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1.5 Ni Steel for LPG Tanks with a Superior Bond-Arrest Property

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Abstract:

Various methods are proposed to ensure the brittle fracture safety of cylindrical LPG tanks. Nippon Steel developed a 1.5Ni steel with excellent brittle crack initiation and propagation arrest characteristics. The duplex ESSO test method was proposed as a method for evaluating the brittle crack propagation arrest performance of the new steel, and it was studied for its relationship with the NRL drop-weight test method, among other test methods.

1. Introduction

Fracture accidents, particularly brittle fracture accidents, of large steel structures bring about serious social damage. The prevention of brittle fracture is thus extremely important when we consider the safety of large steel structures. Almost all steel structures demand steels that are strong and tough enough to prevent their brittle fracture. The development of such strong and tough steels has contributed to the prevention of brittle fractures.

Low-temperature liquefied gas storage tanks, especially liquefied petroleum gas (LPG) tanks, have in the past exploded in brittle fracture accidents and caused significant damage. Learning from these accidents, the people concerned developed the idea of double integrity where by brittle fractures should be prevented and that, should a brittle fracture initiate, its propagation should be arrested. If a brittle crack, once initiated, is arrested after propagating only a small distance, the worst situation, i.e., an explosion arising from the diffusion of a large volume of gas, can be avoided.

This paper introduces a 1.5Ni steel developed as LPG tank steel and imparted with excellent brittle crack initiation resistance and brittle crack propagation arrest capability at LPG temperatures, and it describes the brittle fracture safety of the 1.5Ni steel when used to fabricate LPG tanks.

2. Safety Considerations and Property Requirements of Low-Temperature Storage Tanks

In an LPG tank brittle fracture accident in Qatar in 1977, the leaking gas evaporated and exploded, causing a fire and great damage.

This accident triggered demand for reviewing the safety of liquefied gas storage tanks on a worldwide scale.In 1979, Cuperus, at

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a research foundation of Shell, designer and builder of the Qatari petroleum refining complex where the accident occurred, proposed the concept of double integrity by adding another safety factor to brittle fracture safety[1].

Tanaka et al.[2] developed the short crack arrest (SCA) test method and experimentally proved that double integrity can be realized by securing short crack arrest capability. They also proposed a procedure for assuring the safety of low-temperature liquefied gas storage tanks in the following fracture design steps: (1) demand for no defects; (2) effective hydrostatic test; (3) high resistance to fracture; (4) crack arrest at shorter brittle cracks; (5) propagation arrest of longer cracks; (6) prevention of unstable ductile fracture; and (7) safety outer tank.

This double integrity enhances the safety of low-temperature liquefied gas tanks and produces such safe low-temperature liquefied gas tanks that an unexpected situation does not lead to a serious accident.

2.1 Required brittle crack initiation resistance

Brittle crack initiation resistance can be evaluated by the crack-tip opening displacement (CTOD) and the stress intensify factor K_c. Here is used the CTOD, which can also be used to evaluate the initiation of brittle fracture after small-scale yielding.

The CTOD value required when short-period earthquakes are taken into account is reported to be 0.085 mm in a study of the 9Ni steel for LNG tanks[3]. Tanaka et al. report that according to past experience, structures made of steels with a minimum critical CTOD value of 0.1 mm in welds are safely used[4].

The above discussion shows that the crack initiation resistance required of LPG tank steels is the minimum critical CTOD value of 0.1 mm for both the base metal and the weld metal at -50°C (fracture toughness is required at 5°C lower than the normal LPG temperature of -45°C).

2.2 Required crack arrest capability

A brittle crack initiated from a surface defect can be arrested in the following cases: (1) pop-in due to material property inhomogeneity; (2) SCA due to change in restraint with crack penetration to the opposite surface; (3) long crack arrest (LCA) due to material discontinuity as a result of crack penetration into another material (such as base metal or crack arrestor). The SCA capability[5] whereby cracks are arrested while they are still short is the least damaging and most practical crack arrest property.

The SCA test method[4] was developed as a model test to simulate the SCA capability and allowed the evaluation of the SCA ability. A subsequent study[5] clarified that the SCA test results can be evaluated by the stress intensity factor K_{ca} obtained by the more popular duplex ESSO test method and that the SCA capability can be evaluated on the safe side by the duplex ESSO test using a 150-mm long crack initiation part.

As far as crack arrest in the heat-affected zone (HAZ) of a weld (hereinafter referred to as bond crack arrest) is concerned, in the duplex ESSO test, the crack is likely to deviate under the influence of weld residual stress and is difficult to evaluate properly. The SCA capability can be evaluated if the duplex ESSO test specimen is prestrained at a stress of 90% of the base-metal yield stress to remove the welding residual stress.

The above discussion indicates that the crack arrest capability required of LPG tank steels should be such as to arrest cracks under the design stress in the duplex ESSO test of the base metal and weld metal with a crack initiation part length of 150 mm at -50°C.

3. Production Considerations of 1.5Ni Steel

The basic study described in the previous report[6] found it necessary to add about 1.5% of nickel to improve steel plate strength and toughness (see **Fig. 1**).

It was made clear that nickel additions up to about 6% degrade the CTOD property in the CTOD test conducted to simulate the weld HAZ (see **Fig. 2**). In the CTOD test of weld joints made in a 1.9Ni-0.1Mo steel produced at the mill on a trial basis, the value of CTOD at -50°C was not sufficient and was under 0.1 mm in the HAZ of shielded metal arc welds manually made by using ferritic (α) electrodes (see **Fig. 3**).

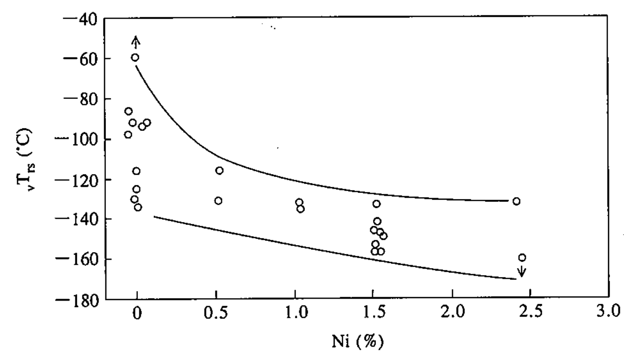

Fig. 1 Effect of nickel content on Charpy V-notch toughness of steel plate

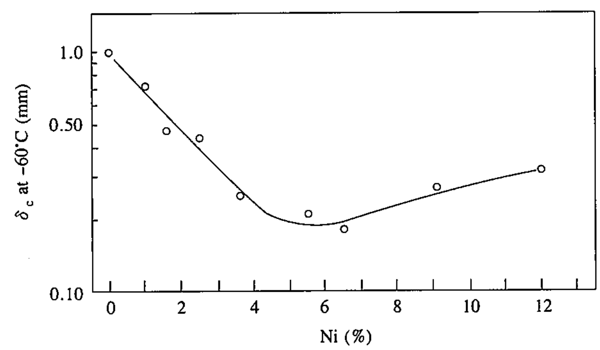

Fig. 2 Effect of nickel content on CTOD of simulative heat-affected zone

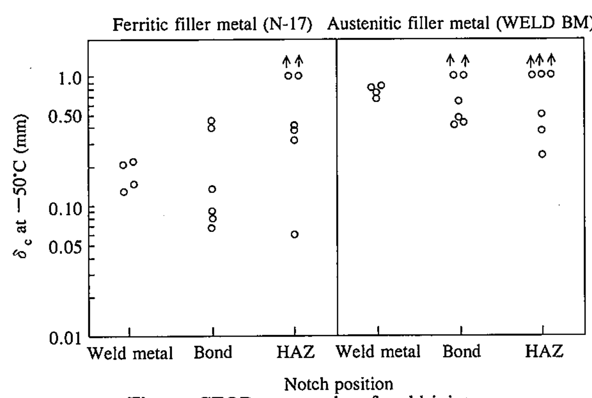

Fig. 3 CTOD test results of weld joints

Based on these experimental results, the 1.5Ni steel was trial made at the mill according to the following ideas:

(1)Set the nickel content at 1.5% to accomplish plate strength and toughness comparable to those of the previous trial-made 1.5Ni steel.

(2)Do not add molybdenum, a hardenability increaser, to improve the CTOD of weld joints and weldability, and add trace amount of niobium to inhibit the formation of grain-boundary ferrite.

(3)Produce steel plates by the combination of accelerated cooling and tempering.

4. Properties of Trial 1.5Ni Steel

Table 1 lists the chemical compositions of the 1.5Ni steel produced at the mill on a trial basis in the present work and the 1.5Ni steel trial made previously.

4.1 Mechanical properties of base metal

The tensile and Charpy impact test results of 8, 19, and 38-mm thick trial-made steel plates are shown in **Table 2**. The three steel plates have good base-metal strength and toughness, which are satisfactory for N-TUF365. Since the brittle crack initiation and arrest properties both increase in severity with increasing plate thickness, the test results of the 38-mm thick steel plates alone are discussed in the following sections.

4.2 Crack arrest capability of base metal

The crack arrest capability of the base metal was evaluated by the temperature-gradient ESSO test and NRL drop-weight test. The ESSO test results are shown in **Fig. 4**, and the NRL drop-weight test results are shown in **Fig. 5**.

The NRL drop-weight test measured the ratio of shear area (SA) at each test temperature in addition to the nil-ductility transition temperature (NDT). The NRL drop-weight test specimens measured 12.7-mm thick and were Type P-3.

(1)The temperature (TK_{ca}-5900) at which the K_{ca} value as an index of long-crack arrest capability[3] is 5,900 N/mm$^{3/2}$ was a good -60°C.

(2)The NDT of the NRL drop-weight test was -110°C. The ratio of shear area at this temperature was a small 18%. **Photo 1** shows typical examples of fracture surfaces.

In the authors' previous study[7], they clarified that the temperature (T_{SA50}) at which the ratio of shear area in the NRL drop-weight test is 50% is an effective means for evaluating the crack arrest capability. TK_{ca}-5900 and T_{SA50} are related as shown in **Fig. 6**.

(3)TK_{ca}-5900 and T_{SA50} are linearly related. This means that the present trial-made 1.5Ni steel is improved in both T_{SA50} and TK_{ca}-5900 as compared with the previous trial-made 1.5Ni steel. Assuming that the K_{CA} exceeds 5,900 N/mm$^{3/2}$ at the -50°C design temperature of LPG tanks according to this relationship, the T_{SA50} required in the NRL drop-weight test is -79°C.

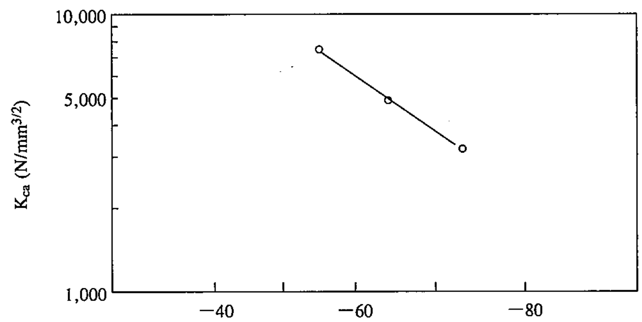

Fig. 4 Temperature-gradient ESSO test results

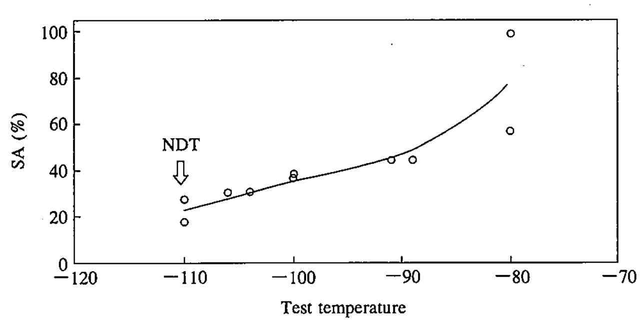

Fig. 5 NRL drop-weight test results

Table 1 Chemical compositions of trial-made 1.5Ni steels

(Nb and Ti in ppm, and other elements in mass%)

	C	Si	Mn	Ni	Mo	Nb	Ti	Ceq_{IIW}
Present trial-made steel	0.06	0.19	1.39	1.51	-	80	100	0.39
Previous trial-made steel	0.06	0.25	1.20	1.49	0.11	-	120	0.38

Table 2 Mechanical properties of base metal

Test item	Tensile test (JIS No. 5 specimens)				Charpy impact test (JIS No. 4 specimens)						
Plate thickness (mm)	Orientation	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Orientation	1/4t			1/2t		
						$_vE_{-60°C}$(J)		$_vT_{rs}$(°C)	$_vE_{-60°C}$(J)		$_vT_{rs}$(°C)
						Average	Minimum		Average	Minimum	
8	L	456	520	38	L	-	-	-	107	101	<-150
	T	481	527	39	T	-	-	-	118	113	<-150
19	L	510	550	52	L	372	363	<-150	390	375	<-150
	T	517	562	49	T	363	357	<-150	388	373	-135
38	L	489	545	61	L	374	370	<-150	348	267	-146
	T	506	560	59	T	353	348	<-150	335	275	-110

L for rolling direction; T for direction normal to rolling direction; subsize Charpy impact test specimens for 8-mm thick plates; and t for plate thickness.

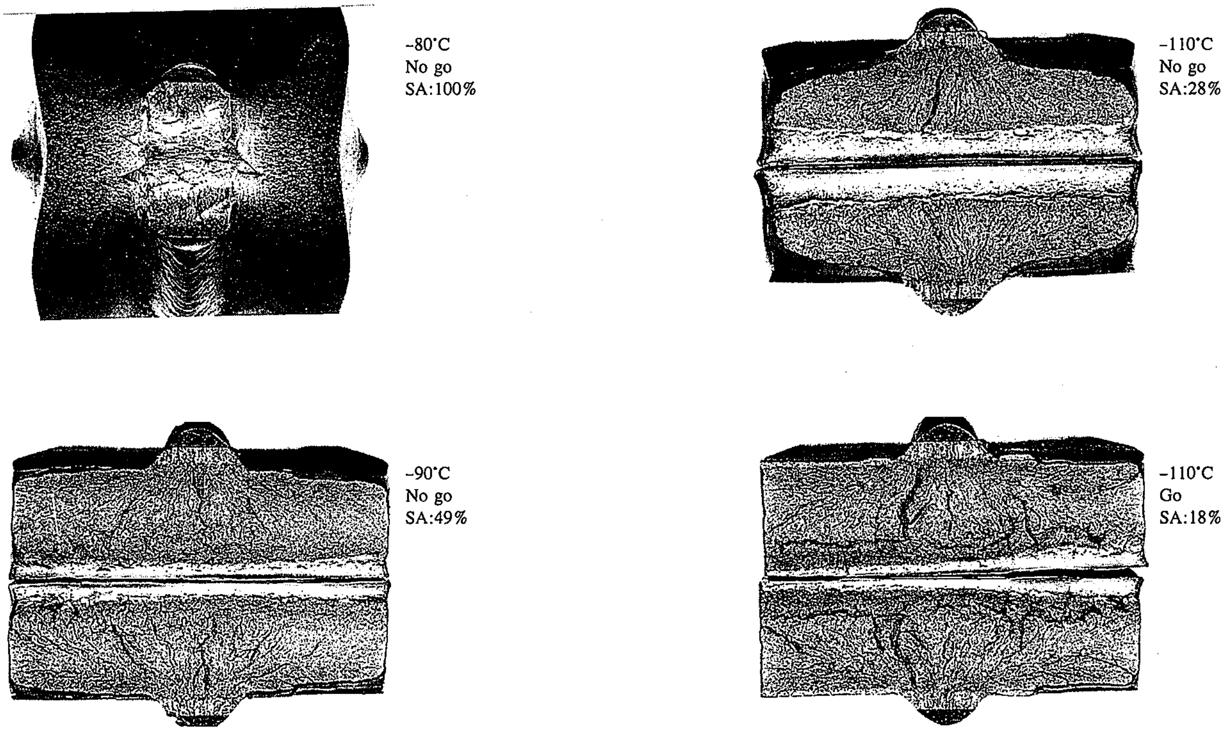

Photo 1 Typical fracture surfaces of NRL drop-weight test specimens

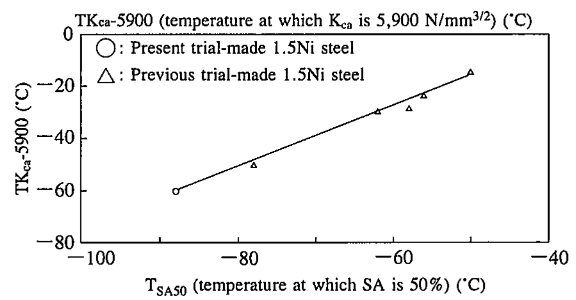

Fig. 6 Relationship between NRL drop-weight test and ESSO test

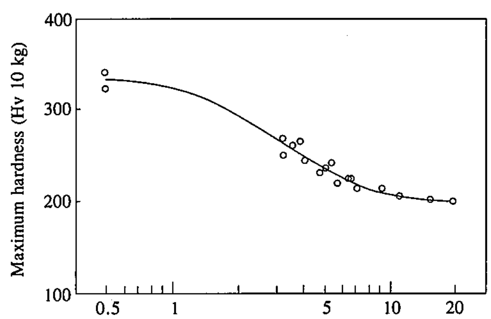

Fig. 7 Taper hardness test results

The temperature difference of about 20°C between the T_{SA50} and NDT means that the specified T_{SA50} of 79°C translates into the specified NDT of about -100°C.

4.3 Weldability of present trial-made 1.5Ni steel

The weldability of the present trial-made 1.5Ni steel was studied by the taper hardness test and y-groove weld cracking test of weld joints made in 38-mm thick plates.

Fig. 7 shows the taper hardness test results of the present trial-made 1.5Ni steel. The Vickers hardness is about 340 even in the arc-struck region and is a good 230 where the heat input is 18 kJ/cm.

Fig. 8 shows the y-groove weld cracking test results of the present trial-made 1.5Ni steel. Low temperature weld cracking did not occur when the initial plate temperature was as low as 0°C. These results confirm that the weldability of the present trial-made 1.5Ni steel is good.

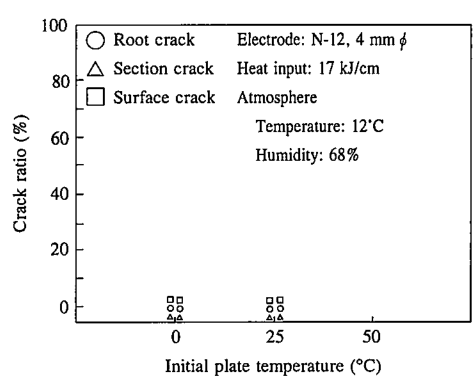

Fig. 8 y-groove weld cracking test results

4.4 Mechanical properties of weld joints

Table 3 shows the tensile test results of weld joints. Simulating the tank sidewall plate vertical welds that require a relatively large heat input and represent a severe stress condition, weld joints were made in the present trial-made 1.5Ni steel by the shielded metal arc welding (SMAW) process and the gas-tungsten arc welding (GTAW) process.

4.4.1 Strength of weld joints

The SMAW joints were made by using the 3.5Ni and 6.5Ni ferritic (α) filler metals N-13 and N-16, respectively, and the 70Ni austenitic (γ) filler metal WELD196, while the GTAW joints were made by using the 75Ni austenitic (γ) filler metal FILLER196. All filler metals were produced by Nippon Steel Welding Products & Engineering.

The SMAW and GTAW joints were strong and failed in the base metal (BM) region with satisfactory results. When the weld joints made by using the ferritic filler metals were tensile tested after postweld heat treatment (PWHT), they exhibited sufficient strength.

4.4.2 Charpy impact test results of weld joints

Table 4 lists the Charpy impact test results of the weld joints.

(1)The minimum Charpy impact value of the SMAW joints made by using the ferritic N-13 was a good 96 J at -50°C. At -80°C, the minimum Charpy impact value was 8 J in the weld metal (WM) and about 30 J in the HAZ (bond-1 to bond-3).

(2)The Charpy impact values of the SMAW joints made by using the ferritic N-16 were high at both -50 and -80°C. The minimum Charpy impact value was a good 59 J in the HAZ (bond and bond-1).

(3)The Charpy impact value of the SMAW joints made by using the austenitic WELD196 was higher than that of the SMAW joints made by using the ferritic N-13 and N-16. The minimum Charpy impact value at -80°C was 112 J in both the as-welded (AW) and PWHT conditions.

(4)The Charpy impact test results of the GTAW joints made by using the austenitic FILLER196 were good, with the minimum Charpy impact value at -80°C being 41 J in the AW condition and 111 J in the PWHT condition.

4.4.3 CTOD test results of weld joints

Fig. 9 shows the CTOD test results of the SMAW joints made by using the ferritic N-16 and the austenitic WELD196.

Table 3 Tensile test results of weld joints

Welding process	Welding conditions			Welding material	PWHT	Tensile test		
	Welding position	Groove shape	Heat input (kJ/cm)		(580°C)	Specimen	Tensile strength (N/mm²)	Fracture location
SMAW	Vertical	X	21-35	N-13mod.	No	Joint No. 1	576	Base metal
							570	Base metal
	Vertical	X	42-56	N-16mod.	No	Joint No. 1	573	Base metal
	Vertical	X	41-51	WELD196	No	Joint No. 1	556	Base metal
							560	Base metal
					Yes	Joint No. 1	546	Base metal
							544	Base metal
GTAW	Vertical	X	41-51	FILLER196	No	Joint No. 1	547	Base metal
							544	Base metal
					Yes	Joint No. 1	540	Base metal

Table 4 Charpy impact test results of weld joints

Welding process	Welding material	PWHT	Temperature (°C)	Charpy impact test results $_vE$ (average/minimum)					
				Thickness position	Notch location				
					WM	Bond	Bond-1	Bond-2	Bond-3
SMAW	N-13mod.	No	-50	1/4t	103/96	100/ 96	214/201	-	268/227
			-80	1/4t	34/8	63/ 28	122/ 31	-	233/194
	N-16mod.	No	-50	1/4t	141/132	154/137	260/240	-	-
				2/1t	83/80	168/139	147/129	-	-
			-80	1/4t	90/69	96/ 74	79/ 59	-	-
				1/2t	47/34	65/ 38	90/ 79	-	-
	WELD196	No	-50	1/4t	120/113	213/167	230/204	281/266	322/304
				1/2t	109/104	154/146	175/131	260/197	324/316
			-80	1/4t	120/116	124/112	125/116	149/115	324/312
				1/2t	107/102	100/ 79	109/ 87	192/ 65	308/278
		Yes	-50	1/4t	113/108	155/135	208/178	223/190	-
				1/2t	111/104	155/145	251/229	289/265	-
			-80	1/4t	113/110	125/115	120/112	133/117	-
				1/2t	97/78	90/ 71	99/ 54	206/184	-
GTAW	FILLER196	No	-50	1/4t	149/141	168/129	265/254	267/256	-
				1/2t	159/153	262/254	269/264	287/280	-
			-80	1/4t	141/138	111/ 41	254/230	242/218	-
				1/2t	160/158	194/ 57	166/101	265/252	-
		Yes	-50	1/4t	108/99	168/154	195/185	270/254	-
				1/2t	144/144	171/135	217/153	254/250	-
			-80	1/4t	104/93	152/111	161/143	241/214	-
				1/2t	135/132	193/137	199/197	175/ 72	-

Bond: 50% each of WM and HAZ. Bond-1: 1 mm from bond into HAZ. Bond-2: 2 mm from bond into HAZ. Bond-3: 3 mm form bond into HAZ.

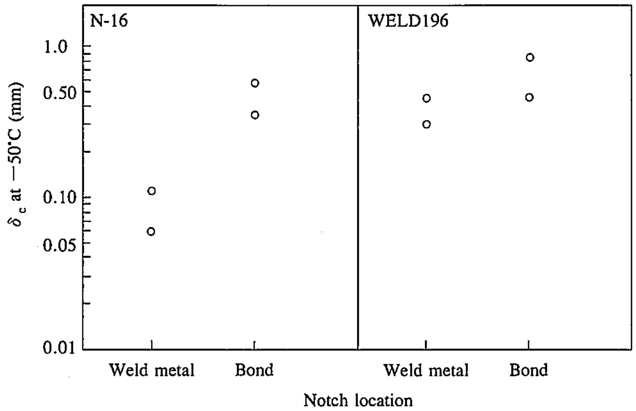

Fig. 9 CTOD test results of weld joints (SMAW/AW)

(1)The CTOD value was less than 0.1 mm in the WM of some of the SMAW joints made by using the ferritic N-16, but was 0.36mm or more in the bond region.

(2)The CTOD value was not less than 0.31 and 0.48 mm in the WM and bond, respectively, of the SMAW joints made by using the austenitic WELD196.

Fig. 10 shows the CTOD test results of the GTAW joints made by using the austenitic FILLER196.

(3)The CTOD value was high and satisfactory in both the AW and PWHT conditions.

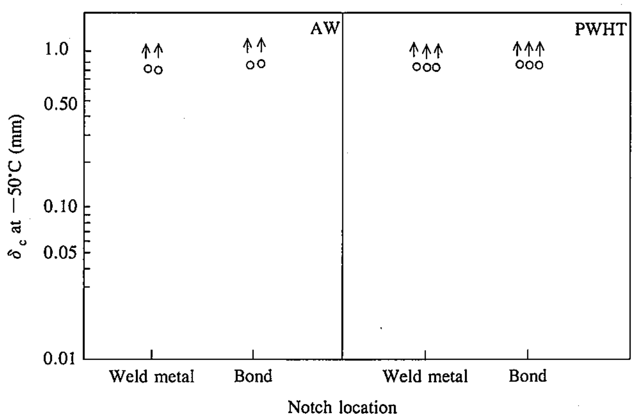

Fig. 10 CTOD test results of weld joints (GTAW)

Table 5 NRL drop-weight test results of weld joints

Welding process	Welding material	PWHT	Notch location	Test temperature (°C) -80	-85	-90	-95	-100	-110	NDT (°C)
SMAW	N-13mod.	No	WM*			● ●				-
			Bond*	○ ○		● ●		● ●		≒-85
	N-16mod.	No	WM			○ ○				-
			Bond			●				-
	WELD196	No	WM			○○○		○○○	○○○	≦-115
			Bond			○○△				-
GTAW	FILLER196	No	Bond			○ ○		○ ○	○ ○	≦-115

Test specimens: Types P-3 and P-1*
Evaluation: ○ No go; ● Go; △ No test

4.4.4 NRL drop-weight test results of weld joints

Table 5 lists the NRL drop-weight test results of the weld joints.

(1)The NDT of the weld joints made by using the ferritic N-13 and N-16 was about -85 to -90°C and somewhat unsatisfactory.

(2)The NDT of the weld joints made by using the austenitic filler metals was −115°C or lower and satisfactory.

4.4.5 Duplex ESSO test results of weld joints

Large weld joints (notched in the bond) were duplex ESSO tested by the method illustrated in **Fig. 11**. The duplex ESSO test results are given in **Table 6**. The crack initiation part was connected to the test plate by using a filler metal of such poor toughness as to facilitate brittle crack propagation. The crack initiation part was side-grooved to allow the brittle crack to go straight into the bond.

Given the possibility of brittle crack propagation being influenced by weld residual stresses, some weld joints were tested by preloading to remove the residual stresses.

(1)The brittle crack propagated through the test plate in the weld joints made by using the ferritic N-13, and with and without preloading.

(2)The brittle crack was arrested in the test plate in the weld joints made by using the austenitic FILLER196, and with and without preloading.

The stress intensify factor K_{ca} calculated from the applied stress and crack length ranged from 6,300 to 8,900 N/mm$^{3/2}$ and exceeded the value of 5,900 N/mm$^{3/2}$ required to arrest long cracks as described in the section 4.2. It was already described that the NDT required to arrest long cracks in the base metal was about −100°C

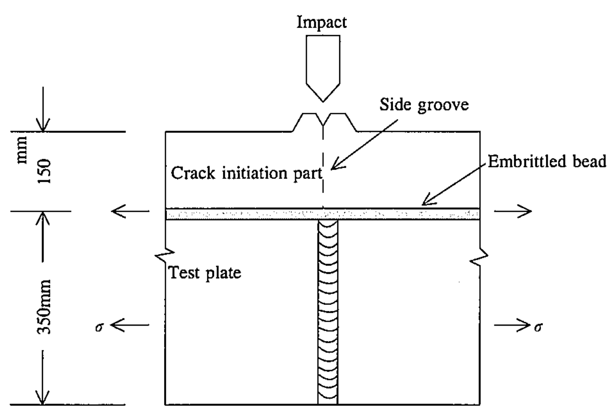

Fig. 11 Duplex ESSO test method

Table 6 Duplex ESSO test results of weld joints

Welding process	Welding material	PWHT	Notch location	Preapplied stress (N/mm²)	Applied stress (N/mm²)	Test result judgment	Crack propagation length (mm)
SMAW	N-13mod.	No	Bond	-	265	●	-
				436	262	●	-
GTAW	FILLER196	No	Bond	-	242	○	188
				-	265	○	176
				-	294	○	236
				436	262	○	197

10. Preapplied stress is 90% of yield stress of base metal.

in relation to the NRL drop-weight test. When weld joints exhibited an NDT of less than –100°C, they were confirmed to have a high enough crack arrest capability in the results of both the NRL drop-weight test and duplex ESSO test.

5. Service Performance of Commercial 1.5Ni Steel

Nippon Steel has developed a 1.5Ni steel as low-temperature steel with excellent fracture toughness, and has manufactured and supplied 1,200 tons of the 1.5Ni steel for use in two LPG tank construction projects. As already described, the new 1.5Ni steel met the minimum NDT requirement of –95°C specified for these two projects.

6. Future Problems

6.1 Reduction in nickel content

The authors have studied the reduction in the nickel content of LPG tank steels by applying the technique of refining the HAZ microstructure by intragranular transformation and experimentally demonstrated that good fracture toughness can be obtained with a lower nickel content of about 0.5%. This study will be continued toward the commercial production of such a lower-nickel LPG tank steel.

6.2 Effect of welding materials on bond crack arrest capability

The weld joints made by using the ferritic N-13 did not exhibit satisfactory bond crack arrest capability in the present experimental work. There is the possibility of the bond crack arrest capability improving in combination with other ferritic filler metals. This possibility will be studied further.

6.3 Crack arrest test methods

In the test methods employed to evaluate crack arrest in the WM of weld joints, it assumes increasing importance to control crack initiation and to evaluate and remove the residual stresses produced in the weld joints. The toughness of the WM is generally lower than that of the BM. The crack initiation and propagation regions must be embrittled further. The duplex ESSO test uses a crack initiation part of low toughness in the crack propagation region. The SCA test deposits embrittled beads to facilitate brittle crack propagation.

In recent years, electron beam welding (EBW) has been proposed as one method for embrittling the test plate. This should be studied as compared with the conventional test methods.

References

1) Cuperus, N.J.: Proceedings for 10th World Petroleum Congress, London, Heyden & Son, 1979. Panel Discussion 17, Paper 3
2) Tanaka, K., Sato, M., Isikawa, T.: Proceedings for Intern. Conf. on Fracture Toughness Testing Method, Interpretation and Application, London, March 1982, Paper 18
3) Machida, S., Ishikura, N., Kubo, N., Katayama, N., Hagiwara, Y., Arimochi, K.: Journal of High Pressure Institute of Japan. 29 (6), 25-39 (1991)
4) Tanaka, K., Sato, M., Isikawa, T.: Nippon Steel Technical Report. (32), 37-43 (1987)
5) The ASTM Committee on Fracture Testing of High-Strength Sheet Materials. ASTM Bulletin, (January 1960), 29-40
6) Imagunbai, M., Chijiiwa, R., Aikawa, N., Nagumo, M., Horiya, T., Ohashi, M.: Seitetsu Kenkyu. (318), 51 (1985)
7) Chijiiwa, R., Imagunbai, M., Matsuda, H.: Tetsu-to-Hagané. 80, S436 (1994)