KAWASAKI STEEL TECHNICAL REPORT
No.17 (October 1987)

Mechanical Properties of 9% Ni Steel Plates Produced from Continuously Cast Slabs

Ryoji Kinaka, Osamu Furukimi, Takahiro Kubo, Taketo Okumura, Masahiro Shingyoji, Junichi Kudo

Synopsis :
From a low-P(0.006% max), low-S(0.002% max) continuously cast slab, 9% Ni steel plates for LNG storage tanks were produced by the direct quenching and tempering process (MACS-T) and reheat-quenching and tempering process (RQ-T). In the MACS-T process, slab-reheating and finish-rolling temperatures were increased in order to increase ductile fracture energy by decreasing the amount of precipitated austenite. Reliability for LNG storage tanks was examined by conducting fracture toughness tests on these steel plates and their welded joints. As a result, it was shown that these steel plates and their welded joints had good crack initiation and arrest toughness.

Mechanical Properties of 9% Ni Steel Plates Produced from Continuously Cast Slabs*


Ryoji Kinaka
Staff Assistant Manager, Plate & Pipe Control Sec., Chiba Works**


Osamu Furukimi
Senior Researcher, New Materials Research Center, High Technology Research Labs.


Takahiro Kubo
Researcher, Plate Lab., Plate Research Dept., I & S Research Labs.


Taketo Okumura
Staff Manager, Steel Products Technology Dept., Steel Technology Div.


Masahiro Shingyoji
Staff Manager, Steel Products Technology Dept., Steel Technology Div.


Junichi Kudo
Senior Researcher, Laboratory II, Mizushima Research Dept., I & S Research Labs.

Synopsis:

From a low-P (0.006% max), low-S (0.002% max) continuously cast slab, 9% Ni steel plates for LNG storage tanks were produced by the direct quenching and tempering process (MACS-T) and reheat-quenching and tempering process (RQ-T). In the MACS-T process, slab-reheating and finish-rolling temperatures were increased in order to increase ductile fracture energy by decreasing the amount of precipitated austenite. Reliability for LNG storage tanks was examined by conducting fracture toughness tests on these steel plates and their welded joints. As a result, it was shown that these steel plates and their welded joints had good crack initiation and arrest toughness.

1 Introduction

Hitherto, 9% Ni steel plates for liquefied natural gas (LNG) ground storage tanks have been produced from slabs made by ingot casting. It has been demonstrated by fracture mechanical analysis[1)] that structures made of these steel plates provide sufficient safety at a service temperature of −163°C. However, no paper has been published on the safety evaluation of LNG storage tanks of 9% Ni steel plates produced from continuously cast slabs.

With the recent remarkable progress in continuous casting techniques and techniques for making ultra-clean steels, stable control of phosphorus and sulfur content in steels to less than 0.006% and 0.002%, respectively, has now become possible. The techniques for making ultra-clean steels such as dephosphorization and desulfurization of molten steel have substantially improved low temperature toughness of 9% Ni steels and contributed greatly to the stability of their mechanical properties[2,3)].

Meanwhile, a new process, MACS (Multipurpose accelerated cooling process), that replaces the reheat-quenching of quenched and tempered steels by using on-line water quenching after plate rolling has been developed in the past few years, and great strides have been made in plate rolling techniques. For 9% Ni steels, the standardization of steel products manufactured by the accelerated cooling process has been carried out by the American Society for Testing and Materials (ASTM) and designated A844.

The effects of manufacturing conditions such as slab reheating temperature on the mechanical properties of steel plates produced from continuously cast slabs by the MACS process was investigated in laboratory simulations. Furthermore, the toughness of base metal and welded joints of steel plates actually produced in a plant by the conventional reheat-quenching and tempering process (RQ-T) and the direct-quenching and tempering

* Originally published in *Kawasaki Steel Giho*, **18**(1986)4, pp. 327-333

** Presently on assignment to Companhia Siderurgica de Tubarão process (MACS-T) was investigated, and the applicability of the 9% Ni steel plates produced by the above-mentioned processes to LNG storage tanks was evaluated. This paper presents the results of such investigation and evaluation.

2 Optimum Manufacturing Conditions for MACS-T Process

When the MACS-T process (direct quenching just after plate rolling and further tempering) is applied to 9% Ni steel, factors related to plate production conditions that affect strength and toughness of base metal include (1) slab reheating temperature, (2) finish-rolling temperature, (3) cooling rate after rolling, and (4) tempering temperature. Using continuously cast slabs whose chemical composition is given in **Table 1**, the slab reheating temperature, finish-rolling temperature, and cooling rate after rolling were studied to determine their effect on the strength and toughness of base metal. The phosphorus and sulfur contents of the steels tested were as low as 0.002% and 0.001%, respectively. The steels were subjected to tempering at 570°C for 60 min.

The Charpy impact test and tensile test were conducted at various slab reheating and finish-rolling temperatures. The results of these tests are shown in **Fig. 1**. The Charpy absorbed energy at −196°C increased as slab reheating temperature and finish-rolling temperature were raised. Because the fractured surface displayed 100% ductility, the absorbed energy shown in Fig. 1 is ductile fracture energy. This is because brittle fracturing did not occur at −196°C owing to the low phosphorus and sulfur contents. It has already been clarified that the increase in ductile energy corresponds to a decrease in the amount of austenite precipitated during tempering[4]. Because the number of nucleation sites for phase transformation to austenite increases during tempering when the slab-reheating temperature and finish-rolling temperature are lowered, the amount of precipitated austenite increases in the MACS-T steel with decreasing slab reheating and finish-rolling temperatures. This precipitated austenite phase causes small dimples and lowers the ductile fracture energy. The tensile strength and yield point were not influenced by the slab-reheating temperature and increased a little on the low-temperature side of the finish-rolling temperature.

The relationship between cooling rate after rolling and strength and toughness of base metal is shown in **Fig. 2**. No changes were observed at cooling rates from 11 to 20°C/s and strength increased when the cooling rate increased from 20 to 40°C/s. On the other hand, dependence of toughness on the cooling rate was not observed.

It was found from the above-mentioned results that

Table 1 Chemical composition of steel tested (%)

C	Si	Mn	P	S	Ni	Al	N
0.06	0.24	0.59	0.002	0.001	8.98	0.029	0.0037

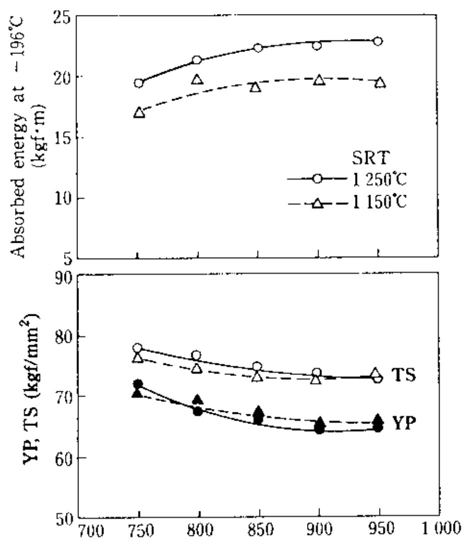


Fig. 1 Effects of slab reheating and finish-rolling temperatures on the strength and the toughness of 9%Ni steel plate produced by MACS-T process

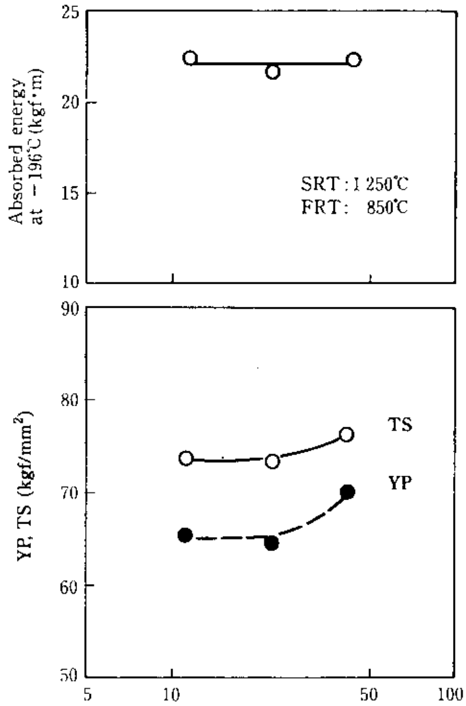


Fig. 2 Effects of cooling rate after hot rolling on the strength and the toughness of 9%Ni steel plate produced by DQ-T process

(1) ductile fracture energy increases when the slab reheating and finish-rolling temperatures are raised, and that (2) the strength and toughness of base metal are good when the cooling rate after rolling ranges from 10 to 40°C/s. This cooling temperature range corresponds to that used for 20-mm to 70-mm thick steel plates in actual direct-quenching devices.

Photo 1 Sulfur print test result of 9%Ni steel plate produced by MACS-T process

3 Characteristics of 9% Ni Steel Plates Produced from Continuously Cast Slabs

Based on the above-mentioned results of the laboratory experiment, steel plates were produced from low phosphorous and low sulfur continuously cast slabs by the conventional RQ-T process and by the MACS-T process with slab reheating and finish-rolling temperatures raised. Tests were conducted to evaluate the mechanical properties of the base metals, vertical TIG welded joints, and flat SAW joints of these steel plates. The chemical compositions of the steel plates tested are given in **Table 2**. The manufacturing process of steel plates is shown in **Fig. 3**. The plate thicknesses were 6, 15, and 35 mm for the RQ-T steel and 35 mm for the MACS-T steel. The cooling rate in the MACS process was 30°C/s.

Table 2 Chemical compositions of steel plate products (%)

Steel	Thickness (mm)	C	Si	Mn	P	S	Ni	Al_{total}	N_{total}	O
RQ-T	6	0.06	0.24	0.61	0.004	0.001	9.14	0.027	0.0041	0.0023
	15	0.06	0.24	0.61	0.004	0.001	9.10	0.027	0.0041	0.0026
	35	0.06	0.25	0.61	0.004	0.001	9.07	0.029	0.0044	0.0023
MACS-T	35	0.06	0.23	0.62	0.004	0.001	9.09	0.028	0.0042	0.0021
Ladle analysis		0.06	0.24	0.61	0.004	0.001	9.06	0.032	0.0043	0.0028
Specification of ASTM A 553-II		≦ 0.13	0.15 ~ 0.30	≦ 0.90	≦ 0.035	≦ 0.040	8.50 ~ 9.50			

Desulfurization of molten pig iron
↓
LD refining (150 tons)
↓
Desulfurization (flux injection)
↓
RH degassing
↓
Continuous casting
↓
Slab surface conditioning
↓
Slab heating
↓
Plate rolling
↘ Direct quenching (MACS) ↙
Ultrasonic testing
↙ ↘
Heat treatment (RQ-T) Heat treatment (T)
↘ ↙
Mechanical testing

Fig. 3 Manufacturing process

The sulfur print test was conducted on steel plate specimens taken in the longitudinal direction according to JIS G0560. As is apparent from the result of the sulfur print test for the MACS-T steel shown in **Photo 1**, center segregation of sulfur was not observed in steel plate with a sulfur content reduced to as low as 0.001%.

3.1 Properties of Base Metals

3.1.1 Mechanical properties

The tensile test, bend test, Charpy impact test, and strain aging Charpy impact test were conducted on the base metals. The tensile test and Charpy impact test were also carried out after post-weld heat treatment (PWHT). For strain aging, a 5% strain was given at room temperature in the transverse direction and then the steel was subjected to the aging treatment at 250°C for 60 min. With respect to PWHT conditions, the temperature was 560°C, the holding time was 75 min for 6-mm thick plates, 95 min for 15-mm thick plates, and 145 min for 35-mm thick plates, which were air cooled after heating. **Table 3** shows the results of these tests. Irrespective of the process and direction of tension and whether PWHT was conducted or not, the yield strength, tensile strength, and elongation showed almost constant values and all met the specification values of ASTM A553. The Charpy impact test results of the base metals and steels treated by strain aging all sufficiently met those specification values; the absorbed energy of a Charpy test on full-size specimens at -196°C ($_{V}E_{-196}$) was 20 kgf·m or more for the base metals and 18 kgf·m or more for the steels treated by strain aging. Furthermore, no difference in $_{V}E_{-196}$ was observed whether PWHT was conducted or not. A comparison of $_{V}E_{-196}$ between the RQ-T steel and MACS-T steel reveals that the latter gives slightly higher values under all of the conditions.

Table 3 Mechanical properties of tested plates

Steel	Thickness (mm)	Direction	Tension test: Base metal YP (kgf/mm²)	Base metal TS (kgf/mm²)	Base metal El (%)	PWHT YP (kgf/mm²)	PWHT TS (kgf/mm²)	PWHT El (%)	Bend test $R=1.0t$ 180°	Charpy impact test*: Base metal −170°C vE (kgf·m)	Base metal −170°C L.E. (mm)	Base metal −196°C vE (kgf·m)	Base metal −196°C L.E. (mm)	Strain aging −170°C vE (kgf·m)	Strain aging −170°C L.E. (mm)	Strain aging −196°C vE (kgf·m)	Strain aging −196°C L.E. (mm)	PWHT −170°C vE (kgf·m)	PWHT −170°C L.E. (mm)	PWHT −196°C vE (kgf·m)	PWHT −196°C L.E. (mm)
RQ-T	6	L	66.1	76.5	27	65.5	75.7	30	Good	10.1	1.76	9.1	1.82					9.1	2.07	8.9	2.04
		C	65.8	76.6	27				Good	9.1	1.68	8.5	1.69	7.9	1.78	7.1	1.71				
	15	L	65.8	72.3	39	65.1	71.7	38	Good	24.4	2.26	24.3	2.15					24.0	2.35	23.7	2.29
		C	65.6	71.9	37				Good	23.0	2.24	22.5	2.11	21.0	2.18	18.5	1.88				
	35	L	64.8	73.8	32	63.8	73.0	31	Good	23.1	2.34	22.2	2.21					22.5	2.26	21.4	2.18
		C	64.1	73.4	31				Good	22.7	2.37	21.2	2.20	19.8	2.03	18.5	1.96				
		Z	62.8	73.0	34																
MACS-T	35	L	63.5	73.6	31	62.3	72.8	32	Good	23.8	2.43	22.8	2.48					24.1	2.42	22.7	2.21
		C	64.0	73.8	31				Good	24.0	2.45	22.7	2.08	21.1	2.22	20.1	2.12				
		Z	65.0	75.1	34																
Specification of ASTM A553-II		L	60≦	70 ~ 85	20≦					3.5≦	0.38≦										
		C								2.8≦											

* Specimen size of 6 mm thick plate is 5 × 10 mm.

3.1.2 COD test

In accordance with the BS 5762[5] of the British Standards Institution, the three point bend COD test was conducted on specimens taken from 6-mm and 35-mm thick base metals and steels treated by strain aging. The thickness of the specimens was the same as the original thickness of rolled steel plates, and a fatigue notch about 2 mm in length was formed at the tip of a machined notch on each specimen. The COD test results are shown in **Figs. 4 and 5**. The COD test results on the base metals were sufficient for LNG storage tank steel plates, and a completely ductile fracture occurred at −170°C in all specimens. Furthermore, the RQ-T steel showed somewhat higher COD values than the MACS-T steel. Although COD decreased a little due to the 5%

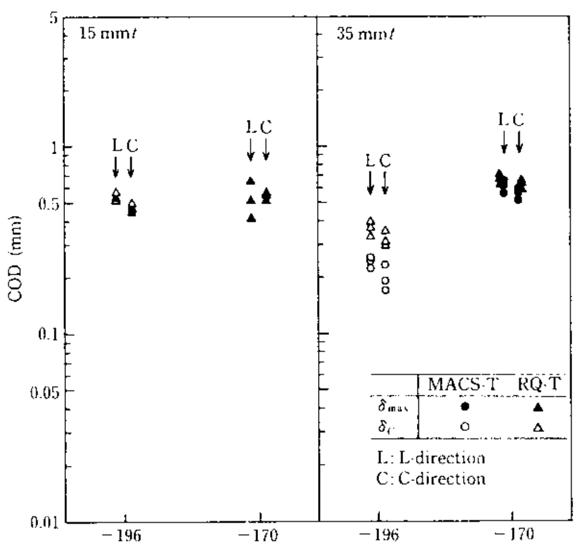


Fig. 4 COD test results on the base metals of 9%Ni steel plates produced by MACS-T and RQ-T processes

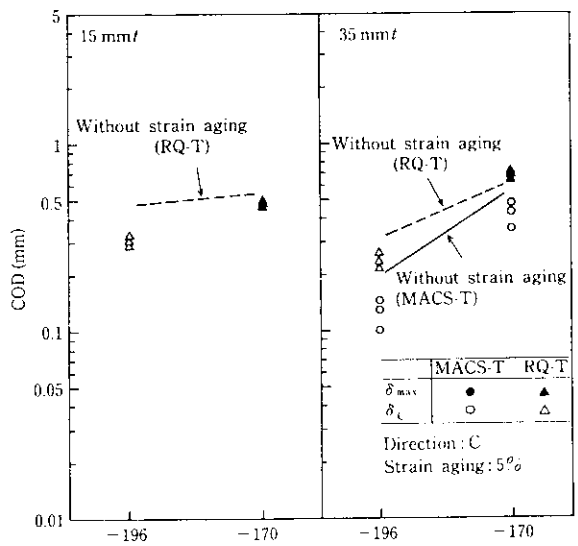


Fig. 5 COD test results on the base metals of strain aged 9%Ni steel plates produced by MACS-T and RQ-T processes

prestrain aging, the degree of this decrease was low; the critical COD value was 0.35 mm or more in all the cases at −170°C and it was found that the steel in question met the requirements for LNG storage tank steel plates from the standpoint of brittle fracture initiation toughness.

Although the COD test results showed that the RQ-T steel is superior to the MACS-T steel in terms of brittle fracture initiation, the MACS-T steel showed higher brittle fracture energy than the RQ-T steel in the Charpy impact test as given in Table 3. It seems this is because the amount of precipitated austenite decreased due to the higher slab reheating and finish-rolling temperatures in the MACS-T process, and so the brittle fracture initiation toughness of the MACS-T steel was inferior to the RQ-T steel.

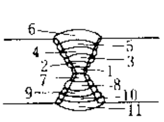
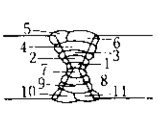
3.2 Performance of Welded Joints

An investigation was made into the performance of welded joints of 35-mm thick RQ-T and MACS-T steel plates. The groove geometry of joints and welding conditions are shown in **Table 4**. The double Vee groove was adopted as the groove geometry. The vertical TIG welding and flat submerged arc welding (SAW) processes were employed. Filler 196 was used as the welding wire and Flux 10 was used as the flux for SAW. Eleven-layer welding was conducted with heat inputs of 31 to 33 kJ/cm.

3.2.1 Mechanical properties of welded joints

The results of tensile test and guided-bend test for welded joints are shown in **Table 5**. The strength of each joint was 73 kgf/mm² or more at room temperature and met the specification for base metal. The results of the longitudinal-bend test showed that each welded joint provided good ductility. The V-notched Charpy impact test was conducted using specimens taken at the center of the weld metal, the bond (WM/BM = 1) and the HAZ-2-mm (2 mm from the bond toward the base metal side). The test results are shown in **Figs. 6** and **7**.

Table 4 Welding conditions

Welding method	Welding material	Groove dimensions	Welding conditions: Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)
Vertical TIG	Wire: Filler 196 1.2 mmφ		220	9.5	3.5	36
			300	10	6	30 (33)*
Flat SAW	Wire: Filler 196 3.2 mmφ Flux: Flux 10		520	32	32	31
				34	34	(31)*

* Average

Table 5 Mechanical properties of welded joints

Welding method	Steel	Thickness (mm)	Tension test: TS (kgf/mm²)	Tension test: Break location*	Bend test**: Surface side	Bend test**: Backing side
Vertical TIG	RQ-T	35	74.9	WM	Good	Good
			74.3	WM		
	MACS-T	35	78.1	WM+Bond	Good	Good
			77.4	WM+Bond		
Flat SAW	RQ-T	35	76.3	WM	Good	Good
			76.9	WM		
	MACS-T	35	74.8	WM	Good	Good
			73.5	WM		

* WM: Weld metal

** ASME Sec. IX, $R=3\frac{1}{3}T$ (T=9.52 mm)

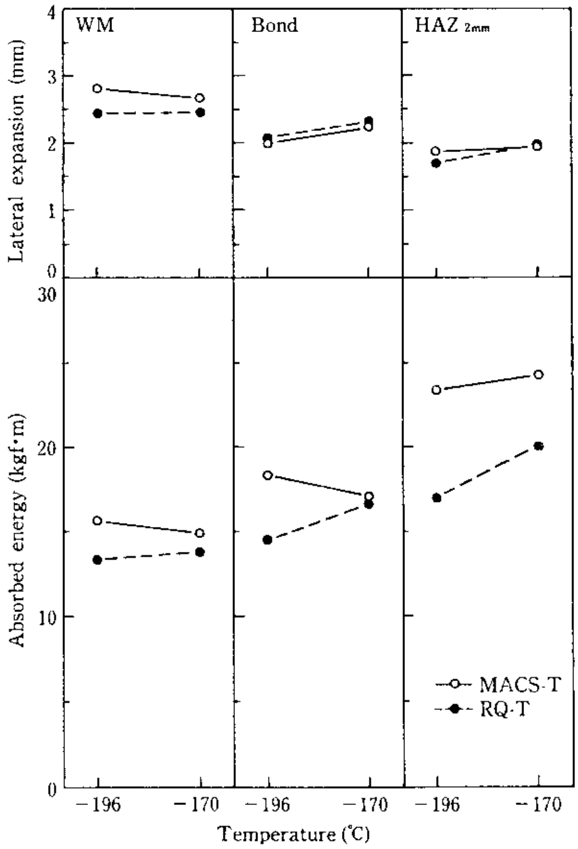


Fig. 6 Charpy test results on the vertical TIG welded joints of 9%Ni steel plates produced by MACS-T and RQ-T processes

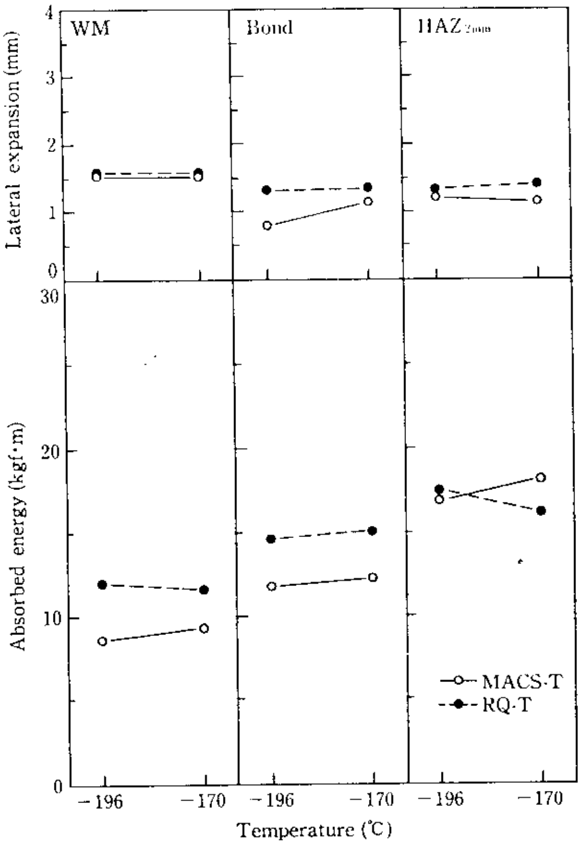


Fig. 7 Charpy test results on the horizontal SAW joints of 9%Ni steel plates produced by MACS-T and RQ-T processes

The absorbed energy and lateral expansion for all notch positions met the the ASTM specification values for the base metal. No significant difference was observed between the RQ-T steel and MACS-T steel.

3.2.2 COD test of welded joints

In accordance with BS 5762[5], the COD test was carried out using specimens taken from the center of the weld metal, the bond, and the HAZ-2-mm. The test results are shown in **Figs. 8** and **9**. The COD values for each welded joint were lower than those of the base metals shown in Figs. 4 and 5. A pop-in was observed in the specimens which yielded COD values between 0.08 and 0.45 mm. However, the COD at −170°C was 0.5 mm or more for the welded joint of the RQ-T steel and 0.2 mm or more for that of the MACS-T steel. Thus, the welded joints were also proved to be satisfactory for LNG storage tanks.

3.2.3 Center-notched cross-welded joint tensile test

The center-notched cross-welded joint tensile test was carried out to study the brittle fracture initiation

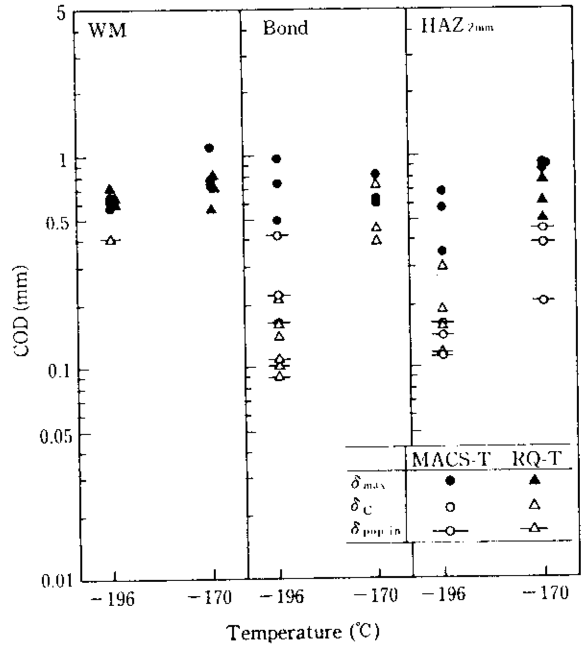


Fig. 8 COD test results on the vertical TIG welded joints of 9%Ni steel plates produced by MACS-T and RQ-T processes

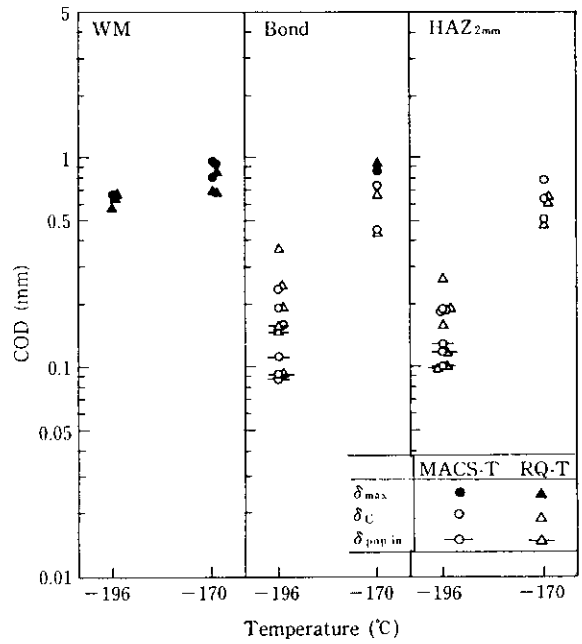


Fig. 9 COD test results on the horizontal SAW joints of 9%Ni steel plates produced by MACS-T and RQ-T processes

property in a case where a large defect is present in a butt welded joint of 35-mm thick steel plate. The specimen geometry is illustrated in **Fig. 10**. The specimen was the same thickness as the steel plate. The through-thickness notch was made in the HAZ-2-mm of test bead so that

Table 6 Center-notched-cross-welded-joint tension test results

Welding method	Steel	Specimen dimensions (mm)			Test temperature (°C)	Maximum load (tonf)	Maximum Stress (kgf/mm^2)		K_C ($kgf/mm^{3/2}$)	Clip gage opening displacement V_g (mm)			Critical COD δ_C (mm)		
		Thickness	Width	Notch length, 2C			σ_{gross}	σ_{net}		Upper	Lower	Ave.	Upper	Lower	Ave.
Vertical TIG	RQ-T	35.84	400	37.00	−171	1 144	79.9	88.1	611.3	1.96	1.57	1.77	1.50	1.21	1.35
	MACS-T	35.38	400	38.00	−170	1 102	77.9	86.1	604.9	2.58	—	—	1.93	—	—
Flat SAW	RQ-T	35.75	400	43.55	−170	1 158	81.0	90.9	673.2	2.22	1.91	2.07	2.05	1.77	1.91
	MACS-T	35.31	400	39.80	−170	1 134	80.3	89.2	631.1	1.89	1.55	1.72	1.64	1.34	1.49

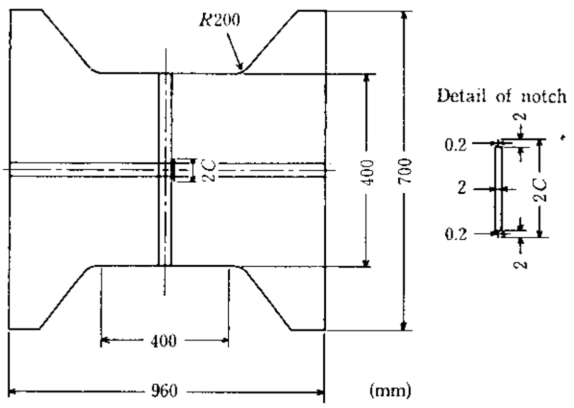


Fig. 10 Geometry of center-notched-cross-welded-joint test specimen

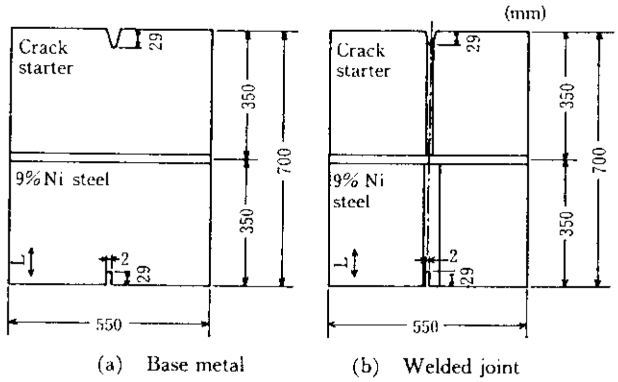


Fig. 11 Geometry of duplex ESSO test specimens

the notch length was 4 mm longer than the width of the weld bead, in order to introduce residual stress.

The tensile test was conducted at −170°C using these specimens in a 8000-t test rig. During the test, the crack opening was measured with clip gages installed at both ends of the notch. The test results are summarized in **Table 6**. The maximum net section stress (σ_{net}) exceeded 86 kgf/mm^2 at −170°C, which is more than the tensile strength specified for the base metal. The critical COD exceeded 1.2 mm which was larger than those measured by the three point bend test. Similar phenomena were observed in 80-kgf/mm^2 quenched-and-tempered steels[6] and Al-killed steels for low-temperature service[7]. The cause of these phenomena is mostly attributable to the difference in the sharpness of the notch tip. It is also attributable to the difference in the degree of restraint against deformation at the notch tip; that is, the degree of restraint against deformation at the notch tip is lower in the wide plate tensile test specimen than in the three point bend test specimen. Ductile fractures occurred in all cases. The ductile crack departed from the HAZ and propagated through the weld metal. The experimental results showed no great difference between the RQ-T steel and MACS-T steel.

3.2.4 Duplex ESSO test

The duplex ESSO test was conducted to investigate the brittle-crack arrestability of the base metal and butt welded joints. The specimen geometry is shown in **Fig. 11**. Each specimen was prepared by welding a normalized-and-tempered (NT) 9% Ni steel plate, as the crack starter, to 15-mm and 35-mm thick 9% Ni steel plates as the base metal and also to their butt welded joints. In the duplex ESSO test of butt welded joints, the 3.5% Ni filler metal was used on the U-groove of the crack-starter plate so that a brittle crack could propagate through this part and reach the HAZ-2-mm part of the test plate.

The test was conducted at −170°C and −196°C in 1 200-t and 8 000-t test rigs. The test results are listed in **Table 7**. In the base metals and welded joints, brittle cracks were arrested just after they had reached the tested plates.

4 Safety Evaluation

When the safety of LNG storage tanks is considered, it is first necessary to prevent fractures in weld zones. However, even if a fracture should occur in a welded

Table 7 Duplex ESSO test results

Steel		Specimen dimensions (mm) Thickness	Width	Test temperature (°C)	Load (tonf)	σ_{gross} (kgf/mm²)	Go/No Go
Base metal	RQ-T	15.95	680	−196	434	40.0	No Go
		16.03	680	−196	436	40.0	No Go
		16.07	680	−172	437	40.0	No Go
		16.05	680	−172	437	40.0	No Go
		35.80	680	−190	974	40.0	No Go
		35.88	680	−190	976	40.0	No Go
		35.86	680	−171	976	40.0	No Go
		35.78	680	−171	974	40.0	No Go
	MACS-T	35.68	680	−190	970	40.0	No Go
		35.67	680	−191	970	40.0	No Go
		35.60	680	−169	968	40.0	No Go
		35.68	680	−172	970	40.0	No Go
Vertical TIG	RQ-T	35.73	700	−170	875	35.0	No Go
		35.76	700	−170	934	37.3*	No Go
	MACS-T	35.61	700	−170	873	35.0	No Go
		35.41	700	−170	994	40.0	No Go
Flat SAW	RQ-T	35.79	700	−173	1 002	40.0	No Go
		35.79	700	−172	752	30.0	No Go
	MACS-T	35.33	700	−172	742	30.0	No Go
		35.32	700	−169	806	32.6*	No Go

* Crack started with no blow

joint and a through-thickness crack propagates through one wall plate along the welded joint, it is necessary to arrest the crack at the base metal. From this point of view, the safety of the RQ-T and MACS-T 9% Ni steel plates produced from continuously cast slabs is evaluated as follows.

4.1 Fracture Initiation Property

A method of applying the critical COD to the safety evaluation of structures has been established as WES 2805[8] by the Japan Welding Engineering Society. The safety of a welded joint of a 35-mm thick steel plate was evaluated as an example assuming the following conditions:

(1) Angular distortion	15 mm/1 000 mm
(2) Offset	1.5 mm
(3) Weld bead width	26 mm
(4) Design stress	16.7 kgf/mm² (ASME Boiler and Pressure Vessel Code, Sec. VIII, Div. 1)
(5) Assumed defect	Semi-elliptical surface defect (depth $b = 0.15t$, surface length $a = 2t$, plate thickness $= t$)
(6) Critical COD of welded joint	$\delta_C = 0.2$ mm (minimum value for the welded joint of MACS-T steel plate) $\delta_C = 0.5$ mm (minimum value for the welded joint of RQ-T steel plate)

The strain e acting on the defect is given by the following equation:

$$e = e_1 + e_2 + e_3$$

where e_1: Strain due to boundary force
e_2: Strain due to residual stress
e_3: Local concentrated strain generated by weld defect

From the design stress, e_1 is calculated as follows: $e_1 = 8.4 \times 10^{-4}$. Assume that a surface defect exists in the T joint and the residual stress is 60% as large as the specified yield strength. Then, $e_2 = 1.80 \times 10^{-3}$. Since $e_3 = (k_t - 1)e_1$ and the k_t due to angular distortion (w) and offset (h) is given by $k_t = 1 + 3(w + h)/t$, e_3 is given by $e_3 = 1.18 \times 10^{-3}$.

Therefore, the strain acting on the defect is calculated as follows: $e = 3.82 \times 10^{-3}$. When the strain e acts on a through-thickness defect of $2\bar{a}$ in length, the opening displacement δ generated at the tip of the defect is given by the following equation:

$$\delta = 3.5e\bar{a}$$

Therefore, the maximum allowable defect length that does not cause this steel to fracture when $e = 3.82 \times 10^{-3}$ is determined. This length is $2\bar{a} = 29.9$ mm for the welded joint of the MACS-T steel and $2\bar{a} = 74.8$ mm for that of the RQ-T steel.

When this through-thickness defect is converted into a surface defect which is equivalent in terms of fracture mechanics, the surface defect length $2a$ is infinity at $b = 0.15t = 5.3$ mm.

In the three point bend test of MACS-T welded steel joints, some specimens exhibited brittle fracture and pop-in at −170°C. The COD value at the occurrence of pop-in was as high as 0.21, 0.39, and 0.45 mm. In the notched wide-plate tensile test, the pop-in as observed in the small-scale three point bend test was not observed. All cracks, initiated at the tips of notches cut into the HAZ of welded joints, were of brittle fractures that propagated through the soft weld metal. Furthermore, the maximum net section stress exceeded 86 kgf/mm², which is higher than the specified yield strength and is almost equivalent to the yield stress at −170°C. It is not expected, therefore, that brittle fractures can occur in the welded joints even if a defect of a certain size exists. It is concluded that the welded joints of these steel plates have sufficient ductility and strength.

4.2 Crack Arrestability

In the duplex ESSO test conducted on these steel plates and welded joints, brittle cracks were arrested immediately after they reached the tested plates. The stress intensity factor, when the crack reached the tested plate after propagating through the crack-starter plate, was calculated by the following equation[9].

$$K_{ca} = \sigma_{gross}\sqrt{\pi c}\sqrt{\frac{2W}{\pi c}\tan\frac{\pi c}{2W}}$$

where c is the crack length after the arrest and W is the specimen width. The brittle fracture arrest toughness K_{ca} is 1 220 $kgf/mm^{3/2}$ or more. The result demonstrates that the tested steel plates have arrestability sufficient to arrest a 3 000-mm long crack[10] at the design stress.

On the other hand, the empirical study[11] and the dynamic analysis[12] indicated that the stress intensity factor at the tip of a long crack in propagation was about 600 $kgf/mm^{3/2}$ maximum. This indicates that a crack can be arrested even by steel plate with a K_{ca} of about 600 $kgf/mm^{3/2}$. Since the K_{ca} values of the tested steel plates exceeded 1 220 $kgf/mm^{3/2}$, they have sufficient crack arrestability.

In summary, both RQ-T and MACS-T steel plates produced from continuously cast slabs were found to be used safely for the construction of LNG storage tanks.

5 Conclusions

An laboratory study was performed on direct quenching conditions for low-P-and-low-S 9% Ni steel plates produced from continuously cast slabs, and a safety evaluation was carried out on base metal and welded joints of the RQ-T steel and MACS-T steel, which were produced in the mill. As a consequence, the following results were obtained:

(1) When steel plates were produced by the direct quenching and tempering process (MACS-T), ductile fracture energy increased as the slab reheating temperature and finish-rolling temperature was raised.

(2) In both RQ-T steel plates (by the reheat-quenching and tempering process) and MACS-T steel plates produced in the mill, the COD values of SAW and TIG welded joints at −170°C exceeded 0.2 mm. This fact indicated that a $2\bar{a}$ through-thickness defect of 29.9 mm for MACS-T steel and 74.8 mm for RQ-T steel can be allowed at the design stress.

(3) In both RQ-T steel plates and MACS-T steel plates, even a brittle crack that has propagated through one wall plate width along a welded joint can be arrested by the base metal.

It was ascertained from these results that 9% Ni steel plates produced from continuously cast slabs of both RQ-T steel and MACS-T steel ensure great safety as materials for LNG storage tanks.

6 Acknowledgment

This report is based on the results of joint research with Ishikawajima-Harima Heavy Industries Co., Ltd.

The authors would like to extend their sincere thanks to Mr. Takesuke Kohno, Mr. Norihiko Katayama, Mr. Takehiro Murayama, and Dr. Shoichiro Kaihara of Ishikawajima-Harima Heavy Industries Co., Ltd. for their great cooperation and helpful advice in making this study.

References

1) S. Suzuki, Y. Nakano, K. Hirose, T. Okumura, H. Nishikawa, and M. Satoh: *Kawasaki Steel Giho*, **14**(1982)1, 28
2) O. Furukimi, S. Suzuki, and Y. Nakano: *Tetsu-to-Hagané*, **68**(1982)5, S487
3) Y. Nakano, S. Suzuki, A. Kamada, and K. Hirose: *Advances in Cryogenic Engineering Materials*, **28**(1982),127
4) O. Furukimi, Y. Nakano, S. Ueda, and T. Tanaka: *Tetsu-to-Hagané*, **72**(1986)10, 1621
5) British Standards Institution: BS 5762(1979)
6) Y. Nakano: "The Effect of Test Method on J-Integral value for HT80 Steel," Report for Technical Committee, JI Committee of Steel Sectional Meeting of Japan Welding Eng. Soc., July(1977), Private Communication
7) S. Kaihara, et al.: Quarterly Journal of the Japan Welding Society, 2(1984)3, 455
8) Japan Welding Engineering Society: WES 2805 "Method of Assessment for Defects in Fusion Welded Joints with Respect to Brittle Fracture," (1980)
9) Japan Welding Engineering Society: WES 3003 "Evaluation Criterion of Structural Steels for Low Temperature Application," (1973)
10) K. Tanaka, M. Satoh, and T. Ishikawa: "Fatigue COD and Short Crack Arrest Test," International Conference of Fracture Toughness Testing, June(1982), London
11) Y. Nakano: *Journal of the Society of Materials Science, Japan*, 31(1982)344, 463
12) T. Kanazawa, S. Machida, H. Yajima, and M. Aoki: *Journal of Society for Naval Architecture*, 11(1973)