KAWASAKI STEEL TECHNICAL REPORT

No.40 (May 1999)

Steinless Steel and Steel Platel

Properties of High Toughness 9% Ni Heavy Section Steel Plate and Its Applicability to 200 000 k l LNG Storage Tanks

Takahiro Kubo, Akio Ohmori, Osamu Tanigawa

Synopsis :

A 50 mm thick 9% Ni steel plate containing Nb and less Si has been manufactured for LNG storage tanks with a capacity of 200 000 kl. Reduction of Si content and the addition of a Nb significantly improved HAZ toughness without a fall in strength. Furthermore, the developed steel plate and its welded joints, which were made of Ni-based weld materials, exhibited excellent strength and toughness in actual tanks. Flaw assessment proved that the developed steel plate and its welded joints have sufficient resistance to brittle fracture initiation and propagation.

Properties of High Toughness 9% Ni Heavy Section Steel Plate and Its Applicability to 200 000 kℓ LNG Storage Tanks*

Takahiro Kubo
Senior Researcher,
Plate & Shape Lab.,
Techinical Res. Labs.

Akio Ohmori
Plate & Shape Lab.,
Technical Res. Labs.

Osamu Tanigawa
Assistant General
Manager, Plate Control
Sec., Technical Control
Dept.,
Mizushima Works

Synopsis:

A 50 mm thick 9% Ni steel plate containing Nb and less Si has been manufactured for LNG storage tanks with a capacity of 200 000 kℓ. Reduction of Si content and the addition of a Nb significantly improved HAZ toughness without a fall in strength. Furthermore, the developed steel plate and its welded joints, which were made of Ni-based weld materials, exhibited excellent strength and toughness in actual tanks. Flaw assessment proved that the developed steel plate and its welded joints have sufficient resistance to brittle fracture initiation and propagation.

1 Introduction

Recently, as the consumption of liquefied natural gas (LNG) has been increasing, 9% Ni steel has been increasingly used in inner tanks of double-shell aboveground storage tanks for LNG. Furthermore, as the amount of transported LNG has been increasing, tanks have become larger, and a plate thickness of 50 mm is required in the lowest portion of the shell for 200 000 kℓ tanks[1,2]. Sufficient safety of the base metal and welded joints has been confirmed for the 9% Ni steel in thicknesses up to 40 mm, and there has been an extensive record of construction of this size. Increasing the plate thickness up to 50 mm, however, causes a decrease in strength through the deterioration of hardenability, reducing the margins between actual strength and minmum standard values. Furtermore, from a viewpoint of safety, the high toughness is required for the steel plate and its welded joints because the constraints against deformation increase with plate thickness.

Taking these conditions into consideration, the authours have developed a 50 mm thick, high strength and high toughness 9% Ni steel plate containing Nb and less Si (low Si/Nb-added steel). Issues to be discussed in this paper are (1) the technical basis of the chemical compositions of low Si/Nb-added steel, (2) the properties of the 50 mm thick steel plate produced in the factory, (3) the properties of its welded joints, and (4) the applicability of the steel plate and its welded joints to actual LNG tanks in terms of safety against brittle fracture initiation and propagation.

2 Design of Chemical Compositions for Heavy Section 9% Ni Steel Plate

It has been proved by previous studies of 9% Ni steel plates that lowering C and Si content is effective in increasing the toughnesses of the base metal and the heat affected zones (HAZs) by reducing the martensite islands[3], but that lowering C content excessively causes a deterioration of the toughness of the coarse-grained HAZ[4]. In this study, the effect of lowering Si content on the HAZ toughness and the effect of adding of Nb on strength of the base metal and toughness of the HAZs were studied.

The chemical compositions of steels used in the tests are shown in **Table 1**. Steel A had a conventional chemical composition, Steel B varied only in Si content and Steel C varied only in Nb content. Each steel was rolled to a plate, then double quenched and tempered in the laboratory. The HAZs were simulated by giving the heat

* Originally published in *Kawasaki Steel Giho*, **30**(1998)3, 167–173

Table 1 Chemical compositions of steels used in preliminary tests

(mass%)

Series	C	Si	Mn	P	S	Ni	Nb
A	0.05	0.25	0.60	0.003	0.001	9.0	—
B	0.06	0.08~0.25	0.40	0.003	0.001	9.0	—
C	0.05	0.16	0.40	0.003	0.001	9.0	Trace~0.03

A: Conventional steel
B: Steels to study effect of Si content on toughness
C: Steels to study effect of Nb content on strength and toughness

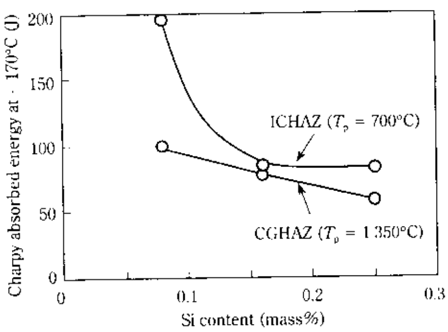


Fig. 1 Effect of Si content on toughness of synthetic heat affected zones of 9% Ni steel

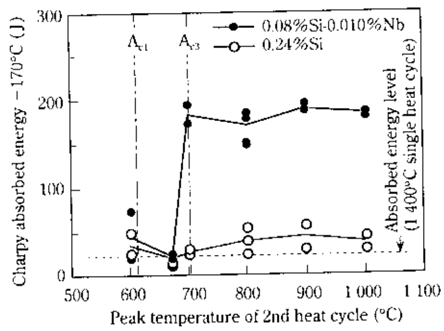


Fig. 3 Effect of second peak temperature on toughness of double cycled heat affected zones (first peak temperature: 1 400°C)

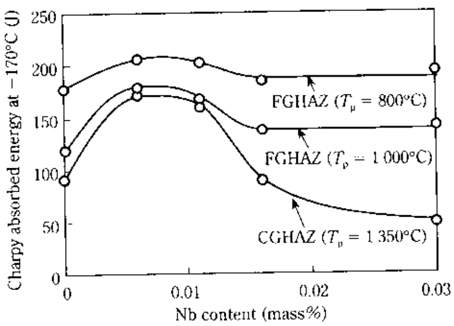


Fig. 2 Effect of Nb content on toughness of synthetic heat affected zones of 9% Ni steel

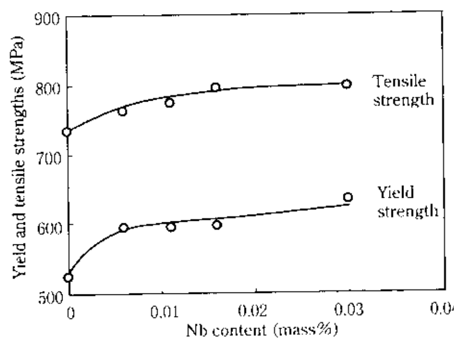


Fig. 4 Effect of Nb content on strength of 9% Ni steel plate

cycles of the actual weld.

Figure 1 shows the relation between the toughness of the single cycled HAZs and the Si content. The toughness improved with lowering Si content, particularly that of HAZ heated at 700°C remarkably improved by lowering Si content to 0.08%. This result was attained because lowering the Si content helped to reduce martensite islands[5].

The relation between the toughness of single cycled HAZs and the content of Nb, which is the element that increases the strength of the base metal, is shown in **Fig. 2**. The toughness of HAZs was improved by adding Nb in a range between 0.006% and 0.010%. This small addition of Nb caused the refining of microstructures through the pinning effect on NbC and restrained the grain growth; as a result, the microstructures of HAZ became fine. On the other hand, Nb addition of over 0.010%, which either made large NbC grow or increased soluble Nb, did not increase the toughness of HAZs.

Generally, the weld of a heavy section steel plate experiences the multi heat cycle. **Figure 3** shows the effect of the second peak temperature on the toughness of double cycled HAZs which were heated to the coarse grain HAZ temperature (1 400°C) in the first heat cycle. The toughness of the low Si/Nb-added steel was easily restored by reheating in temperatures over A_{c3} transition temperature (705°C). This was attributed to the refining of the recrystallized microstructures.

The relation between the strength of the steel plate and the Nb content is shown in **Fig. 4**. The strength increased with Nb content up to 0.006%, but not above that amount. The increase in strength by Nb addition was caused by NbC which was precipitaed in ferrite during the second quenching and tempering processes. The soluble Nb content at 800°C of the first quenching temperature of these steels was calculated to be about 0.006%, and Nb which was added over this content did not contribute to precipitation hardening because that occurred only during the first quenching process.

As a result of the studies, the contents of Si and Nb for the 50 mm thick 9% Ni Steel plate were determined to be 0.08% and 0.010%, repectively.

3 Method for Evaluating Properties

3.1 Steel Plate

On the basis of the laboratory study, the low Si-Nb type 9% Ni steel plate (JIS G3127 SL9N590) having a thickness of 50 mm was produced in the factory, and the properties of the steel plate and its welded joints were evaluated. A schematic flow of the manufacturing process is shown in **Fig. 5**. The chemical composition of the steel plate is shown in **Table 2**.

3.2 Welding

The steel palte was welded, in accordance with an actual above-ground LNG storage tank, with the submerged arc welding (SAW) as horizontal girth joints, and the shielded metal arc welding (SMAW) and the gas tungsten arc welding (GTAW) as vertical joints. The welding materials used were hastelloy 70% Ni type ones which are usually used for the welding of actual LNG tanks. The welding conditions are shown in **Table 3**.

3.3 Evaluation of Properties

3.3.1 Properties of base metal

The mechanical properties of the base metal were evaluated by tensile tests and Charpy impact tests at −196°C. The brittle fracture initiation toughness was evaluated by the CTOD tests at −170°C according to the Japan Welding Engineering Society Standard WES1108–1995 "Testing method for crack tip opening displacement (CTOD)". The brittle crack arrest toughness was also evaluated by the duplex ESSO tests at −170°C and −196°C. The geometries of duplex ESSO test specimens are shown in **Fig. 6**. After the specimen was cooled and subjected to stress, the brittle crack was initiated and propagated in the crack starter plate to make it run into the test plate.

3.3.2 Properties of welded joints

The mechanical properties of the welded joints were evaluated by welded joint tensile tests, bend tests and Charpy impact tests at −196°C. The notch positions in the Charpy impact test specimens were at weld metal (WM), fusion line (the ratio of weld metal to steel plate at notch position is one, FL), 1 mm from the FL (HAZ 1 mm) and 3 mm from the FL (HAZ 3 mm).

The brittle fracture initiation toughness was evaluated by the CTOD tests and the wide plate tensile tests at −170°C. The geometries of the wide plate tensile test specimens are shown in **Fig. 7**. The through-thickness notch was located at the FL. The crack tips in the SMAW joint specimen were located at HAZs of 2 mm from the weld toes where tensile welding residual stress induced by the horizontal weld existed. It has been

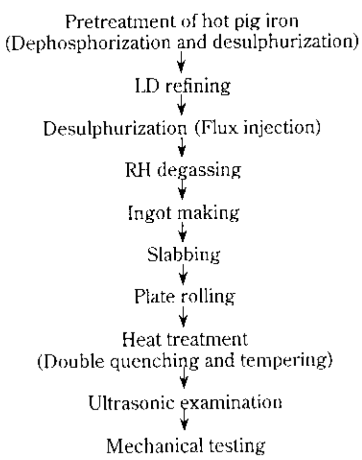


Fig. 5 Manufacturing process of 9% Ni steel plate

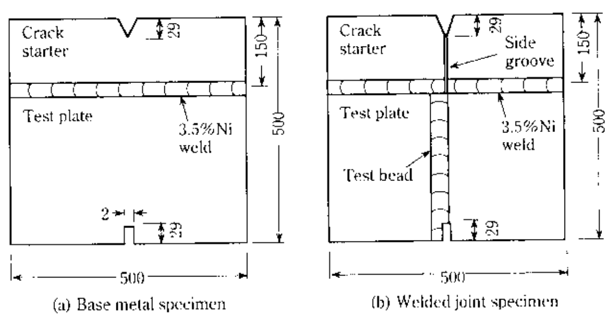


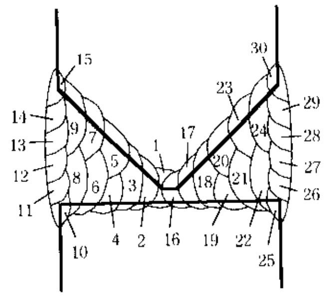
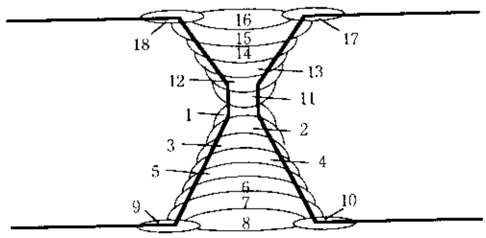
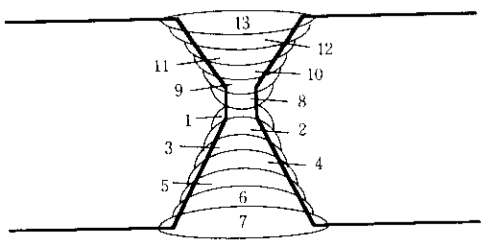
Fig. 6 Geometries of duplex ESSO test specimens

Table 2 Chemical compositions of steel plate

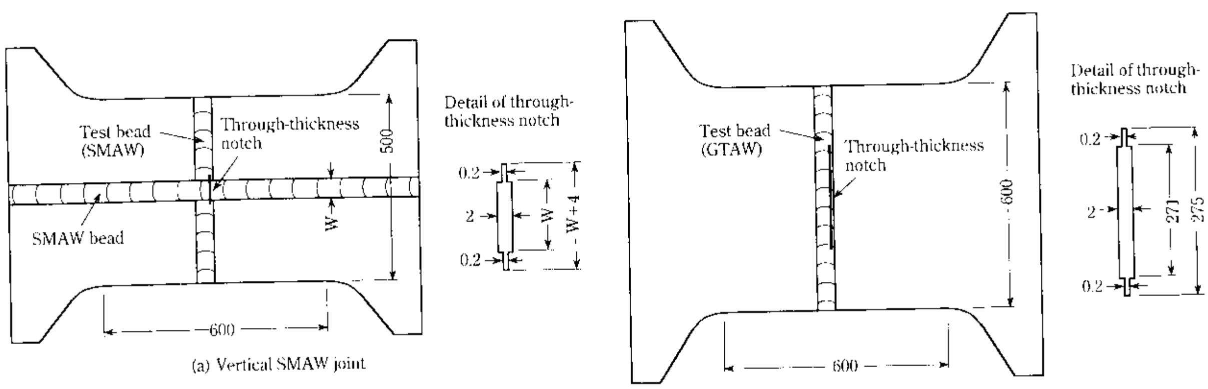
(mass%)

	C	Si	Mn	P	S	Ni	Nb	Al	N	O
Product	0.05	0.09	0.60	0.003	0.0007	9.47	0.010	0.034	0.0033	0.0011
Ladle analysis	0.05	0.08	0.60	0.002	0.0008	9.44	0.010	0.031	0.0030	0.0019
Requirement in JIS SL9N590	≦0.12	≦0.30	≦0.90	≦0.025	≦0.025	8.50~9.50				

Table 3 Welding conditions

Welding method	Welding material	Groove configuration and pass sequence	Welding conditions			
			Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)
SAW (Horizontal)	AWS ERNiCrMo-4 1.6 mmϕ (Hastelloy)		240~300	27~28	20~60	8~22 (10)*
SMAW (Vertical)	AWS ENiCrMo-6 3.2, 4.0 mmϕ (Hastelloy)		120~140	22~23	3.1~8.7	20~55 (41)*
GTAW (Vertical)	JIS Z3332 YGT9Ni-2 1.2 mmϕ (Hastelloy)		260~300	10	4.5~7.0	26~37 (30)*

*Average value



(a) Vertical SMAW joint

(b) Vertical GTAW joint

Fig. 7 Geometries of wide plate tensile test specimens of welded joints

Table 4 Mechanical properties of steel plate

Direction	Location	Tensile test (at room temp.) Base metal YS (MPa)	TS (MPa)	El. (%)	Charpy impact test (at −196°C) Base metal vE (J)	L.E. (mm)	Strain aging vE (J)	L.E. (mm)
L	1/4 t	634	713	33	300	2.43	270	2.21
C	1/4 t	634	715	32	280	2.36	280	2.34
Z	1/2 t	—	711	—	—	—	—	—
Requirement in JIS SL9N590		≧590	690~830	≧20	≧41			

YS: Yield strength TS: Tensile strength El.: Elongation vE: Absorbed energy L.E.: Lateral expansion
Strain aging: 5% strain, 250°C for 60 min

shown by Machida et al. that the brittle crack which may be initiated and propagated along the weld of the 9% Ni steel plate could be arrested before it became as long as 5.5 times the plate thickness[6]. Thus, the notch length of the GTAW joint specimen was 5.5 times the plate thickness so that the resistance to the initiation of the brittle fracrture from the arrested crack could be evaluated.

The duplex ESSO tests were performed at −170°C. The geometry of the specimen is shown in Fig. 6. The side grooves were machined on the surfaces of the crack starter plate to make the brittle crack run into the FL of the weld.

4 Properties of Base Metal

4.1 Mechanical Properties

The mechanical properties of the steel plate are summarized in **Table 4**. The steel plate satisfied the requirement of strength for JIS SL9N590 steel plate. In the Charpy impact tests at −196°C, all specimens showed 100% shear areas and the absorbed energies exceeded 280 J. The change in absorbed energy caused by the strain aging was small.

4.2 Fracture Toughness

4.2.1 Brittle fracture initiation toughness

The CTOD test results of the base metal and its strain-aged material are shown in **Fig. 8**. Brittle fracture did not take place in any speciments at −170°C and the CTOD values were larger than 1 mm. Deterioration of CTOD values caused by the strain aging was quite small.

4.2.2 Brittle crack arrest toughness

The results of the duplex ESSO test of the base

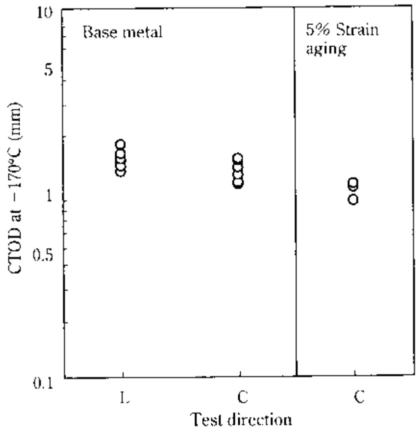


Fig. 8 Resistance to brittle fracture initiation of 9% Ni steel plate indicated by CTOD test

metal are shown in **Table 5**. The brittle crack which propagated in the crack starter plate was arrested when it ran into the base metal, even under test conditions of −196°C and applied stress of 400 MPa. The value of the brittle crack arrest toughness (K_{ca}) was calculated to be 303 MPa · m$^{1/2}$ or more.

5 Properties of Welded Joints

5.1 Mechanical Properties

The results of the welded joint tensile test and the bend test are shown in **Table 6**. Each welded joint satisfied the requirement of strength for base metal and had good ductility. **Figure 9** shows the Charpy impact test results of the welded joints at −196°C. All specimens, regardless of welding method and notch position, showed 100% shear areas, and the absorbed energies

Table 5 Results of duplex ESSO test of steel plate

Material	Test position	Thickness (mm)	Width (mm)	Test temperature (°C)	Applied stress (MPa)	Crack length (mm)	Judgment	K_{ca} (MPa · m$^{1/2}$)
Base metal	Base metal	50	500	−170	350	169	No go	≧268
		50	500	−196	400	164	No go	≧303

Table 6 Mechanical properties of welded joints

Welding method	Tensile test		Bend test
	TS (MPa)	Location of rupture	
SAW	701	Weld metal	Good*1
SMAW	706	Weld metal	Good*1
GTAW	719	Weld metal	Good*2

*1 Side bend test, Radius of bend = 167 mm
*2 Face and root bend tests, Radius of bend = 100 mm

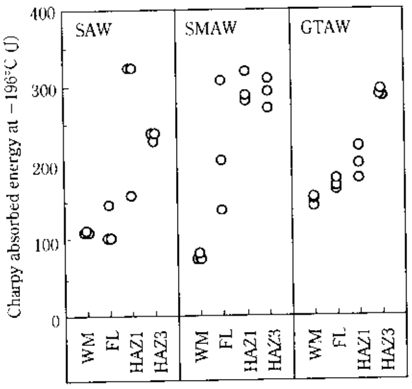


Fig. 9 Charpy impact properties of 9% Ni steel welded joints (WM: Weld metal, FL: Fusion line, HAZ1: HAZ 1 mm, HAZ3: HAZ 3 mm)

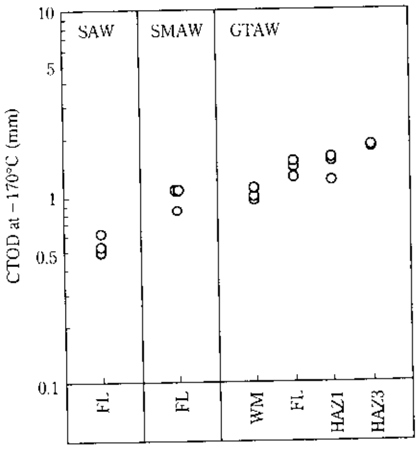


Fig. 10 Resistance to brittle fracture initiation of 9% Ni steel welded joints indicated by CTOD test (WM: Weld metal, FL: Fusion line, HAZ1: HAZ 1 mm, HAZ3: HAZ 3 mm)

were much larger than the required value for base metal.

5.2 Fracture Toughness

5.2.1 Brittle fracture initiation toughness

The CTOD test results at −170°C of the welded joints are shown in **Fig. 10**. The CTOD values were larger than 0.83 mm for the vertical SMAW and GTAW joints. The CTOD values of the horizontal SAW joint were smaller than those of the vertical ones. Because the ductile crack deviated into the weld metal as soon as it was initiated from the fatigue notch tip in the test of SAW joint, the obtained CTOD values were those of the weld metal.

The results of the wide plate tensile test of the welded joints are shown in **Table 7**. No specimen fractured in brittle manner and each showed its maximum load after general yielding. The ductile crack which initiated from the crack tip deviated into the weld metal and propagated there. The maximum net stresses were larger than the yield strength of the steel plate at room temperature. The obtained CTOD values were larger than 1 mm for the SMAW joint and larger than 3 mm for the GTAW joint.

5.2.2 Brittle crack arrest toughness

The results of the duplex ESSO test of the vertical welded joints are shown in **Table 8**. In each specimen, the brittle crack which propagated in the crack starter plate was arrested when it ran into the FL. The K_{ca} values were estimated to be 268 MPa · m$^{1/2}$ or more for the SMAW joint and 303 MPa · m$^{1/2}$ or more for the GTAW

Table 7 Results of wide plate tensile of welded joints

Welding method	Thickness (mm)	Width (mm)	Notch length (mm)	Temperature (°C)	Maximum net stress (MPa)	CTOD (mm)
SMAW	50	500	40.0	−170	799	1.04
GTAW	50	600	274.6	−170	841	3.45

Table 8 Results of duplex ESSO test of welded joints

Welding method	Test position	Thickness (mm)	Width (mm)	Test temperature (°C)	Applied stress (MPa)	Crack length (mm)	Judgment	K_{ca} (MPa · m$^{1/2}$)
SMAW	Fusion line	50	500	−170	350	169	No go	≧ 268
GTAW	Fusion line	50	500	−170	400	164	No go	≧ 303

joint.

6 Safety Evaluation for Fracture

To ensure the safety of LNG tanks, the following two characteristics are required of the materials: (1) enough toughness to prevent the initiation of brittle fracture and (2) enough toughness to arrest the brittle crack propagation and prevent catastrophic fracture. These characteristics are particularly required of the weld, where flaws may exist, and where stress concentration and residual stress do exist. Thererfore, in this study, the characteristics needed to prevent the initiation of brittle fracture, and to arrest brittle crack propagation were evaluated using the fracture toughness test results of both the steel plate and its welded joints. The evaluated portions were both the vertical joint and the T-cross portion of the vertical joint and the circumferential joint at the bottom level of the shell plate.

6.1 Properties to Prevent Brittle Fracture Initiation

The properties to prevent the initiation of the brittle fracture were evaluated according to the Japan Welding Engineering Society Standard WES2805–1997 "Method for Assessing for Flaws in Fusion Welded Joints with respect to Brittle Fracture and Fatigue Crack Growth". In this study, the characteristics were assessed for the fracture initiation toughness by referring to the fracture mechanics parameter (δ) estimated from the applied strain and the size of cracks grown from the initial flaw by fatigue.

In the evaluation, the following conditions were assumed.

(1) Geometrical discontinuity: 12 mm/m (Angular distortion of 10 mm/m and misalignment of 2 mm)
(2) Initial flaw: Semielliptical surface flaw at weld toe
(3) Size of initial flaw: 75 mm long × 10 mm deep (Length ($2a_0$) of $1.5t$ and the depth (b_0) of $0.2t$, where t is the plate thickness. This flaw is large enough to detect by inspection either during fabrication or production.)
(4) Design stress: 164 MPa (Stress during normal operation)[7,8] and 375 MPa (Maximum stress)[9]
(5) Values related to fatigue crack propapation: 2 000 times from 0 to 164 MPa (Based on empty/fill cycle of 1/week over the 40-year life of a tank)

The bending stress (σ_b) caused by the angular distortion was also considered in the evaluation[10]. The initial flaw can grow by fatigue during operation of an LNG storage tank and the grown crack after 40 years of operation can be estimated to be 77.0 mm long and 11.4 mm deep.

The WES2805 gives the fracture mechanics parameter (δ), which is the crack tip opening displacement when the strain is applied to the crack, by Eq. (1).

Table 9 Comparison between required CTOD values and the minimum CTOD values of welded joints

Welding method	Stress* (MPa)	Required CTOD value (mm)	Minimum CTOD value (mm)
SAW	164	0.116	0.49
	375	0.241	
SMAW	164	0.078	0.83
	375	0.203	
GTAW	164	0.076	0.96
	375	0.201	

*164 MPa: Normal operate condition
375 MPa: Maximum stress condition

$$\delta = \begin{cases} \varepsilon_Y \bar{a}(\pi/2)(\varepsilon/\varepsilon_Y)^2 & \varepsilon/\varepsilon_Y \leqq 1.0 \\ \varepsilon_Y \bar{a}(\pi/8)\{9(\varepsilon/\varepsilon_Y)-5\} & \varepsilon/\varepsilon_Y > 1.0 \end{cases} \cdots (1)$$

where ε_Y is the yield strain of the material. The values of ε_Y used in the evaluation were those of the weld metals, which were lower than that of the base metal. $\bar{a}$ is the effective crack size parameter and is defined as the equivalent through thickness crack with length $2\bar{a}$ which has the same K value as the surface crack. ε is the local strain given by Eq. (2).

$$\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \cdots\cdots (2)$$

where, ε_1 is the strain corresponding to boundary force, ε_2 is the one corresponding to welding residual stress and ε_3 is the one corresponding to stress concentration.

δ obtained according to WES2805 can be regarded as the required CTOD value under the assumed conditions. **Table 9** shows the required CTOD values in comparison with the minimum CTOD values obtained by the fracture toughness tests. Although the maximum design stress is assumed to be the applied stress, each welded joint has a fracture toughness at least twice the required CTOD value. It should be noted that the fracture toughness value obtained by the fracture toughness test is not for the brittle fracture initation but for the ductile fracture.

In the wide plate tensile test, the specimen which had larger notch ($\bar{a}$ was 20.0 mm for the SMAW joint and 137.3 mm for the GTAW joint) than the assumed crack ($\bar{a}$ was 12.9 mm) did not fracture in a brittle manner. Furthermore, the obtained CTOD values were at least five times the required value and the maximum gross stress was much larger than the maximum design stress.

The evaluation clearly proved that the developed steel plate and its welded joints have sufficient resistance to brittle fracture initiation when they are used in actual LNG storage tanks.

6.2 Properties to Arrest Brittle Crack Propagation

The properties to arrest the brittle crack propagation of the base metal and the vertical welded joints were evaluated by the duplex ESSO tests. Although the test conditions were severer than the actual design ones of the LNG storage tanks, the brittle cracks were arrested in all tests. The K_{ca} values, which were obtained by the tests, are equivalent to the lengths of brittle crack that the material can arrest under maximum design stress: 416 mm or more for the base metal, 326 mm or more for the SMAW joint and 416 mm or more for the GTAW joint. These values are larger than 5.5 times the plate thickness, which is the length of the arrested brittle crack that was initiated and propagated along the weld of the 9% Ni steel plate[6]. It is well known that cracks which propagate along the FL tend to deviate toward the material with lower strength[11]. For the weld of the LNG storage tanks, the yield strength of the weld metal, whose microstructure is austenite, is much lower than that of the steel plate. Thus, a brittle crack would change into a ductile one and be arrested when it runs into the weld metal.

It was clearly proved through the above evaluation that the developed steel plate and its welded joints have sufficient toughness to arrest brittle crack propagation and thus prevent catastrophic fracture.

7 Conclusion

Low Si 9% Ni steel with a small addition of Nb having a thickness of 50 mm has been successfully produced in the factory. Various tests of the base metal and its welded joints were carried out, assuming an LNG storage tank with a capacity of 200 000 kℓ. Furthermore, their applicability to actual tanks was evaluated using the flaw assessment procedure proposed by WES2805. The main conclusions are as follows:

(1) The developed low Si-Nb type 9% Ni steel plate of 50 mm thickness satisfies all requirements for JIS G3127 SL9N590 steel plate.

(2) The welded joints of the developed steel plate have sufficient toughness to prevent brittle fracture initiation.

(3) The steel plate and its welded joints have sufficient toughness to arrest brittle crack propagation and thus prevent catastrophic fracture.

(4) The properties of the developed steel plate and its welded joints are sufficient for LNG storage tanks.

8 Acknowledgments

The authors wish to thank Emeritus Prof. S. Machida of the University of Tokyo for his help in conducting this study. They also wish to thank Chicago Bridge & Iron Company and Koyo Iron Works & Construction Company for their cooperation in manufacturing the welded joints and obtaining the test data used in this study.

Refernces

1) T. Yamakawa, Y. Chida, K. Niimi, T. Ishiyama, J. Iwagami, and S. Nakayama: *Kawasaki Juko Giho*, **130**(1996), 33–38
2) N. Nishioka, A. Deguchi, Y. Kawasaki, and M. Tada: *Mitsubishi Juko Giho*, **33**(1996)4, 238–241
3) H. Ichinose, J. Tanaka, M. Yamada, H. Koshiga, J. Tanaka, and T. Ikoma: *Nippon Kokan Giho*, **57**(1972), 357–370
4) T. Kubo, O. Furukimi, T. Yamaura, and Y. Saito: *Quarterly Journal of JWS*, **8**(1990)2, 229–235
5) T. Kubo, A. Ohmori, Y. Kataoka, H. Ishii, and O. Tanigawa: *CAMP-ISIJ*, **9**(1996), 437
6) S. Machida, N. Ishikura, N. Kubo, N. Katayama, S. Muramoto, Y. Hagiwara, and K. Arimochi: *JHPI*, **31**(1993)1, 19–13
7) American Society of Mechanical Engineers: ASME Boiler and Pressure Vessel Code, Sec. VIII, Pressure Vessels, Div. 1, (1989)
8) Technical Maintenance Committee, Japan LP Gas Association: "Report of Research Committee for Durability of Tanks for Low Temperature Service (Analysis)", (1978)
9) The Japan Gas Association: "Guideline for Above-ground LNG Storage Tank", (1981)
10) T. Yada: *J. Soc. of Naval Architects of Jpn.* **199**(1966), 134
11) K. Arimochi, M. Nakanishi, S. Satoh, F. Minami, M. Toyoda, and K. Satoh: *Quarterly Journal of JWS*, **1**(1983)2, 232–239