KAWASAKI STEEL TECHNICAL REPORT
No.17 (October 1987)

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Ryoji Kinaka, Taketo Okumura, Hisae Terashima, Sho Minagawa, Yoshifumi Nakano, Shigeto Matsumoto

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

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

Hisae Terashima
Dr. Engi., Senior Researcher, Plate Lab., Plate Research Dept., I & S Research Labs.



Sho Minagawa
Kawatetsu Galvanizing Co., Ltd.

Yoshifumi Nakano
Ph. D., Senior Researcher, Laboratory II, Mizushima Research Dept., I & S Research Labs.

Shigeto Matsumoto
Senior Researcher, Plate Lab., Plate Research Dept., I & S Research Labs.

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Investigation has been made on the properties of continuously cast 38 mm thick SLA37 steel plates for LPG storage tanks. The crack arrest toughness K_{ca} of the steel plates manufactured by Kawasaki Thermomechanical Rolling (KTR) and Multipurpose Accelerated Cooling System (MACS) processes was higher than 600 kgf/mm$^{3/2}$ at −50°C. In vertical MIG, TIG, SAW, and horizontal SAW of steel plates manufactured by the quenching and tempering (QT) process, and in EGW with a high weld heat input of 65∼115 kJ/cm of QT, KTR, and MACS steel plates, bond properties measured at the fusion line of welded joints are 7 kgf·m and over in ${}_vE_{-50°C}$, 0.3 mm and over in −50°C COD value, and 470 kgf/mm$^{3/2}$ in K_{ca}. The foregoing results proved the technical feasibility of the production of SLA37 steel plate for LPG storage tanks by using the combination of continuous casting and QT, KTR and MACS processes.

1 Introduction

Current practice for storing large quantities of LPG uses the double-shell cylindrical tank specially designed for the dual effects of low temperature and atmospheric pressure. Its only drawback is a 40 000-t storage limitation, and this is due mainly to the fact that carbon steel plates SLA33B (yield point 33 kgf/mm^2, quenched and tempered) for pressure vessels for low-temperature service (specified under JIS G3126) are used for the tank proper, and designed with a maximum thickness of 38 mm, beyond which plates are required to be stress-relieved. A higher storage aimed within a limited land area demands an increase in storage capacity per tank, but the construction of a 55 000-t tank using SLA37 steel plate, which is one grade higher in strength, was not an easy task.

Further, in order to shorten field construction periods for a larger tank, an automatic and high-efficiency field welding method was urgently needed to replace the shielded metal arc welding (SMAW) and the submerged arc welding (SAW), which were mainly used for the conventional field welding of LPG storage tanks; the effort to solve this problem called for the development of electrogas arc welding or others, along with a review of conventional welding methods.

Parallel with the above were noticeable developments in the steel sector; namely, the production of very clean steels and the adoption of continuous casting process both in steel refining, and the controlled rolling method KTR (Kawasaki Thermomechanical Rolling) and accelerated cooling method MACS (Multipurpose Accelerated Cooling System) both practiced in the plate rolling mill in addition to the conventional quenching and tempering (QT) method.

Against the foregoing backdrop, a series of tests was conducted with the following research objectives in order to develop 38-mm thick SLA37 steel plates made from continuously cast slabs:

(1) Study on how to apply various automatic welding of

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* Originally published in *Kawasaki Steel Giho*, **18**(1986)4, pp. 321-326

** Presently on assignment to Companhia Siderurgica de Tubrão conventional QT steel plates

(2) Ascertainment of the basic properties, fracture toughness, welded-joint properties and formabilities of KTR- and MACS-processed steel plates

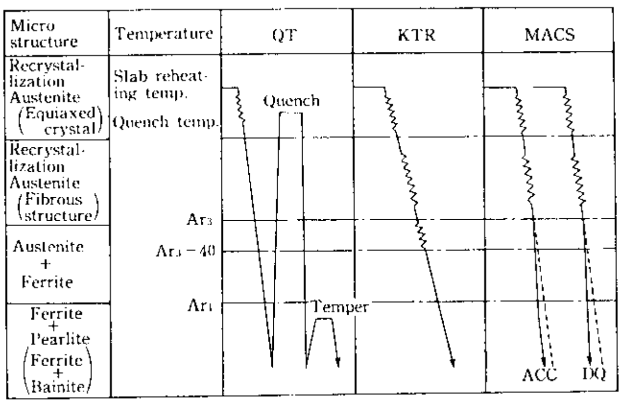
(3) Ascertainment of the properties of welded joints of QT-, KTR- and MACS-processed steel plates produced by large heat input welding

This report presents an outline of the test results obtained.

2 Design Concept of Sample Steel Plates

2.1 Manufacturing Methods of Al-killed Steel Plates for Low-Temperature Service

As steelmaking techniques and steel plate manufacturing techniques have made progress, the QT method is being replaced by the KTR method and MACS method in the manufacture of Al-killed steel plates for low-temperature service and continuously cast slabs are used in place of slabs from ingots. Furthermore, the standardization of these new manufacturing processes in JIS are being carried forward. A comparison between the conventional method and new methods for manufacturing steel plates is schematically shown in **Fig. 1**. Kawasaki Steel has established manufacturing conditions for bringing out the best features of steel plates produced by each manufacturing process.



QT: Quench temper
KTR: Kawasaki thermomechanical rolling
MACS: Multipurpose accelerated cooling system
ACC: Accelerated (Controlled) Cooling
DQ: Direct Quenching

Fig. 1 Schematic diagram of manufacturing process of SLA 37

2.2 Measures to Improve Applicability of Al-killed Steels for Low-Temperature Service to Large Heat Input Welding

The composition series of steel grade SLA37 for LPG storage tanks are low-C composition series designed by adding various alloying elements to Si-Mn steels as the basic composition to improve the low-temperature toughness of the base metal and welded joints. Particularly, there are two composition series excellent in low-temperature toughness: Cu-V-Ni and Nb series. Characteristics of these two composition series are given in **Table 1**. By adopting the low-C type, the toughness of the welded joint can be improved in addition to the improvement of the low-temperature toughness of the base metal. However, since the toughness of welded joints obtained by large heat input welding decreases due to grain coarsening, the addition of these alloying elements alone is insufficient for ensuring the toughness at −45°C or below. The grain refining of the heat-affected zone utilizing fine precipitates produced by adding REM and Ti is effective in this respect.

Table 1 Characteristics of chemical composition

Process	Type of chemical composition	Purpose of alloying elements	Characteristic
QT KTR	Low C-Cu-V-Ni	· Cu, V and Ni additions contribute to raising the strength. · Ni addition improves low temperature toughness. · REM and Ti additions prevent the toughness deterioration of the high heat input weld joint.	The carbon equivalent is slightly high value because of Cu, V and Ni additions, but the low temperature toughness is superior.
MACS	Low C-Nb	· Nb addition contributes to raising the strength. · The effect of refining the grain size by Nb addition improves the low temperature toughness. · REM and Ti additions and the reduced Si content prevent the toughness deterioration of the high heat input weld joint.	The carbon equivalent is low because of raising the strengh through the Nb addition only, and the weld ability is superior.

In the MACS steel, the Si content was decreased to improve the properties of welded joints made by the large heat input welding. As is apparent from **Fig. 2** which shows an example of effect of the Si content on the toughness of welded joint,[1] Si contents ranging from 0.1 to 0.13 wt.% are most suited to the toughness of welded joints. Since the Si content of SLA37 specified in JIS, however, ranges from 0.15 to 0.55 wt.%, in reality the range from 0.16 to 0.18 wt.% was aimed at. The effect of the Nb content on the toughness of welded joints[1] is shown in **Fig. 3**. As is apparent from this figure,

Table 2 Chemical composition of materials

(%)

Process	Sample	C	Si	Mn	P	S	Cu	Ni	V	Nb	Al	Ti	REM	N	C_{eq}*
QT	Ladle	0.08	0.22	1.54	0.005	0.004	0.16	0.22	0.026		0.037	0.008	0.006	0.0036	0.36
	Product	0.08	0.22	1.54	0.006	0.004	0.17	0.22	0.026		0.038	0.007	0.006	0.0040	0.36
KTR	Ladle	0.08	0.30	1.57	0.006	0.003	0.20	0.40	0.040		0.034	0.008	0.006	0.0041	0.37
	Product	0.08	0.29	1.56	0.006	0.004	0.18	0.41	0.040		0.037	0.007	0.006	0.0048	0.37
MACS	Ladle	0.06	0.16	1.47	0.008	0.002				0.012	0.019	0.007	0.006	0.0035	0.31
	Product	0.07	0.17	1.45	0.008	0.002				0.014	0.022	0.007	0.004	0.0036	0.32
Specification of SLA 37		≤0.18	0.15 ~ 0.55	0.80 ~ 1.60	≤0.035	≤0.035									

* $C_{eq}=C+\frac{Mn}{6}+\frac{Si}{24}+\frac{Cr}{5}+\frac{Mo}{4}+\frac{V}{14}$

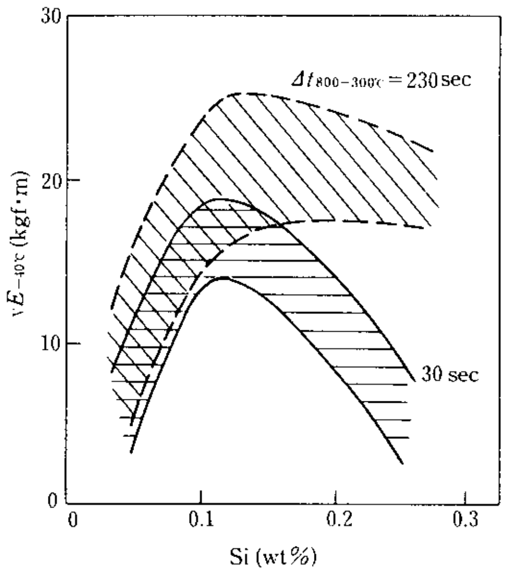


Fig. 2 Effect of Si content on absorbed energy at −40°C of synthetic heat affected zone of 0.09%C-1.4%Mn-Ti-REM steel

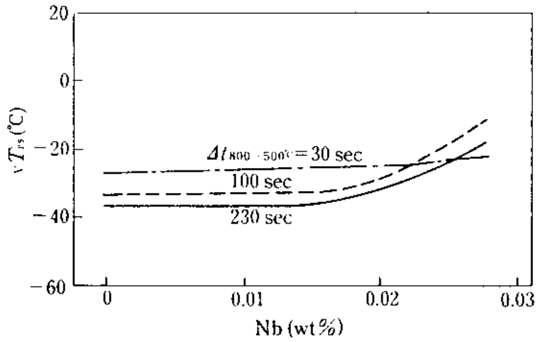


Fig. 3 Effect of Nb content on V notch charpy fracture appearance transition temperature of synthetic heat affected zone of 0.07%C-1.5%Mn-Ti-REM steel

the toughness decreases at Nb contents of 0.025 wt.% or more and appropriate Nb contents are 0.020 wt.% or less.

Based on this basic philosophy of composition design, steel plates were made for trial in an actual plant. The chemical compositions of these sample steel plates are shown in **Table 2**. The manufacturing process employed involves refining by a 150-t BOF, RH degassing, continuous casting, plate rolling and heat treatment.

3 Base Metal Properties

3.1 Basic Properties

The tensile and bend tests and Charpy V-notch impact test were conducted on sample steel plates. Results of these tests are shown in **Table 3**. All of the

Table 3 Mechanical properties of base metal

Process	Thickness	Direction	Tensile test			Bend test 180°	Charpy V-notch test(1/4 t)		
			YS (kgf/mm²)	TS (kgf/mm²)	El (%)	$R=1.5t$	$_{V}E_{-60}$ (kgf·m)	$_{V}T_{rE}$ (°C)	$_{V}T_{rs}$ (°C)
QT	38	L	44.7	53.2	39	Good	31.1	<−120	<−120
		C	44.3	52.7	39	Good	28.3	<−120	<−120
KTR	38	L	41.0	50.8	37	Good	26.6	−112	<−120
		C	42.5	52.3	36	Good	21.7	−105	<−120
MACS	38	L	44.3	51.5	35	Good	27.6	−121	<−120
		C	45.0	51.7	34	Good	22.2	−92	−98
Specification of SLA 37			≥37	50~60	≥20	1.5 t	—	≤−55	—

Table 4 Fracture toughness of base metal*

Steel	Three point bending COD test**	Deep notch test		ESSO test			Double tensile test		
	δ_C (mm)	σ_{net} (kgf/mm²)	K_C (kgf/mm$^{3/2}$)	K_{Ca} (kgf/mm$^{3/2}$)	Classification*** A (°C)	Classification*** G (°C)	K_{Ca} (kgf/mm$^{3/2}$)	Classification*** A (°C)	Classification*** G (°C)
QT	>1.70 >1.73	58.6	634.2	190	−31	−64	210	−35	−67
KTR	>1.75 >1.79	53.8	550.5	600	−75	−105	700	−94	−138
MACS	1.51 1.41	56.7	580.2	660	−67	−88	700	−74	−103

* Tested at −50°C
** BS 5762
*** WES 3003

sample steel plates met the values of yield strength and tensile strength specified in JIS (YS ≧ 37 kgf/mm² and TS ≧ 50 kgf/mm²). Furthermore, all results of the bend test were good. Results of the Charpy V-notch impact test obtained in each sample steel plate were also good with toughness of more than 20 kgf·m at −60°C and both $_{V}T_{rE}$ and $_{V}T_{rs}$ of less than −90°C. As with results obtained in the past, the value of absorbed energy was high in the QT steel and anisotropy was not observed. In contrast, anisotropy was observed in the KTR steel between the direction parallel to the rolling direction and the direction normal to the rolling direction. The MACS steel gave characteristics intermediate between the QT steel and the KTR steel, which seem to vary depending on plate rolling conditions.

3.2 Fracture Toughness

Various fracture toughness tests including the COD (crack opening displacement) test were conducted on the base metals of these sample steel plates. Results of these tests are shown in **Table** 4. The COD test was carried out in accordance with BS 5762[2]; a through-thickness notch was made in the specimen and a fatigue crack was introduced at the end of the notch.

If the evaluation method shown in WES 3003—Evaluation criterion of rolled sheets for low temperature application[3]—is adopted for the evaluation of COD-values, the toughness value δ_C required of a steel plate is given by the following equation from $\sigma = \sigma_{y_0}/2$, proof yield strength of steel plate $\sigma_{y_0} = 37$ kgf/mm² and Young's modulus $E = 21\,000$ kgf/mm²:

$$\delta_C = \frac{3.85\sigma_{y_0}}{E} \times \frac{1\,100}{\sigma y_0} \cdots\cdots (1)$$

$$\therefore\ \delta_C = 0.20$$

As shown in Table 4, all the δ_C-values at −50°C are more than 1.2 mm. This demonstrates that all of the steel plates have very high toughness.

The deep notch test was conducted using specimens with a notch of 160 mm full length and 0.1 mm end radius. The fracture toughness value K_C in the deep notch test was calculated by the following equation:

$$K_C = \sigma_g\sqrt{W\tan(\pi c/W)} \cdots\cdots (2)$$

where σ_g: Nominal stress at the maximum load
W: Specimen width
$2c$: Notch length

Results of the deep notch test were satisfactory and the fracture stress σ_{net} was sufficiently higher than the specified yield strength. The temperature gradient type ESSO test and double-tension test were conducted to study the brittle crack arrest capability of the sample steel plates. The stress intensity factor at a temperature at the brittle crack arrest position (brittle crack arrest toughness K_{Ca}) was calculated using Eq. (3). A comparison between results of these tests between the KTR and MACS steels and the QT steel is given in **Fig.** 4. A good agreement is observed between the results of ESSO and double-tension tests.

$$K_{Ca} = \sigma\sqrt{2W\tan(\pi C_a/2W)} \cdots\cdots (3)$$

where σ: Gross stress
C_a: Length of crack starter
W: Specimen width

The results of the ESSO test and double-tension test reveal that the brittle crack arrest toughness of the sample steel plates is in the following order: KTR steel ≧ MACS steel > QT steel. That is, the brittle crack arrest capability of the KTR and MACS steels is higher than that of the QT steel.

3.3 Fatigue Properties

The fatigue crack propagation rate and threshold range of stress intensity factor for crack propagation (ΔK_{th}) were determined to investigate the fatigue properties of the sample steel plates. Results of the measurement are shown in **Table** 5. No significant difference among the steel plates was observed. The ΔK was calculated by the following equation (ASTM E647-83[4]):

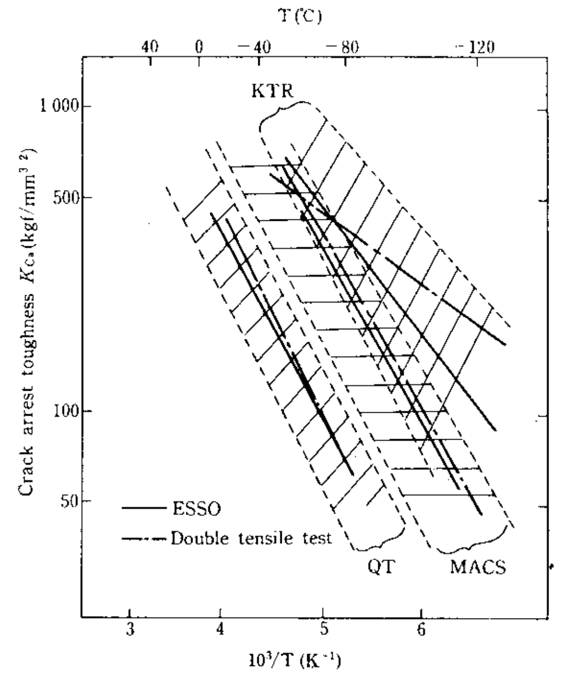


Fig. 4 Relation between crack arrest toughness K_{Ca} and test temperature

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \times \frac{(2+\alpha)}{(1-\alpha)^{1.5}}(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \cdots\cdots(4)$$

$$\frac{da}{dN} = C(\Delta K)^m$$

Table 5 The value of m and C obtained in fatigue crack propagation tests

Steel	Material constants	
	m	C
QT	3.20	5.71×10^{-11}
KTR	3.06	1.04×10^{-10}
MACS	3.36	3.35×10^{-11}

where ΔK: Range of stress intensity factor
ΔP: Load range
B: Specimen thickness
W: Specimen width
a: Crack length
N: Number of cycles
C, m: Material constants
α: a/W

The ΔK_{th} of the QT and MACS steels was 19 and 16 kgf/mm$^{3/2}$, respectively.

4 Properties of Welded Joints

4.1 Welding Conditions

Welding Conditions for the sample steel plates used for investigating the properties of welded joints are shown in **Table 6**. Welding was conducted in the same manner as in actual LPG tanks, i.e., in a manner that the rolling direction of the steel plates was the same as the

Table 6 Welding conditions

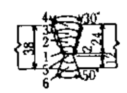
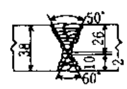
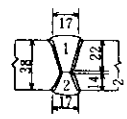
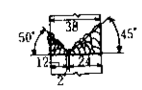
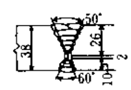
Welding method	Steel	Welding material	Side	Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/cm)	Shape of groove
MIG	QT	KM-3N 1.2 mmφ	Back	126∼131	21.0∼22.0	5.9∼5.2	26.8∼33.0	
			Finish	122∼123	21.5∼22.0	6.5∼5.4	24.4∼30.0	
TIG	QT	KT-50 1.2 mmφ	Back	290∼288	10.0∼10.5	5.5∼4.9	31.3∼37.0	
			Finish	300∼280	10.0∼10.5	5.5∼4.9	32.8∼35.9	
EGW	QT, KTR, MACS	EG-51S 1.6 mmφ	Back	380	40	8.5	107.3	
			Finish	380	40	13.2	69.1	
SAW	QT	KW-50C KF-400H	Back	480	26.0	40.0	18.7	
			Finish	480	26.0	40.0	18.7	
SMAW	QT	KS-81LT 4.0 mmφ	Back	160	25.0	7.2	33.3	
			Finish	148	24.0	6.3	33.6	

Table 7 Mechanical properties of welded joints

Welding method	Process	Tensile test*			Bend test			Charpy V-notch test											
		TS (kgf/mm²)	El (%)	Fracture location	Side bend	Surface bend		Charpy absorbed energy (kgf·m)*						$_{V}T_{rs}$					
								Backing side			Finishing side			Backing side			Finishing side		
						El (%)	Result	WM	Bond	HAZ	WM	Bond	HAZ	WM	Bond	HAZ	WM	Bond	HAZ
MIG	QT	54.7	21.5	WM	Good	38.1	Good	10.1 (47)	10.7 (4)	26.1 (3)	13.8 (32)	13.7 (38)	28.0 (0)	−52	−55	−80	−56	−56	<−80
TIG	QT	56.1	17.3	WM	Good	40:4	Good	28.5 (7)	23.4 (22)	28.5 (3)	21.8 (22)	24.5 (12)	26.8 (3)	<−80	<−80	<−80	<−80	−57	<−80
EGW	QT	57.1	44.7	HAZ-BM	Good	26.2	Good	13.2 (28)	18.5 (28)	23.8 (8)	15.3 (20)	10.0 (47)	20.9 (20)	−62	−60	<−80	<−80	−52	−76
EGW	KTR	57.0	40.7	HAZ-BM	Good	18.7	Good	12.2 (30)	11.8 (38)	18.6 (28)	15.0 (15)	7.3 (43)	12.7 (45)	−70	−57	−73	−75	−55	−57
EGW	MACS	54.3	43.0	HAZ-BM	Good	17.5	Good	11.6 (25)	18.8 (27)	28.7 (0)	15.2 (10)	26.0 (13)	28.8 (0)	−74	−58	<−80	<−80	−68	<−80
SAW	QT	56.6	45.5	HAZ-BM	Good	21.5	Good	5.4 (50)	15.0 (28)	24.6 (0)	6.4 (47)	17.9 (18)	25.3 (0)	−50	−65	<−80	−55	−57	<−80
SMAW	QT	57.5	48.9	HAZ-BM	Good	18.1	Good	14.8 (28)	21.5 (13)	27.3 (0)	18.4 (17)	21.7 (17)	27.3 (3)	−62	<−80	<−80	−80	−75	<−80

* Mean value of 2 test pieces
** Mean value of 3 test pieces, Test temperature −50°C, ( ) Crystallinity percentage

weld line for SAW and perpendicular to the weld line direction for MIG, TIG, EGW and SMAW.

4.2 Basic Properties of Welded Joints

Results of the tensile and bend tests and Charpy V-notch impact test on welded joints are shown in **Table 7**. All values of tensile strength of each welded joint met the requirements specified in the standard for the base metal (SLA37 in JIS G3126). All results of the bend test were also good. Values of absorbed energy at −50°C obtained in each joint were more than 5.0 kgf·m and were satisfactory. In welded joints obtained by EGW that is a kind of the large-heat input welding, the absorbed energy at −50°C in the weld metal, fusion line and HAZ of all the steel plates was more than 10 kgf·m on the backing side and more than 7.0 kgf·m on the finishing side, and all values of $_{V}T_{rs}$ were below −50°C and good.

4.3 Fracture Toughness of Welded Joints

The COD test of the fusion line, HAZ, and weld metal of each welded joint obtained by EGW and the deep notch test and ESSO test of the fusion line of the welded joints were conducted at a test temperature of −50°C. Results of these tests are shown in **Table 8**. The COD value δ_C of each welded joint was more than 0.2 mm, that of the fusion line more than 0.3 mm, and that of the HAZ more than 1.0 mm. Thus, all COD values were good.

Results of the deep notch test of the fusion line reveal that the true fracture stress is sufficiently higher than the nominal stress. The fracture toughness value K_C of the fusion line of EGW joints, which are vertical joints on which circumferential (hoop) stresses act, was more than 436 kgf/mm$^{3/2}$.

The ESSO test was conducted on the fusion line of EGW joints of the KTR and MACS steels and the

Table 8 Fracture toughness of welded joints*

Welding method	Process	Three point bending COD test			Deep notch test (Bond)		ESSO test (Bond)		
		δ_C (mm)			σ_{net} (kgf/mm²)	K_C (kgf/mm$^{3/2}$)	K_{Ca} (kgf/mm$^{3/2}$)	Classification	
		WM	Bond	HAZ				A (°C)	G (°C)
MIG	QT		0.651	>1.856	60.2	601.9			
TIG	QT		0.508	>1.882	59.1	591.0			
EGW	QT	0.201	0.335	>1.843	51.4	525.5			
EGW	KTR	0.412	0.504	>1.676	47.8	489.1	500	<−100	<−100
EGW	MACS	0.204	1.253	>1.824	42.6	435.6	480	−72	−116
SAW	QT		1.171	>1.899	47.9	489.7	470	−66	−104
SMAW	QT		>1.890	>1.330					

* Test temperature, −50°C

fusion line of horizontal SAW joints of the QT steel. Results of these tests are shown in Table 8. As is apparent from this table, the temperatures for A-grade were −66°C or below; the results were equivalent to or better than those obtained in the base metal. Although attempts were made to make cracks propagate along the fusion line of welded joints, the cracks did not propagate along the fusion line in any case but propagated into the base metal, where they were arrested. In terms of crack arrest, a crack which does not go straight ahead in the fusion line but propagates into the base metal is favorable, because the crack deviate from the fusion line while the stress intensity factor is still small. Welding residual stresses are the main cause of the phenomenon in which a crack does not propagate along the fusion line.

Next, an examination is made into the occurrence of brittle fracture in the manufacture of LPG storage tanks. Vertical welded joints are taken into consideration because the maximum stress in a tank is generated as hoop stresses and the magnitude of stresses in the height direction is considered about half of the hoop stresses. The minimum COD value at −50°C or a temperature little lower than that of LPG was obtained in the weld metal when an EGW joint was considered; this value was 0.2 mm. The minimum COD value in the fusion line was 0.3 mm or more. The minimum COD value in the weld metal, i.e., 0.2 mm is adopted here for the discussion.

For welded joints of a tank, a plate thickness of 38 mm, which is the severest plate thickness from the standpoint of brittle fracture, is adopted and the angular distortion and offset are assumed to be 15 mm/1 000 mm and 5 mm, respectively. These angular distortion and offset values assumed are sufficiently conservative in consideration of techniques used for welding a tank.

The method specified in WES 2805[5] of the Japan Welding Engineering Society is adopted as the method of evaluating the occurrence of brittle fracture using COD.

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

$$e = e_1 + e_2 + e_3$$

If e_1, which denotes a stress due to a boundary force, is supposed to be 14 kgf/mm^2 as the design stress, then $e_1 = 6.67 \times 10^{-4}$ is obtained.

The symbol e_2 denotes a strain due to a welding residual stress and is given by the yield strain e_y multiplied by 0.6. Hence, $e_2 = 1.06 \times 10^{-3}$.

The symbol e_3 denotes a strain due to joint shape. If the angular distortion and offset are supposed as mentioned above, then $e_3 = 1.05 \times 10^{-3}$. From the above, the strain $e = 2.78 \times 10^{-3}$ is obtained.

It is considered that the COD value δ and the strain e have the following relationship to the defect parameter $\bar{a}$:

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

Therefore, if COD is supposed to be 0.2 mm, $2\bar{a} = 41$ mm. If this through-thickness defect is converted to a surface defect which is equivalent in terms of fracture mechanics, the surface defect length $2\bar{a}$ is infinity when the depth b is $0.25t = 9.5$ mm. Such large defects can be easily detected by nondestructive testing. Therefore, the safety of LPG storage tanks fabricated using the sample steel plates in this experiment is expected to be sufficiently high.

4.4 Fatigue Crack Propagation in Welded Joints

The relationship between the fatigue crack propagation rate da/dN (mm/cycle) and the stress intensity factor ΔK (kgf/mm$^{3/2}$) in EGW joints of 38-mm thick QT steel plates is shown in **Fig. 5** as an example. The relationship between the two in the weld metal, fusion line, and HAZ is within the range of the relationship in the base metal. Similar results were obtained from other steel plates and welded joints. The fatigue crack propagation test was conducted on steel plates welded by various welding methods. Values of material constants C and m obtained in the test are shown in **Table 9**.

Assuming a storage tank is completely filled with LPG and then completely emptied of this gas twice a day, the stress frequency reaches about 29 000 cycles in a

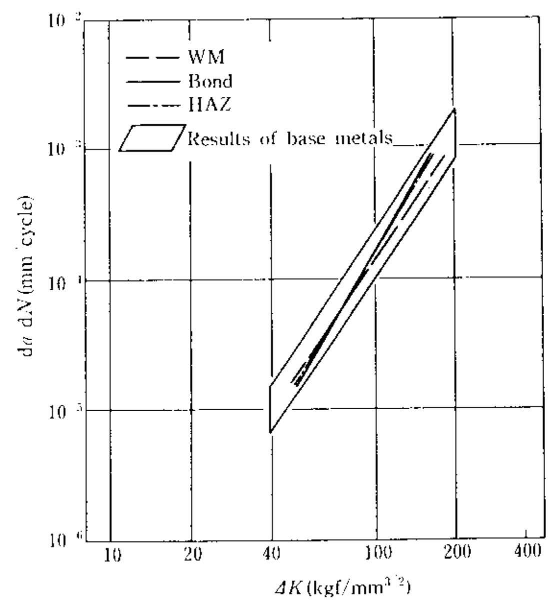


Fig. 5 Relationship between fatigue crack propagation rate da/dN and the range of stress intensity factor ΔK at EGW high heat input welding joints of steel plates produced by QT process

Table 9 The values of m and C obtained in fatigue crack propagation test

Welding method	Process	Notch location	Material constants	
			m	C
MIG	QT	WM	2.79	4.01×10^{-10}
		Bond	3.07	1.19×10^{-10}
		HAZ	3.23	5.89×10^{-11}
TIG	QT	WM	3.48	2.01×10^{-11}
		Bond	3.37	3.15×10^{-11}
		HAZ	3.37	3.31×10^{-11}
EGW	QT	WM	2.98	1.60×10^{-10}
		Bond	3.45	2.23×10^{-11}
		HAZ	3.53	1.50×10^{-11}
EGW	KTR	WM	2.96	2.43×10^{-10}
		Bond	3.04	1.81×10^{-10}
		HAZ	3.44	2.38×10^{-11}
EGW	MACS	WM	3.27	4.83×10^{-11}
		Bond	3.44	2.43×10^{-11}
		HAZ	3.10	1.28×10^{-10}
SAW	QT	WM	3.41	3.33×10^{-11}
		Bond	2.91	2.48×10^{-10}
		HAZ	3.30	4.15×10^{-11}

decade. If a through-thickness crack exists and da/dN is taken as the mean value of the sample steel plates, $1.4 \times 10^{10}(\Delta K)^{3.04}$, the allowable initial-crack length is given as 34 mm from the relation ship between da/dN and ΔK described above.

If this crack is converted to a surface defect, which is the form of crack existing in an actual case, the crack is so large that it is 10 mm deep and 110 mm long. The safety of the sample steel plates was ascertained also from this result.

5 Conclusions

SLA37 steel plates of 38 mm in thickness that provide high applicability to large heat input welding were produced using continuously cast slabs as steel plates for large-capacity LPG storage tanks and the properties of the base metal and welded joints of the steel plates were investigated. As a consequence, the following results were obtained:

(1) The toughness of the base metal of the QT, KTR and MACS steels was good. The absorbed energy was more than 20 kgf·m at −60°C in the direction perpendicular to the rolling direction and the COD value was more than 1.4 mm at −50°C in the direction perpendicular to the rolling direction. In particular, the brittle crack arrest toughness of the KTR and MACS steels thoroughly met requirements for steel plates for LPG storage tanks. The results of the ESSO test and double-tension test indicated that K_{Ca} at −50°C and in the direction perpendicular to the rolling direction was more than 600 kgf/mm$^{3/2}$.

(2) The properties of vertical MIG, TIG, and SMAW joints and horizontal SAW joints of the QT steel were good. All specimens showed toughness of more than 10 kgf·m at −50°C in the fusion line and HAZ, and COD values of more than 0.5 mm at −50°C. Thus, these welding methods can be applied to the fabrication of LPG storage tanks.

(3) The properties of welded joints of the QT, KTR, and MACS steels produced by large heat input welding (EGW, heat input of 65 to 115 kJ/cm) were good. Specimens showed toughness of more than 7 kgf·m, COD values of more than 0.3 mm, and K_{Ca} of more than 480 kgf/mm$^{3/2}$ in the fusion line at −50°C. Thus, EGW can be applied to the vertical welding of side plates of LPG storage tanks.

It was ascertained from the foregoing that it is possible to produce QT, KTR and MACS steel plates suitable to various welding methods used for LPG storage tanks which may be adopted in the future.

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References

1) K. Amano, C. Shiga, and T. Tanaka: Private communication
2) British Standards Institution: BS5762, (1979)
3) The Japan Welding Engineering Society: WES3003, (1983)
4) American Society for Testing and Materials: E647, (1983)
5) The Japan Welding Engineering Society: WES2805, (1980)