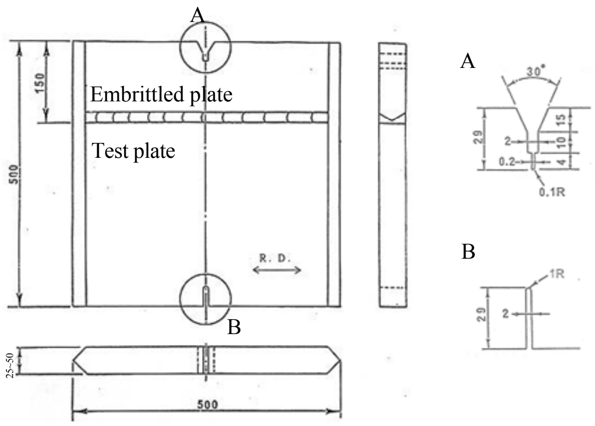


Figure 5 Duplex ESSO specimen

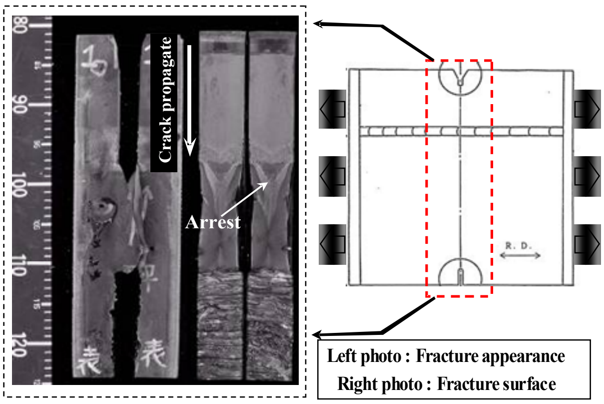


Figure 6 Example of fracture surface of duplex ESSO test (50mmt, -196deg.C)

2.2 Mechanism of Improving Brittle Crack Initiation Resistance

For 7%Ni-TMCP steel plate, brittle crack initiation resistance of welds was investigated. Table 3 provides chemical composition of steels prepared.

Table 3 Chemical composition of steels [mass%]

Mark	C	Si	Mn	Ni	Cr	Mo
Ni simply decreased 7%Ni	0.06	**0.25**	1.20	**7.0**	Tr.	Tr.
Decrease Si and Cr bearing 7%Ni developed	0.05	**0.05**	0.80	**7.1**	**0.41**	0.04
Conventional 9%Ni [7)]	0.05	0.22	0.65	9.2	Tr.	Tr.

Crack initiation property was evaluated by three point bend Crack Tip Opening Displacement (CTOD) testing compliant with BS7448[13)] at Fusion Line (FL) and at weld toe where Gas Tungsten Arc Welding (GTAW) was employed with 70% nickel welding consumables as same as in case of 9%Ni steel plate welding.

Figure 7 shows CTOD test results. Critical CTOD values of decrease Si and Cr bearing steel range in those of conventional 9%Ni steel plate , not only at FL but also at toe. On the other hand, Ni simply decreased steel had low critical CTOD value at toe.

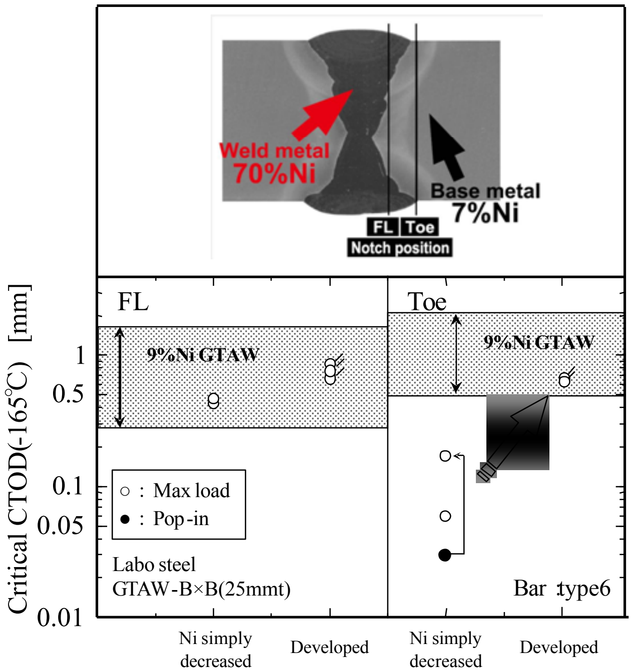


Figure 7 Improvement of CTOD property in welded joint by decrease of Si and Cr bearing

To improve HAZ toughness it should be effective to optimize hardenability of the steel, considering HAZ microstructure tempered by welding cycles[14]. "Tempering" is known as an effective process to precipitate cementite particles in microstructure of steel and mitigate the hardness of matrix to suitable level. However weld toe portions are not tempered due to absence of following passes. Therefore chemical composition should be considered so that microstructure of toe portion is automatically tempered even without following welding passes. It is known that lowering Si content is effective for auto-temper phenomenon at Coarse grained HAZ (CGHAZ) and for decreasing Martensite-Austenite constituent (MA) in Inter-critical coarse grained HAZ (ICCGHAZ)[15]. Cr is also effective to raise hardenability without inhibition of formation of retained austenite.

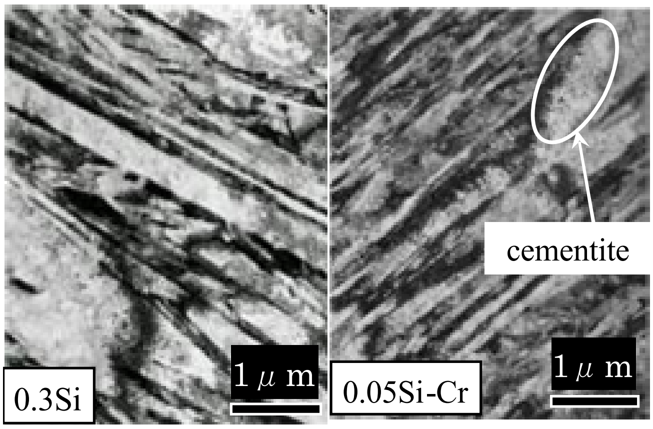


Figure 8 Auto-temper phenomenon in HAZ by decrease Si and Cr bearing

Figure 8 shows HAZ microstructure of 7%Ni-TMCP steel plate with decrease Si and Cr bearing, where Cementite pricipitation is observed.

Figures 9 and 10 show simulated HAZ conditions and Charpy impact test results. vTs, transition temperature from ductile-to brittle in Charpy impact test, was estimated from fracture appearances of Charpy tests at several temperatures. Both at CGHAZ and at ICCGHAZ, vTs of 7%Ni-TMCP steel plate is equivalent to that of 9%Ni steel plate. The reason of superior HAZ toughness of 7%Ni steel plate in spite of Ni reduction by 2% is considered to be attributed to lowering Si.

Targetcondition	1st peak T1 [deg.-C]	2nd peak T2 [deg.-C]
CG HAZ	1400	--
ICCG HAZ	1400	675
	1400	700
	1400	720
	1400	750

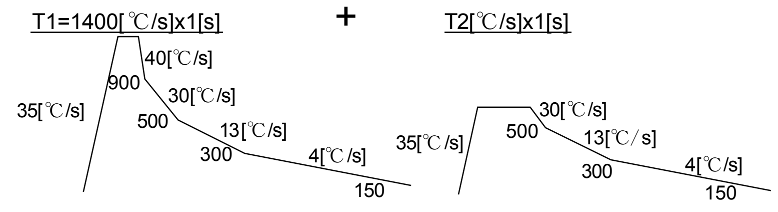


Figure 9 Heat cycle conditions of simulated HAZ

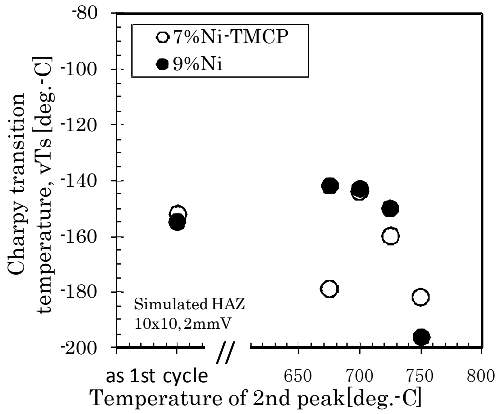


Figure 10 Charpy impact test result of simulated HAZ

3. COMPARISON OF PROPERTIES OF 7%NI-TMCP STEEL PLATE WITH THOSE OF 9%NI STEEL PLATE

In order to evaluate fitness of 7%Ni-TMCP steel plate and its weld for LNG storage tanks, a series of tests were conducted. Several different kinds of plate thicknesses from 6 to 50 mm were chosen to run large scale fracture toughness tests such as duplex ESSO tests, cruciform wide plate tests as well as small scale tests. As a result, it was demonstrated that 7%Ni-TMCP steel plate and its welded joints have quite excellent resistance to brittle fracture as the inner tank, exposed to the cryogenic temperature of LNG.

Table 4 shows the test items conducted to evaluate fitness of 7%Ni-TMCP steel plate and its welded joints for inner tank of LNG storage tanks. The evaluation program is set to be the same as a previous study in order to evaluate 38~55 mm heavy thick 9%Ni steel plate[8)-9)]. Test plate thicknesses were 6, 10, 25, 40 and 50 mm, which covered mass production thickness range of steel for large scale LNG storage tanks.

Table 4 Evaluation program

Thick. [mm]	Subject	Basic mechanical test	Fracture toughness test
6 10 25 40 50	Base metal	Chemical compositions, Macrostructure, Microstructure, Sulfur print, Non-metallic inclusions, Hardness, Side bend test, Tensile test, Low temp. tensile test, 2mmV Charpy test Strain aged Charpy test	CTOD test*, Dynamic tear test ***, Duplex ESSO test ***
	Welded joint	Macrostructure, Microstructure,Hardness, Longitudinal bend test, Tensile test, 2mmV Charpy test	CTOD test*, Cross weld notched wide plate test**
25	Repair welded joint	Tensile test, 2mmV Charpy test	CTOD test

*other than 6mm thickness, **other than 10mm thickness,
***other than 6 and10mm thickness

3.1 Results of Basic Mechanical Tests on Base Metal

Table 5 shows results of chemical composition analysis. Impurity elements are kept to be very low by the latest steel making technology. Table 6 shows results of tensile tests and Charpy impact tests. All of them met the requirements of ASTM A553M-Type1.

Figure 11 shows strain-aged Charpy Impact test results. Absorbed energy indicates excellent value after 5% strain-aged treatment.

Table 5 Chemical compositions [mass%]

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Sol.Al
Ladle	0.05	0.05	0.80	0.001	0.001	0.03	7.13	0.41	0.04	0.030

Table 6 Results of tensile test and Charpy impact test

Thick. [mm]	Tensile property(avg.)				Charpy impact property(avg.)			
	Posi.	Dir.	*0.2YS* [MPa]	*TS* [MPa]	Posi.	Dir.	vE_{-196} [J]	*BA* [%]
6	Full	T	630	720	1/4t*	L	110*	0
10	Full	T	681	741	1/4t**	L	179**	0
25	1/4t	T	648	713	1/4t	L	259	0
40	1/4t	T	635	715	1/4t	L	255	0
50	1/4t	T	655	733	1/4t	L	237	0
ASTM A553M Type1	-	-	585 min.	690 /825	-	-	≧21(6mm) ≧26(10mm) ≧34(25~50mm)	-

* 1/2 sub size specimen ** 3/4 sub-size specimen

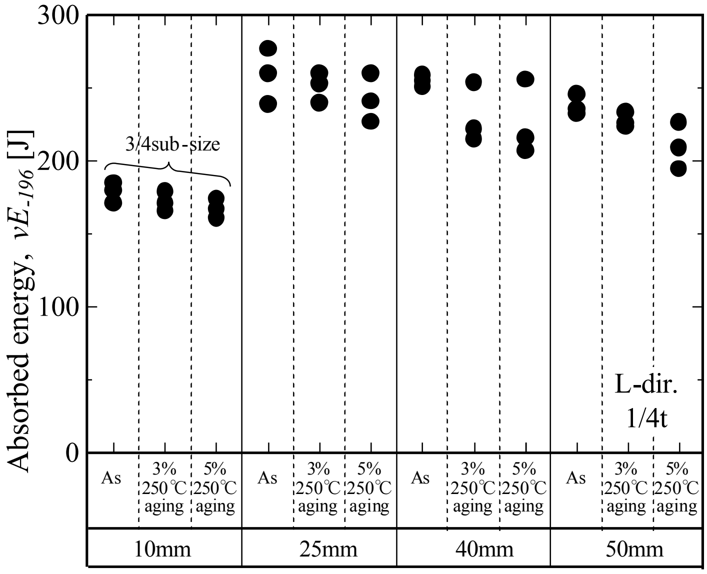


Figure 11　Strain aged Charpy impact test results

3.2 Brittle Crack Propagation Properties

DT test was performed as simplified estimation method for propagation property. As shown in Figure 12, absorbed energy of 7%Ni-TMCP steel plate is superior to that of 9%Ni steel plate.

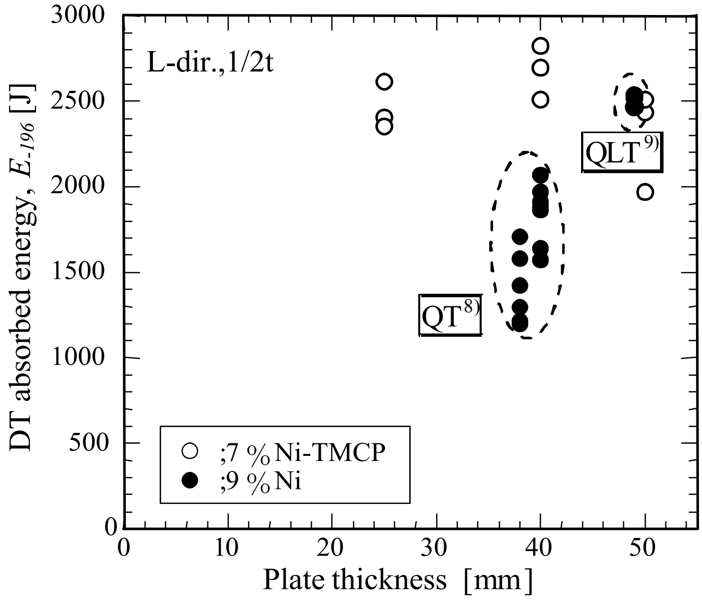


Figure 12　Comparison of DT test results between 7%Ni-TMCP steel plate and 9%Ni steel plate

Duplex ESSO test (Table 7) resulted in “No-Go” under loading 393 MPa at -196 deg.C, which is severer condition compared to the actual operation. The reason why 7%Ni-TMCP steel plate has superior propagation property in spite of lowering nickel by 2% is thought to be effect of retained austenite produced by TMCP with intermediate heat treatment.

Table 7. Comparison of duplex ESSO test result between 7%Ni-TMCP steel plate and 9%Ni steel plate

Steel	Process	Thick. [mm]	Dir.	Temp. [deg.C]	Applied stress [MPa]	Judgment
7%Ni -TMCP	TMCP	25mm	L	-196	393	No-Go
		40mm	L	-196	393	No-Go
		50mm	L	-196	393	No-Go
9%Ni	QT[8]	40mm	L	-196	393	No-Go
	QLT[9]	50mm	L	-196	393	No-Go

3.3 Results of Basic Mechanical Tests on Welded Joints

Welded joints of 7%Ni-TMCP steel plates were prepared in three different welding methods, those are SMAW, GTAW and SAW (Table 8). V groove in case of 6 and 10mm thick plate and double-V groove in case of 25, 40 and 50mm were applied for edge preparation similar to actual tank fabrication. 70% nickel type welding consumables were used. Thus, welding conditions including the edge preparations and the welding consumables are all the same as those of the actual fabrications using 9%Ni steel plates.

Table 8 Welding conditions

Thick. [mm]	Welding Method	Welding material	Position of weld	Max. Heat Input [kJ/mm]
6	SMAW	70%Ni type	Vertical	3.1
10-50	SMAW	70%Ni type	Vertical	4.8
	GTAW		Vertical	4.4
	SAW		Horizontal	2.0

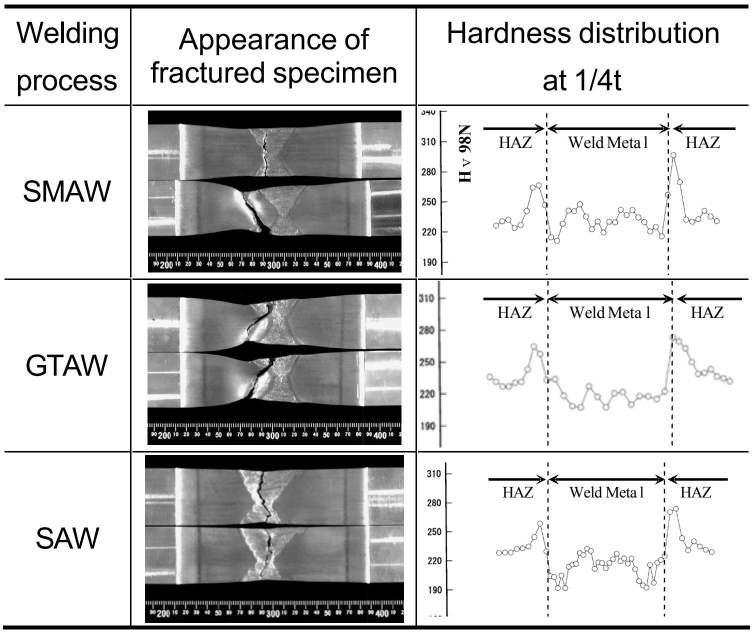
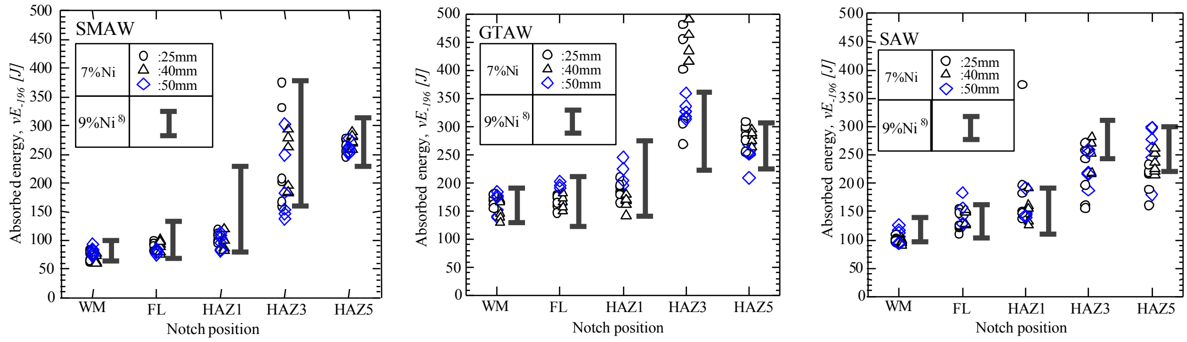


Figure 13 Appearance of fractured specimen of tensile test of welded joints and Vickers hardness distributions (50mm)

Tensile tests of welded joint were performed with ISO 6892[16] specimen. In every thickness and welding condition, tensile strengths show more than 690 MPa which is specified minimum value of A553M-Type1. Fractured appearances of tensile test of welded joint and Vickers hardness in case of 50 mm are exemplified in Figure 13. Fracture path run through or across weld metals corresponding to that the hardness distributions provided a typical profile of an under-matching welded joint[17)-18)].

Figure 14 shows comparison of Charpy impact properties of welded joints. Absorbed energies of 7%Ni-TMCP steel plate are comparable to 9%Ni steel plate in all notch locations and welding conditions.



(a) SMAW (b) GTAW (c) SAW

Figure 14 Comparison of Charpy test results of welded joint between 7%Ni-TMCP steel plate and 9%Ni steel plate

3.4 Brittle Crack Initiation Properties

Figure 15 shows comparison of the critical CTOD of the base plate between 7%Ni-TMCP steel plate and 9%Ni steel plate. Both longitudinal and transverse critical CTOD values of 7%Ni-TMCP steel plate are comparable to 9%Ni steel plate. Critical CTOD values increase as the ligament of specimen get greater corresponding to the plate thickness.

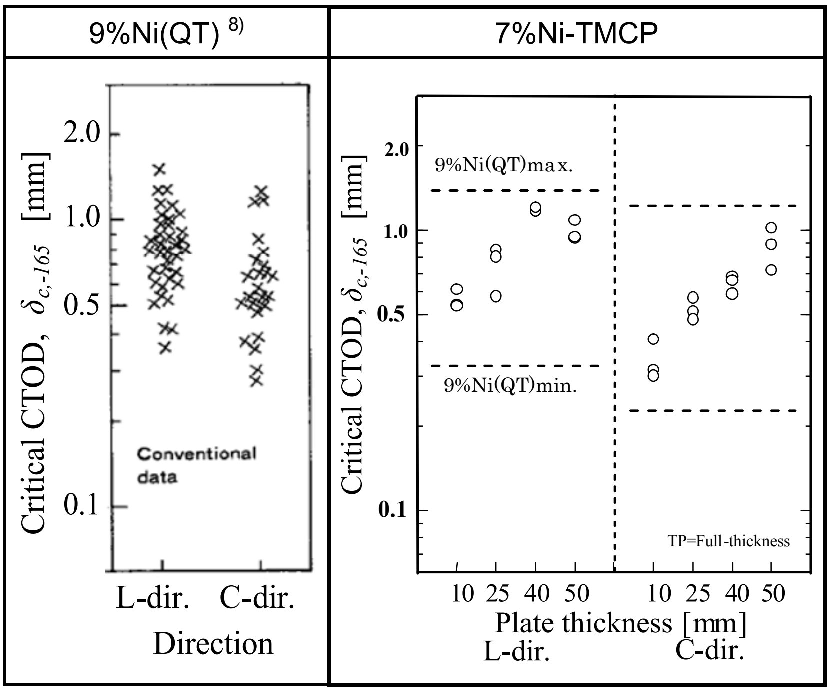
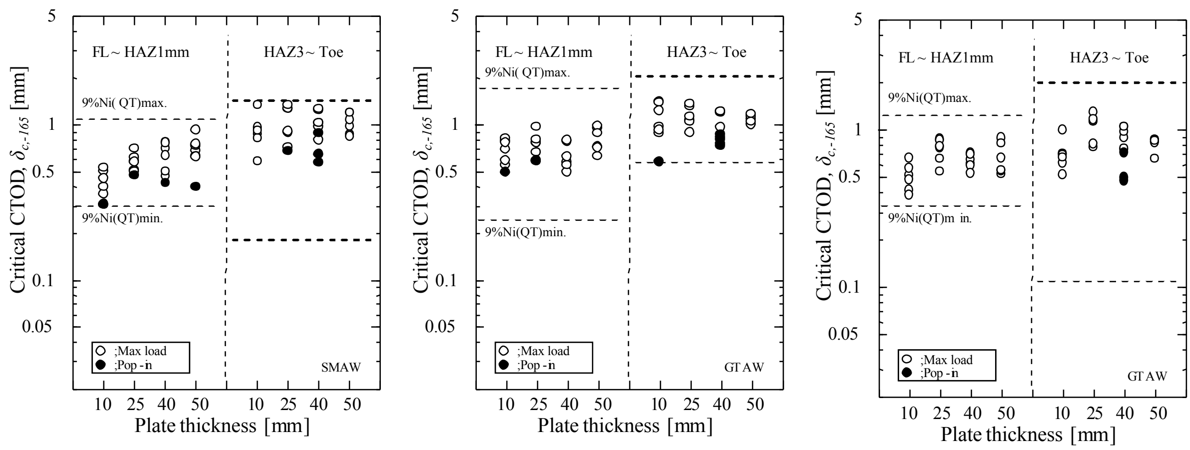


Figure 15 Comparison of CTOD test results of base plate between 7%Ni-TMCP and 9%Ni Steel (Thickness of 9%Ni ; 10mm-50mm)

Comparison of the critical CTOD values of welded joints is shown in Figure 16 except for the fully ductile weld metal. All results including pop-ins are distributed within the range of 9%Ni steel plates' CTOD test results.



(a) SMAW (b) GTAW (c) SAW

Figure 16 Comparison of CTOD test results of welded Joint between 7%Ni-TMCP steel plate and 9%Ni steel plate

Furthermore, cross weld notch wide plate tensile tests were conducted to evaluate safety of the T-cross welded joint of LNG storage tanks. Test specimen and notch location are shown in Figure 17. Through thickness notch was prepared along the vertical weld at the intersection of welds. The radius of tip was sharpened to 0.1mm by electro discharge machining. For 25, 40 and 50mm thick plate, the length of the notch was double of the plate thickness c. For 6mm thick plate, the length was 36mm. Figure 18 shows cross section of the welds. FL is defined as the position that the portion of weld metal is 50% to notch depth.

Vertical welding were performed by GTAW or SMAW according to actual tank fabrication, while horizontal welding were performed by SAW. Test temperature is set to be -165 deg.C, which is design temperature of LNG tank.

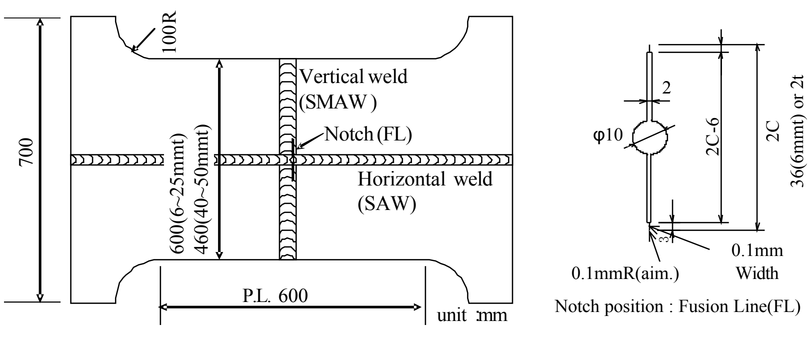


Figure 17 Specimen of cross weld notch wide plate test

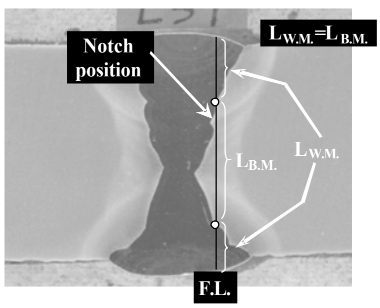


Figure 18 Cross section of notch

The test results are shown in Table 9. Fracture net stresses of all specimens were more than 750 MPa and much higher values than 400 MPa, which is the design stress based on huge scenario earthquake. All specimens were fractured in a ductile manner and no brittle pop-in was observed. Cracks initiated at the HAZ deviated into weld metal with no exception in all specimens (Figure 19 as an example). Considering the fracture stress, it is concluded that initiation and propagation of fracture occurs almost after yielding of the ligament section so there is a very high safety against fracture.

Table 9 Results of cross weld notch wide plate tensile test

Thick. [mm]	Welding method	Dimension		Notch		Temp. [deg.C]	Fracture stress [MPa]		Critical CTOD δ_c [mm]	
		Thick. [mm]	Width [mm]	Posi.	Len. [mm]		σ_{gross}	σ_{net}	Upper	Lower
6	SMAW	6.43	600	FL	36	-166	723	822	1.022	1.254
25	GTAW	26.2	600	FL	50	-167~-181	689	752	3.638	3.788
	SMAW	26.4	600	FL	50	-168~-185	693	756	2.862	3.615
40	GTAW	40.5	460	FL	80	-165~-179	634	768	0.908	1.074
	SMAW	41.6	460	FL	80	-166~-179	671	812	0.956	1.005
50	GTAW	51.9	460	FL	100	-163~-173	631	807	1.910	2.067

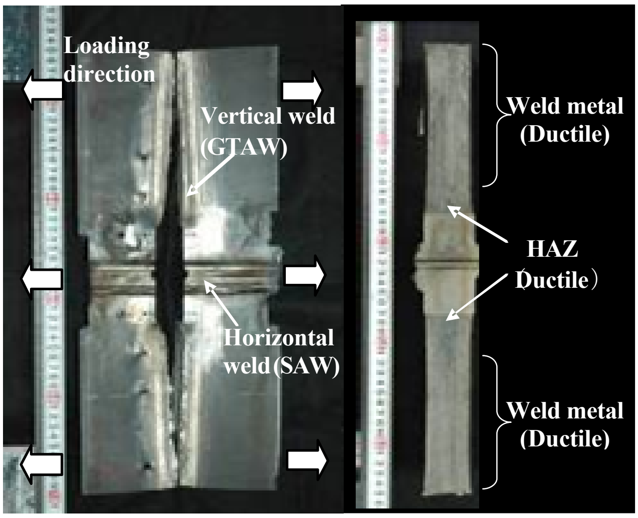


Figure 19 Fracture path and fracture surface of cross weld notch wide plate test (50mmt, GTAW)

Furthermore, comparison of the net stresses of the cross weld notch tensile tests is shown in Figure 20. The net stresses of 7%Ni-TMCP steel plate seems to be comparable to that of the 9Ni steel plate. As all specimens showed a ductile fracture manner in those of austenitic weld metal, a brittle fracture property cannot be evaluated (or compared). It can be said that the welded joints of 7%Ni-TMCP steel plate has a quite high safety against brittle fracture as same as that of 9%Ni steel plate.

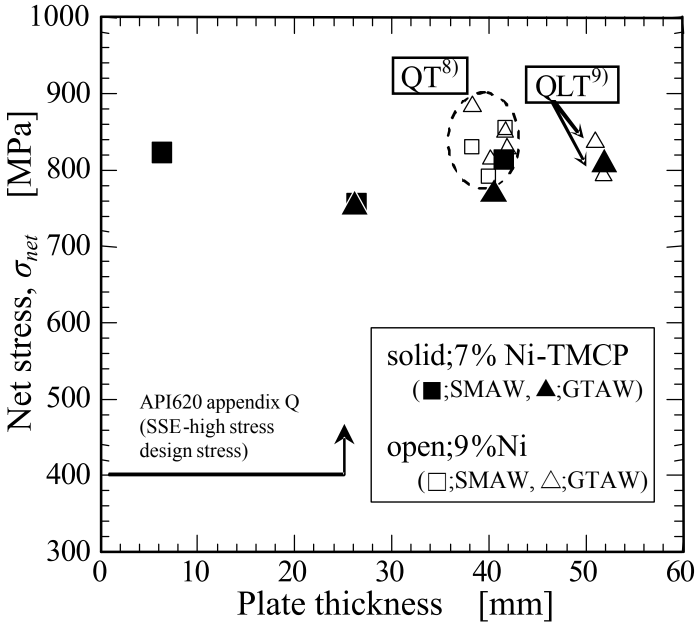


Figure 20 Comparison of net stresses of cross weld notch wide plate test between 7%Ni-TMCP steel plate and 9%Ni steel plate

3.5 Influence of dilution from base metal to weld metal

Weld metal compositions may be influenced by Ni reduction of base metal. So quantification of dilution of chemical composition of base metal was investigated with EPMA, shown in Figure 21. Ni content was detected by every 25μm. This EPMA test results that Ni reduction of base metal by 2% does few influence on Ni content of weld metal. Additionally Charpy impact test of weld metal was performed at 1mm inside from FL. Charpy impact test also results that weld metal toughness is not influenced by Ni reduction of base metal.

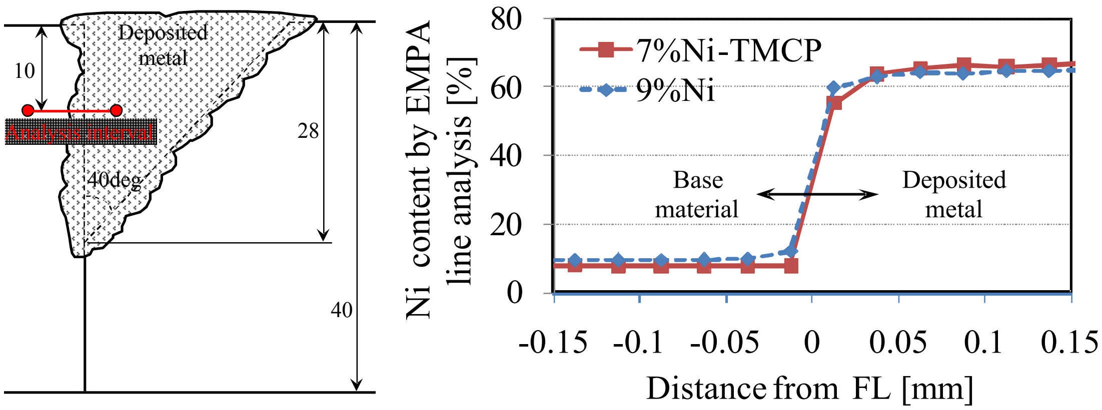
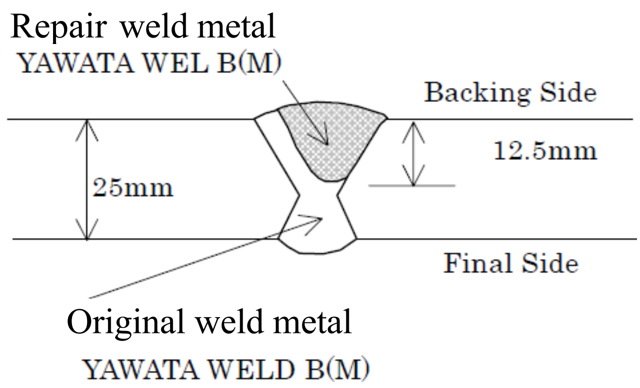


Figure 21 EPMA test results for quantification of dilution of chemical compositions of base plate to weld metal

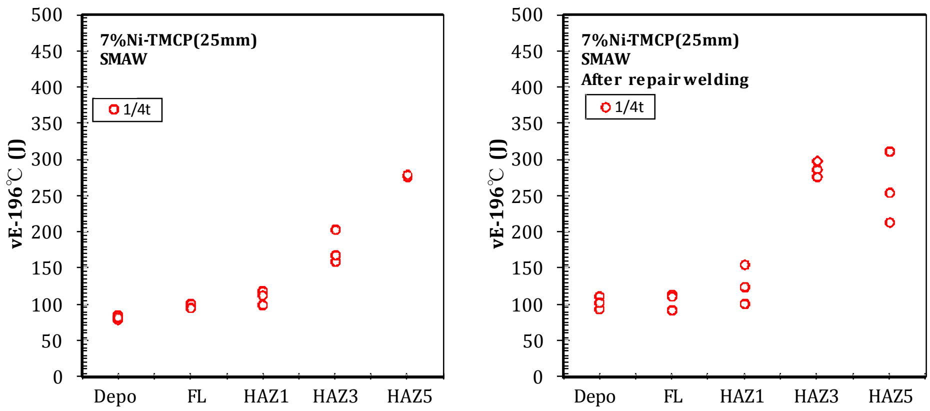
4. PROPERTIES OF REPAIR WELD OF 7%Ni-TMCP STEEL PLATE

As repair welding is a likely process in constructing LNG tank, three-cycle repair welding was simulated for 25 mm thick 7%Ni-TMCP steel plate. Before each cycle of repair welding, groove was prepared by gouging and grinding along FL, considered to be the severest portion of welded joint, as shown in Table 10.

Table 10 Welding condition of repair weld

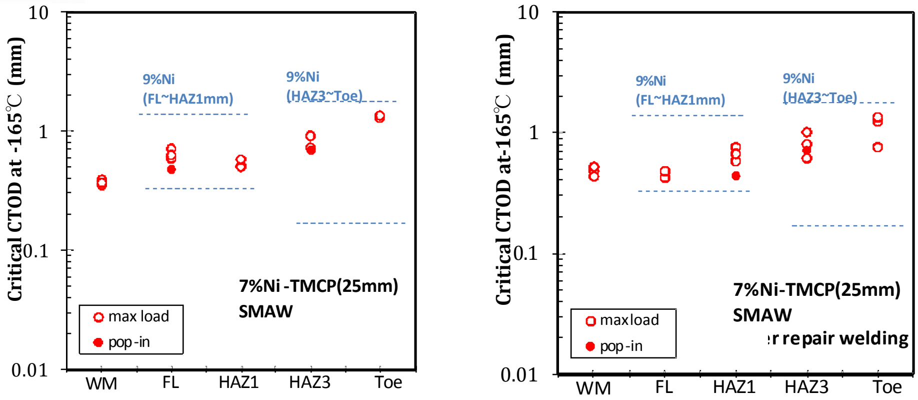
Groove location	Welding condition
	-Welding method; SMAW -Consumable;70% nickel -Position; vertical -Repair Buildup; 2 passes -Repair cycle; 3 times -Heat input; 5.0 kJ/mm* -Interpass temp.; 98 deg.C* *; maximum value for the original & repair weld

Figures 22 and 23 show test results of the repair weld. Tensile strengths of welded joint show more than 690 MPa, which is specified minimum one of A553M-Type 1. Both Charpy absorbed energy at -196 deg.C and critical CTOD at -165 deg.C show excellent values as well as the virgin welded joint.



(a) Original weld (b) Repair weld

Figure 22 Comparison Charpy absorbed energy between the original weld and repair weld



(a) Original weld (b) Repair weld

Figure 23 Comparison Critical CTOD value between the original weld and repair weld

5. CONFIRMATION OF OTHER 7%NI-TMCP STEEL PLATE DATA FOR DESIGNING LNG STORAGE TANK

In order to apply 7%Ni-TMCP steel plate to LNG storage tanks, more data such as physical constants should be required. Young's modulus, poisson ratio, coefficient of linear expansion of 7%Ni-TMCP steel plate are detected to be as same as that of 9%Ni steel plate.

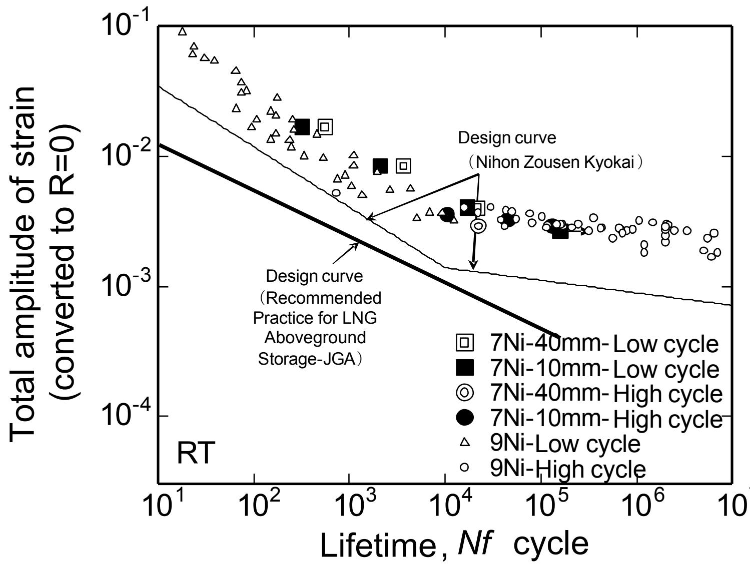


Figure 24 Fatigue test results of base plate

In terms of fatigue properties, test data of wide strain range of 9%Ni steel plate are indicated in Japan. So same means of fatigue test was performed with 7%Ni-TMCP steel plate. Stress was controlled in higher cyclic range, and strain was controlled in lower cyclic range by using cylindrical test pieces. Stress ratio was controlled to minus 1. Fatigue test of base metal results that S-N curve of 7%Ni-TMCP steel is same level as that of 9%Ni steel plate, as shown in Figure 24.

6. APPLICATION OF 7%NI-TMCP STEEL PLATE TO LARGE SCALE LNG STORAGE TANK

In 2010 fiscal year Ministry of Economy, Trade and Industry (METI) of Japan approved to apply 7%Ni-TMCP steel plate to new LNG storage tanks of Osaka Gas. This is why this steel plate and its welded joints satisfy legal requirement of LNG storage tank and allowable stress of 9%Ni steel plate is able to be applied.

Figure 25 Senboku terminal 1 of Osaka Gas

After that , Osaka Gas decided to construct a new full containment LNG storage tank applying 7%Ni-TMCP steel plate in Senboku terminal 1. Osaka Gas has operated four LNG storage tanks, of which one is under-ground and three are above-ground type ones, for 40 years in Senboku terminal 1 as shown in Figure 25. Two of above ground type tanks are to be scraped and a larger scale one is planning to be constructed. The capacity of a new LNG storage tank is 230,000m^3. The construction is planned to start in September 2012 and be completed by November 2015.

7. CONCLUSIONS

7%Ni -TMCP steel plate was developed. This steel was characterized by applying TMCP, followed by intermediate heat treatment, and optimizing chemical compositions to compensate Ni reduction by 2%, compared with conventional 9%Ni steel plate.

Properties of 7%Ni-TMCP steel plates were evaluated by the various fracture toughness tests to confirm their fitness for use in the above-ground LNG storage tanks. As a result it was demonstrated that 7%Ni -TMCP steel plate including welded joints had an excellent resistance to brittle fracture of the inner tank steel exposed to the cryogenic temperature of LNG.

After METI of Japan approved to apply 7%Ni-TMCP steel plate to new LNG storage tanks, Osaka Gas decided to construct a 230,000 m^3 LNG storage tank in Senboku terminal 1.

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