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Verification Test of 720 N/mm^2 High-Strength Steel Plates (Former ASTM A 543 Type B Class 1) for Hybrid High-Strength Steel Containment Vessels for Pressurized Water Reactors (PWRs)

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Abstract:

With a view to practical application to cylindrical high-strength steel containment vessels for pressurized water reactors (PWRs), 720-N/mm^2 low-alloy high-strength steel plates (former ASTM A 543 Type B Class 1 steel plates) manufactured by the basic oxygen furnace (BOF) process were subjected to basic performance, weldability and stress-relief cracking tests, as well as to static and dynamic fracture toughness tests of the base metal and fusion line. The test results indicated that the steel plates fully satisfy the requirements of the applicable standards after quenching and tempering. Moreover, after postweld heat treatment, they are totally free of stress-relief cracking, and exhibit excellent static and dynamic fracture toughness properties. Their weldability can be further enhanced by using improved welding materials. These results led to the conclusion that the steel plate in question is applicable to cylindrical high-strength steel containment vessels for the PWRs.

1. Introduction

Nuclear reactor containment vessels initially used ASTM A 212 Type B, then ASTM A 516 Type 60 or 70, and eventually came to use JIS G 3118 Class SGV 480 (formerly SGV 49) extensively. As the nuclear reactors increased in size, so did their containment vessels. The height of containment vessels for pressurized water reactors (PWRs) were limited by aseismatic designs, which in turn required the maximum operating pressure to be raised from 2.50 to 2.89 kgf/cm^{2}g. To meet this requirement, efforts were directed toward increasing the plate thickness of the JIS G 3118 Class SGV 480 steel[1,2].

Until 1977, the maximum thickness of steel plates that could be used without postweld heat treatment (PWHT) on welded joints was limited to 38 mm by the Technical Standard of the Ministry of International Trade and Industry. The Nuclear Reactor Vessel Material Verification Test Technology Committee of the Japan Power Plant Inspection Institute (presently the Japan Power Engineering and Inspection Corporation) conducted a study to expand to 44.5 mm the plate thickness range of the JIS G 3118 Class SGV 480 steel to be used without PWHT. The study

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Table 1 Chemical composition of ASTM A 543 Type B Class 1-1974 steel plates for HHCV (specifications and manufacturing results)

	Chemical composition (%)			C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Sol.Al	Ceq*4	P_{CM}*5	As	Sb	Sn	B
ASTM A 543 Type B Class 1-1974	Heat analysis			≦0.23	0.20 - 0.35	≦0.40	≦0.020	≦0.020	—	2.60 - 3.25	1.50 - 2.00	0.45 - 0.60	≦0.03	—	—	—				
Requirements specially approved by Japan Power Plant Inspection Institute (A 543 Type B Class 1)			Heat	≦0.13*1	0.20 - 0.35	≦0.40	≦0.020	≦0.020	—	2.60 - 3.25	1.50 - 2.00	0.45 - 0.60	≦0.30	—	≦0.70	—	—	—	—	—
Nippon Steel composition design target value			Heat	0.09	0.25	0.35	≦0.005	≦0.001	—	2.80	1.60	0.50	≦0.03	—	≦0.67	—	—	—	—	—
Present (1986), BOF steel Plate thickness: 50 mm Heat No. SN6076	Heat			0.09	0.24	0.35	0.005	0.001	0.01	2.82	1.64	0.53	tr*2	0.039*3	0.69	0.28	0.002	0.001	0.001	0.0002
	Product	Ingot top	1/4t	0.10	0.23	0.32	0.006	0.001	0.01	2.77	1.63	0.52	tr	0.030	0.69	0.28	0.002	0.001	0.001	0.0002
			1/2t	0.10	0.23	0.32	0.006	0.001	0.01	2.77	1.63	0.52	tr	0.032	0.69	0.28	0.002	0.001	0.001	0.0002
Previous (1975), EF steel Plate thickness: 40 mm Heat No. DH9256	Heat			0.08	0.23	0.35	0.006	0.004	—	2.77	1.54	0.50	—	0.021	0.65	0.26	—	—	—	—
	Ingot top			0.08	0.25	0.36	0.006	0.005	0.03	2.76	1.55	0.51	0.01	0.021	0.65	0.26	0.003	0.007	0.004	0.0001

*1: When C >0.10%, Critical preheating temperature in y-groove weld cracking test should be 100°C or less
*2: V = 0.004% (no vanadium intentionally added)
*3: Total Al
*4: Ceq = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14
*5: P_{CM} = C + Si/30 + Mn/20 + Ni/60 + Cr/20 + Mo/15 + Cu/50 + 5B

Table 2 Mechanical properties requirement of steel plates for nuclear reactor containment vessels (JIS G 3118 Class SGV 480 and ASTM A 543 Type B Class 1)

Item	A 543 Type B Class 1	JIS G 3118 Class SGV 480
Yield strength (0.2% offset)	585 N/mm^2 minimum	265 N/mm^2 minimum
Tensile strength	720 to 860 N/mm^2 (74 to 88 kgf/mm^2)	480 to 590 N/mm^2
Elongation	14% minimum (JIS No. 4 specimen)	17% minimum (JIS No. 1A specimen)
Impact test	At lowest operating temperature Absorbed energy: 68 J (6.9 kgf·m) minimum Lateral expansion: 0.89 mm minimum	At lowest operating temperature Absorbed energy: 29 J (3.0 kgf·m) minimum
Drop weight test	NDT temperature ≦ Lowest operating temperature −33°C	—

result led to the official approval of the plate thickness range expansion, and as a result 44.5 mm thick JIS G 3118 Class SGV 480 steel plates were adopted to fabricate the containment vessel of No. 3 reactor at the Takahama nuclear power plant of Kansai Electric Power Co., Ltd[1,2].

ASTM A 543 Type B Class 1 (A543B1) steel plates with a tensile strength of 720 N/mm^2 (74 kgf/mm^2) were selected as materials of construction for hybrid high strength steel containment vessels (HHCVs). The Nuclear Reactor Containment Vessel High-Strength Steel Technology Study Committee of the Japan Power Plant Inspection Institute examined the applicability of 40 mm and 50 mm thick A543B1 steel plates to nuclear reactor containment vessels with the criteria: 1) safety from the unstable fracture of base steel and welded joints, 2) unnecessity of PWHT and 3) weld cracking insensitivity. It was in 1974 that the use of 50 mm and under thick A543B1 steel plates in nuclear reactor containment vessels was approved[3].

Tables 1 and **2** summarize applicable standards and typical product manufacturing results (chemical composition and mechanical properties) of steel plates for nuclear reactor containment vessels.

Subsequently, the hybrid high strength steel containment vessel (HHCV), pre-stressed concrete containment vessel (PCCV), and spherical shaped containment vessel (SSCV) were comparatively studied for use as 1,100 MW PWR containment vessels. As a result, the PCCV design, whose performance had been proven abroad, was approved and applied first to No. 2 nuclear reactor at the Tsuruga nuclear power plant of Japan Atomic Power Co., Ltd. The Kobe Shipyard of Mitsubishi Heavy Industries, Ltd., for its part, found that the HHCV can be safely designed to the same dimensions as the PCCV, thanks to the recent progress of analysis technology for containment vessel structures.

The above-mentioned company paid attention to the subsequent progress of steelmaking technology (BOF steelmaking and secondary refining) and improvements in welding materials and procedures, and planned to study the fabricability of nuclear reactor containment vessels from 50 mm thick ASTM A 543 Type B Class 1 steel plates. It inquired with Nippon Steel in October 1985 for the supply of sample steel plates. Consequently in 1986, Nippon Steel melted a 160-ton heat of the steel by the BOF process, rolled it into 50 mm thick plates, and supplied them to the said client.

This paper presents the results of the basic performance, cold weld cracking, and stress-relief cracking tests, as well as static and dynamic fracture toughness tests which Nippon Steel conducted on the A543B1 steel plates and their welded joints. The A543B1 steel plates were compared with the previous steel plates (a 60-ton heat of the A543B1 steel made by the electric arc furnace (EF) process) used for approval in 1974 and were studied for safety from brittle fracture under the operating conditions of containment vessels. These test results are also described here.

2. Basic Performance of ASTM A 543 Type B Class 1 Steel Plates

2.1 Chemical composition design and production process

The present A543B1 steel plate is 50 mm thick against the 40 mm thickness of the previous A543B1 steel plate, its PWHT time at 595°C is 3.4 h against 1.6, and its lowest service temperature as containment vessel is lower than for the previous type. Its chemical composition was designed taking these facts into account. As illustrated in **Fig. 1**, the production process consists of strict raw materials selection, hot metal desulfurization and dephosphorization, 160-ton BOF blowing, secondary refining, ingot or continuous casting, and rolling with quenching and tem-

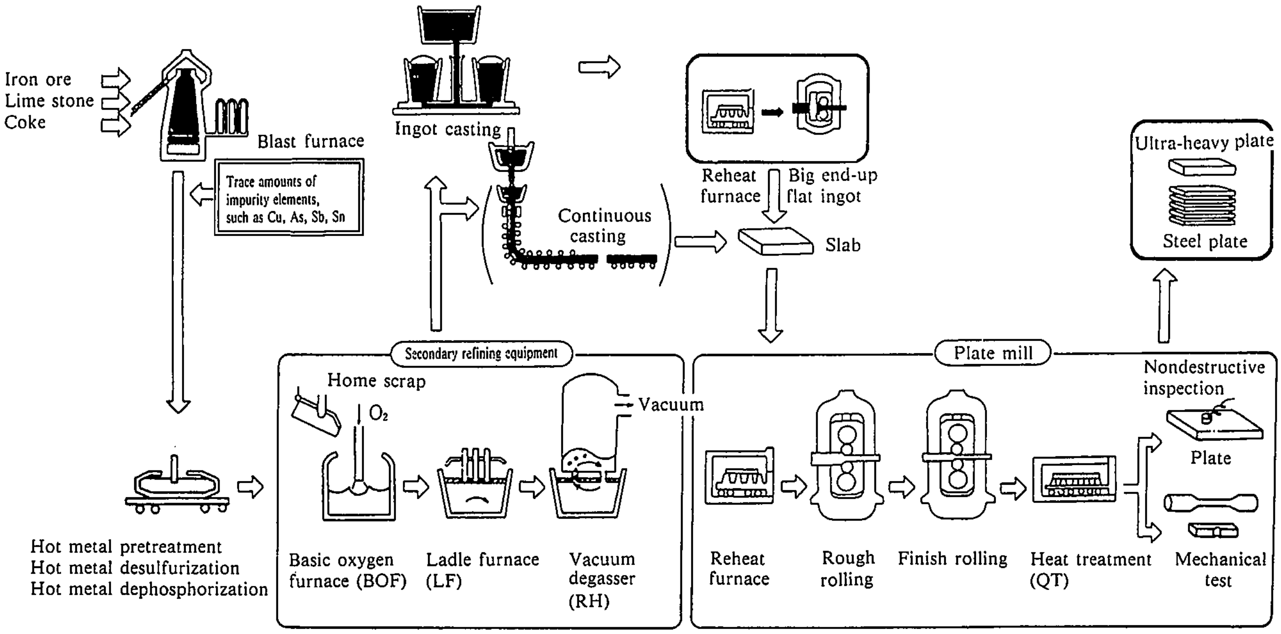


Fig. 1 Schematic illustration of production process for high-strength ASTM A 543 Type B Class 1 steel plates for nuclear reactor containment vessels

Table 3 Tensile test results of present (BOF) and previous (EF) ASTM A 543 Type B Class 1 steel plates (t/4 ; t : thickness)

Heat treatment		Present steel plate (1986) (50 mm)		Previous steel plate (1975) (40 mm)	
		Range	Average	Range	Average
As quenched and tempered (QT)	Tensile strength (N/mm^2)	700-724	710	680-702	692
	Yield strength (N/mm^2)	771-790	780	743-768	757
	Elongation (%)	25-26	25.3	26-28	26.6
	Reduction of area (%)	79-80	79.5	73-77	75.2
Postweld heat treated*1 (PWHT)	Tensile strength (N/mm^2)	689-707	698	668-690	682
	Yield strength (N/mm^2)	762-783	770	740-761	751
	Elongation (%)	24-26	25.3	26-28	26.6
	Reduction of area (%)	80	80	73-78	75.3

*1: PWHT conditions: 549°C × 3.4 h for present steel plates and 595°C × 1.6 h for previous steel plates
A543B1 steel standard (Requirements of Japan Power Plant Inspection Institute):
·Yield strength: ≧ 585 N/mm^2 (60 kgf/mm^2)
Tensile strength: 725 to 860 N/mm^2 (74 to 88 kgf/mm^2)
Elongation (JIS No. 4 specimen, GL = 50 mm): ≧ 14%

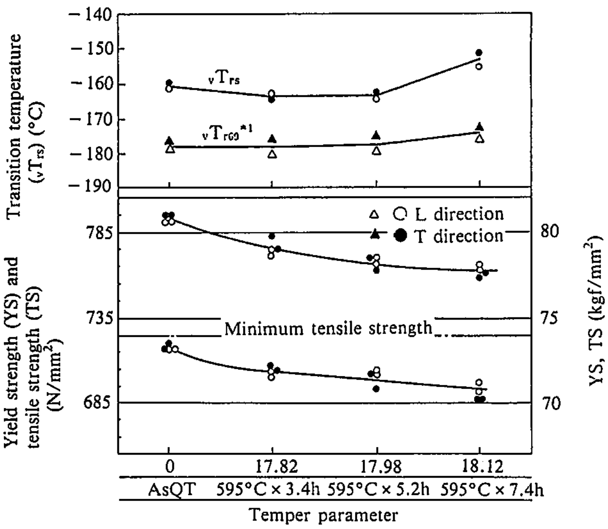


Fig. 2 Effect of PWHT on tensile properties and Charpy impact properties of present ASTM A 543 Type B Class 1 steel plate
*1 $_vT_{r69}$: Absorbed energy transition temperature at which absorbed energy becomes 6.9 kgf·m

pering to 50-mm thick plates. **Table 1** shows the applicable standards, chemical composition design target values, heat analysis, and product analysis. The carbon equivalents Ceq and P_{CM} are slightly higher than those of the previous A543B1 steel plate, and the contents of such impurity elements as phosphorus, sulfur, arsenic, antimony and tin, are lower than for the previous A543B1 steel plate.

2.2 Room temperature and elevated temperature tensile properties

Tensile test specimens were taken in the quarter thickness position (t/4), rolling (L) direction, transverse (T) direction, and ingot top and bottom locations. The results of tensile tests are given in **Table 3**. The tensile test results of the previous A543B1 plate are also shown. The tensile strength and yield strength of the present A543B1 steel plate in the quenched and tempered (QT) condition and the PWHT condition are both 20 N/mm^2 (2 kgf/mm^2) higher than those of the previous A543B1. The present A543B1 differs little from the previous A543B1 in terms of the loss of strength due to PWHT.

Fig. 2 shows the effect of PWHT on the tensile properties of the present A543B1 steel plate. When the quenched and tempered steel plates were post weld heat treated at 595°C for 7.4 h (temper parameter of 18.12), their yield strength and tensile strength both decreased by about 30 N/mm^2.

Fig. 3 shows the elevated temperature tensile properties of the present A543B1 steel plate before and after PWHT. The elevated temperature tensile properties do not appreciably change with PWHT, and the yield strength also fully satisfies the specifications by the Japan Power Plant Inspection Institute.

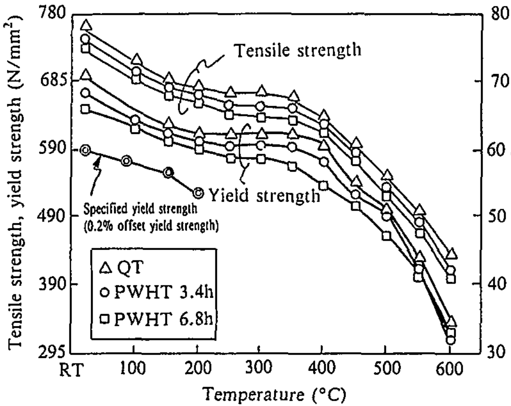


Fig. 3 Elevated-temperature tensile properties of present ASTM A 543 Type B Class 1 steel plate (QT) and after PWHT
Specimen location: t/4, T direction
Elevated-temperature tensile test specimens: 10 mmϕ, GL = 50 mm
PWHT: 595°C × 3.4 h, 6.8 h

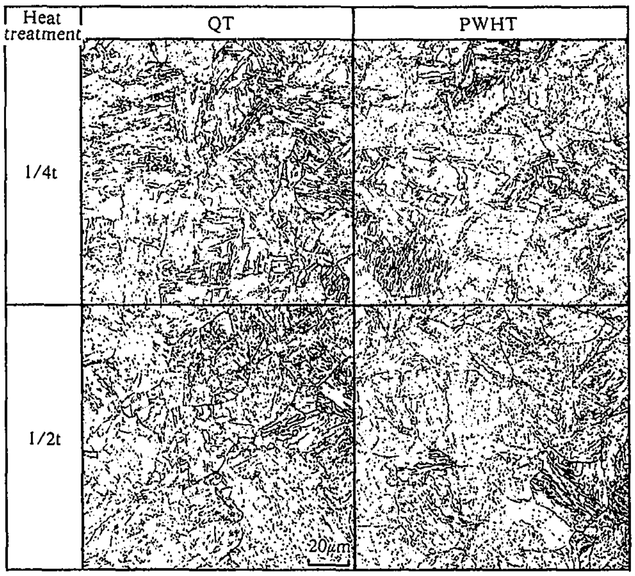


Photo 1 Microstructures of present ASTM A 543 Type B Class 1 steel plate (ingot top side)

2.3 Microstructures

Photo 1 shows the microstructures of the present A543B1 steel plate after quenching and tempering and after PWHT. As seen, the plate exhibits a uniform microstructure irrespective of the through-thickness position.

2.4 Charpy impact properties

Charpy impact test specimens were taken in the quarter thickness position (t/4), rolling (L) direction, transverse (T) direction, and ingot top location. The test results are summarized in **Table 4**. **Fig. 4** shows Charpy impact absorbed energy transition curves. The present A543B1 steel plate exhibits very good notch toughness that fully meets the impact toughness requirements of the Japan Power Plant Inspection Institute.

Table 5 compares the Charpy impact transition temperatures of the present and the previous A543B1 steel plates. The transition temperatures of the present A543B1 steel plate after quenching and tempering and after PWHT are superior to those of the previous A543B1 steel plate, and exhibits smaller decreases in toughness with PWHT. These tendencies can also be seen in **Fig. 2**.

Table 4 Charpy impact test results of present ASTM A 543 Type B Class 1 steel plate (t/4, ingot top side)

Heat treatment	Direction	${}_vT_{r50}$ (°C)	${}_vT_{rs}$ (°C)	${}_vT_{r35mils}$ (°C)	${}_vE_{-13}$ (J)	${}_vE_{-30}$ (J)	${}_vE_{max}$ (J)	LE_{-13} (mm)
QT	L	< −180	< −180	< −180	301 321 313	313 297 304	323	2.21 2.16 2.32
	T	−180	−173	−180	294 307 299	287 309 310	318	2.23 2.35 2.23
QT + PWHT (595°C × 3.4h)	L	< −180	−173	< −180	310 315 313	306 309 304	315	2.25 2.25 2.27
	T	−176	−164	−174	313 296 311	306 291 304	313	2.30 2.21 2.24

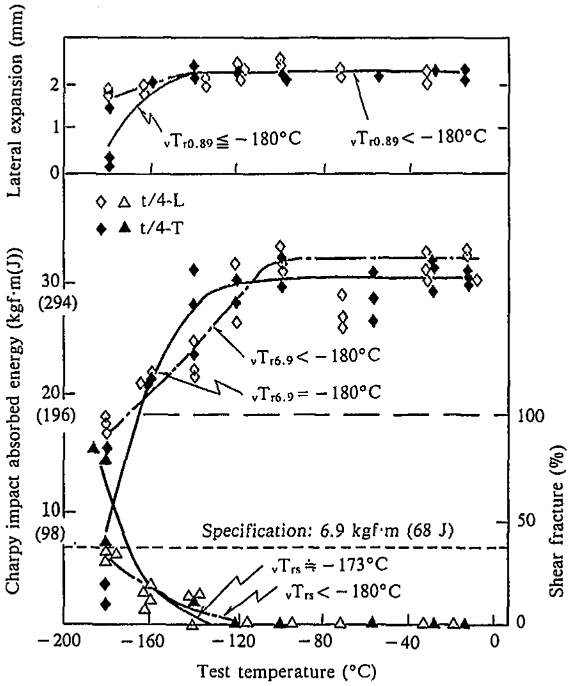


Fig. 4 Charpy impact absorbed energy transition curves of present ASTM A 543 Type B Class 1 steel plate

Table 5 Charpy impact transition temperatures of present and previous ASTM A 543 Type B Class 1 steel plates

(t/4 Plane)

		Present steel plates (50 mm)	Previous steel plates (40 mm)
Quenched and tempered	${}_vT_{rs}$*1	−173 to −180°C max	−150 to −177°C max
	${}_vT_{r50}$*2	−180 to −180°C max	−153 to −189°C max
	${}_vT_{r0.89}$*3	−180 to −180°C max	—
PWHT	${}_vT_{rs}$	−153 to −173°C	−148 to −150°C max
	${}_vT_{r50}$	−172 to −180°C max	−150°C max
	${}_vT_{r0.89}$	−168 to −180°C max	—

*1 ${}_vT_{rs}$: Fracture appearance transition temperature at which shear fracture becomes 50%

*2 ${}_vT_{r50}$: Absorbed energy transition temperature at which absorbed energy becomes 50 ft·lb

*3 ${}_vT_{r0.89}$: Lateral expansion transition temperature at which lateral expansion becomes 0.89 mm

2.5 Strain aging properties

The strain aging test results of the present and the previous A543B1 steel plates are summarized in **Fig. 5** and **Table 6**. The changes in the impact and tensile properties with the amount of strain in the tempered and quenched condition are not appreciably different between the two plates. Despite strain aging, however, the transition temperature of the present A543B1 steel plate is lower than that of the previous A543B1 steel plate.

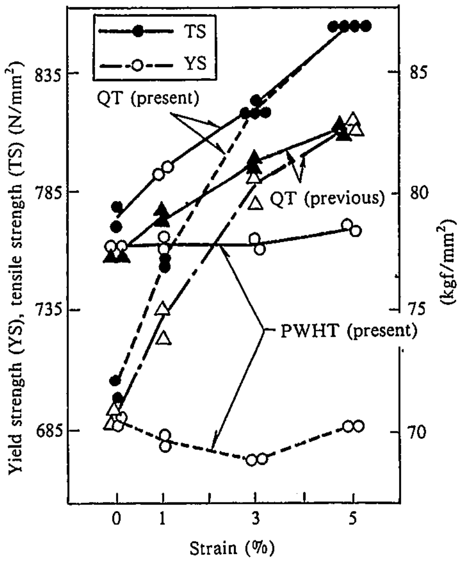


Fig. 5 Strain aging tensile test results of present and previous ASTM A 543 Type B Class 1 steel plates (t = 50 mm)
Specimen size: JIS Z 2201 No. 4
Specimen position: 1/4t plane in T direction
Aging: 250°C × 1 h
PWHT: 594°C × 3.4 h

Table 6 Strain aging Charpy impact test results of present and previous ASTM A 543 Type B Class 1 steel plates

Heat treatment	Prestrain (%)	Direction	Present steel plate (50 mm)		Previous steel plate (40 mm)	
			$_vT_{rs}$ (°C)	$_vT_{r50}$ (°C)	$_vT_{rs}$ (°C)	$_vT_{r50}$ (°C)
QT	0	L	−175	< −180	—	—
		T	−173	< −180	−150	−153
	1	L	< −180	< −180	—	—
		T	−151	−166	−133	−138
	3	L	−165	−175	—	—
		T	−150	−158	−134	−138
	5	L	−170	−179	—	—
		T	−158	−165	−116	−126

Aging: 250°C × 1 h, PWHT: 595°C × 3.4 h

3. Weldability of ASTM A 543 Type B Class 1 Steel Plates: y-Groove Weld Cracking Test Results

Table 7 summarizes the y-groove weld cracking test results and critical preheating temperatures of the present and previous A543B1 steel plates. The present A543B1 steel plate exhibits P_{CM} values slightly higher than those of the previous A543B1 steel plate, but is 50°C lower in the critical preheating temperature for manual welded joints. These results can be attributed to the use of improved welding materials.

Table 7 Critical preheating temperature in y-groove weld cracking test for present and previous ASTM A 543 Type B Class 1 steel plates

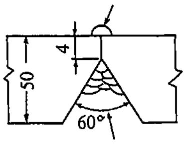
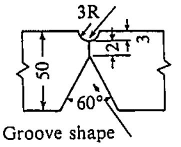
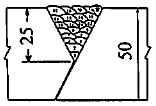
Welding process	Present steel plates (50 mm)	Previous steel plates (40 mm)	Welding conditions
Manual welding	50°C	100°C	175 A × 25 V × 15 cm/min
MIG welding	50°C	75°C	150 A × 20 V × 20 cm/min

Welding atmosphere: 30°C, 80%
Present welding materials:
(1) Manual welding electrode: LBY-75 (diffusible hydrogen content of weld metal: 2.2 ml/100 g)
(2) MIG welding electrode: MGS-70 (diffusible hydrogen content of weld metal: 0.2 ml/100 g)

4. Stress-Relief (SR) Cracking Test of ASTM A 543 Type B Class 1 Steel Plates

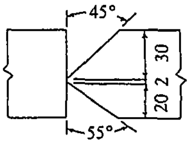
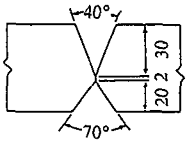
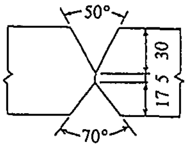
Table 8 shows the results of stress-relief cracking tests con-

Table 8 Stress-relief cracking (SR) test results of BOF-melted ASTM A 543 Type B Class 1 steel plate (50 mm thick[4,5])

Test method	Nippon Steel SR cracking test (T-type)	WES SR cracking test (WES 3005-1977)	y-groove SR cracking test (JIS Z 3158)
Specimen shape (mm) (Thickness × width × length, mm)	Test bead side  Restraint bead side 50 × 220 × 170	Test bead side  Groove shape Restraint bead side 50 × 220 × 170	Bead buildup sequence  50 × 150 × 200
Restraint welding	220A-26V-15cm/min		Restraint welding as per JIS Z 3158
Number of restraint passes	6, 8, 10, 13, 16, 20, 25 (one cycle each)		
Test bead	170A-24V-15cm/min 1 pass	170A-24V-15cm/min 1 pass	170A-25V-15cm/min 22 passes
Evaluation procedure	As per SR cracking evaluation procedure in WES 3005-1977		Examination for SR cracking of macrostructures on four cross sections after PWHT
Test results	No surface and cross-sectional cracks		No cross-sectional cracks (2 cycles)

Welding electrode: LBY-75 (4.0 mmφ), Preheating temperature: 100°C,
Temperature and humidity: 30°C, 80%, PWHT: 595°C × 7.4 h

Table 9 Welding conditions of ASTM A 543 Type B Class 1 steel plate

Welding process	Groove shape (mm)	Welding material	Welding conditions				
			Current (A)	Voltage (V)	Speed (cm/min)	Interpass preheat temp. (°C)	Heat input (kJ/cm)
MIG Double-bevel groove		Wire: MGS-70, 1.2 mmϕ Shielding gas: 80% Ar + 20% CO_2 (30 l/min)	270-300	34-37	18-21	150	32
MIG Double-V groove		Wire: MGS-70, 1.2 mmϕ Shielding gas: 80% Ar + 20% CO_2 (30 l/min)	290-300	35	20-21	150	31
SAW Double-V groove		Wire: KW-103B, 4.8 mmϕ Flux: KB-80C, 12 × 200	610-730	30-32	30-35	120-150	41

ducted on BOF-melted A543B1 steel plates by the Nippon Steel, WES, and y-groove methods. In every test method, stress-relief cracking was not observed in the steel plates[4,5].

The following may be said from the results of studies on the stress-relief cracking of 780-N/mm^2 high-strength steel plates [4-14], of tests on the present A543B1 steel plate, and of tests conducted by Imai et al.[15]:

(1) It was confirmed that the stress-relief cracking sensitivity of the A543B1 steel is low, mainly because it is low in the carbon and phosphorus contents and does not contain vanadium, niobium or whatever else which enhances the stress-relief cracking sensitivity.

(2) It was found that the stress-relief cracking evaluation indexes ΔG and P_{SR} are not correlated with the stress-relief cracking sensitivity of the A543B1 steel.

5. Fracture Toughness of ASTM A 543 Type B Class 1 Steel Plate and Welded Joints

5.1 Welded joints

The A543B1 steel plates were welded by the MIG welding process and submerged arc welding (SAW) process, both of which are employed in the fabrication of containment vessels, under the conditions given in **Table 9**. MIG welded joints were tested in both as-welded and PWHT conditions. **Table 10** shows the Charpy impact test results on the welded joints.

Table 10 Charpy impact test results of welded joints of ASTM A 543 Type B Class 1 steel plate

Welding process	Heat treatment	Notch location	$_vT_{rs}$ (°C)	$_vT_{r50}$ (°C)	$_vE_{max}$ (J)	$_vE_{-13}$ (J)	$_vT_{r35mils}$ (°C)	LE_{-13} (mm)
MIG Double-bevel groove	AW	FL*1	−52	−60	220	192	−61	2.19
		HAZ0.8*2	−111	−151	239	232	−140	2.15
	PWHT	FL	−59	−65	187	181	−67	1.84
		HAZ0.8	−129	< −160	270	277	< −160	2.26
MIG Double-V groove	AW	FL	−71	−76	200	208	−75	2.12
		HAZ0.8	−101	−125	229	219	−124	2.24
	PWHT	FL	−54	−69	197	174	−68	1.88
		HAZ0.8	−88	−108	249	249	−106	2.29
SAW Double-V groove	AW	FL	−57	−66	138	149	−66	1.76
		HAZ0.8	−97	−122	294	286	−115	2.38

*1 FL: Weld fusion line
*2 HAZ0.8: 0.8 mm into heat-affected zone (HAZ) from FL

5.2 Fracture toughness tests

When using the A543B1 steel plate for a containment vessel, it must be confirmed that the plate and its welded joints, the fusion line in particular, are fully safe from brittle fracture under the operating conditions of the containment vessel. To clarify and evaluate the fracture toughness properties of the base metal and fusion line against the specified values[16,17] of the Japan Electric Association (JEAC) and ASME Sec. III, and to quantify their safety under service conditions by fracture mechanics, various tests and comparative studies were made on the steel plate: Static fracture toughness, dynamic fracture toughness, and crack arrest toughness properties were determined according to ASTM E 399 and E 813, the CCA test method, and the ESSO test method, respectively. Since the steel plates were 50 mm thick, the static and dynamic fracture toughness tests were conducted using 2TCT specimens, and the CCA and ESSO tests were conducted using 50 mm thick specimens.

Welded joints were tested by machining a notch in the fusion line that is low in toughness. Double-bevel (K) grooves were also used in addition to X grooves to accurately determine the fusion line toughness properties of the plate.

5.3 Charpy impact properties

Table 11 shows the Charpy impact test and drop weight test properties specified by the Japan Electric Association Standard JEAC 4206-1991 and ASME Sec. III concerning steels for containment vessels. The Charpy impact absorbed energy values at the lowest design temperature (LDT) of −13°C are specified as mean/minimum values of three specimens ≧ 61/54 J. As seen from **Tables 4** and **10**, the base metal and heat affected zone (HAZ) fully meet the specified toughness values.

Table 11 Toughness requirements of containment vessel steels (on the basis of ASTM A 543 Type B Class 1 steel)

	JEAC 4206-1991	ASME Sec. III (NB 2332, NE 4622)
Impact	${}_vE \geqq 61/54$ J at LDT $LE \geqq 0.9/0.75$ mm at LDT	${}_vE \geqq 61/54$ J at LDT $LE \geqq 0.9/0.75$ mm at LDT
	For SGV 480 (SA 516-70), t = 38 to 44.5 mm, without PWHT	
	${}_vE \geqq 68/61$ J at LDT	${}_vE \geqq 68/61$ J at LDT or ${}_vE \geqq 61/54$ J at LDT −6°C
Drop weight test	$T_{NDT} \leqq$ LDT −17°C (A = 17°C)	$T_{NDT} \leqq$ LDT −17°C (A = 17°C)

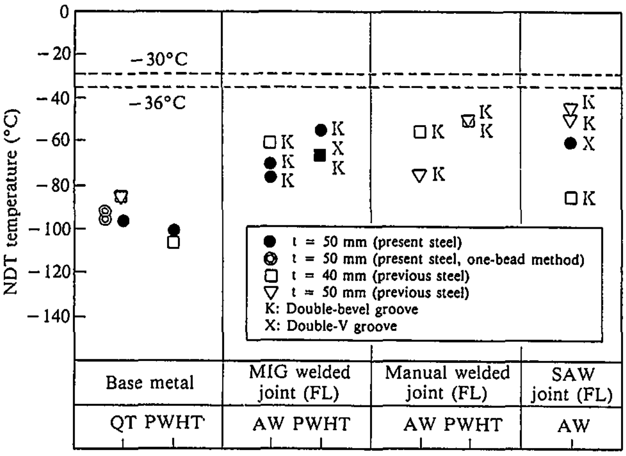


Fig. 6 NDT temperature of ASTM A 543 Type B Class 1 steel plates and weld fusion line (by two-bead method)

5.4 Drop weight properties

The specified nil-ductility transition (NDT) temperature of the drop weight test is the LDT minus 17°C (or −30°C). The results of drop weight test by the two-bead technique are shown in **Fig. 6**. The base metal and fusion line both satisfy the required values, irrespective of whether or not PWHT is performed. NDT temperatures of the previous A543B1 steel plate are also shown for comparison. As indicated, values for the present A543B1 steel plate are equal to or better than those for the previous A543B1 steel plate.

As also shown in **Fig. 6**, the drop weight test of the base metal was performed also by the single-bead technique (ASTM E 208-1986)[18]. The sift of the NDT temperature is only 5 to 10°C, which indicates that the present A543B1 steel plate is fully satisfactory also in terms of the NDT temperature by the single-bead technique.

5.5 Static fracture toughness

Quenched and tempered (QT) and PWHT (595°C × 3.7 h) steel A543B1 steel plates were subjected to the K_{IC} test according to ASTM E 399 and the J_{IC} test according to ASTM E 813, using 2TCT specimens. When the steel plate failed to provide a valid K_{IC} value in the K_{IC} test, it was evaluated by the J value (J_C) at which it fractured.

The base metal test results are all converted into corresponding K values and shown in **Fig. 7**. At the lowest operating temperature of −13°C, the QT and PWHT steel plates both fall in the fracture toughness upper shelf region and exhibit the K_{IC} values obtained in the J_{IC} test. In **Fig. 7**, static fracture test results of the fusion line in the double bevel groove in the MIG welded joints are also shown. The fusion lines in the as-welded and PWHT joints are at the same toughness levels and exhibit fracture toughness transition curves similar to those of the previous A543B1 steel plates.

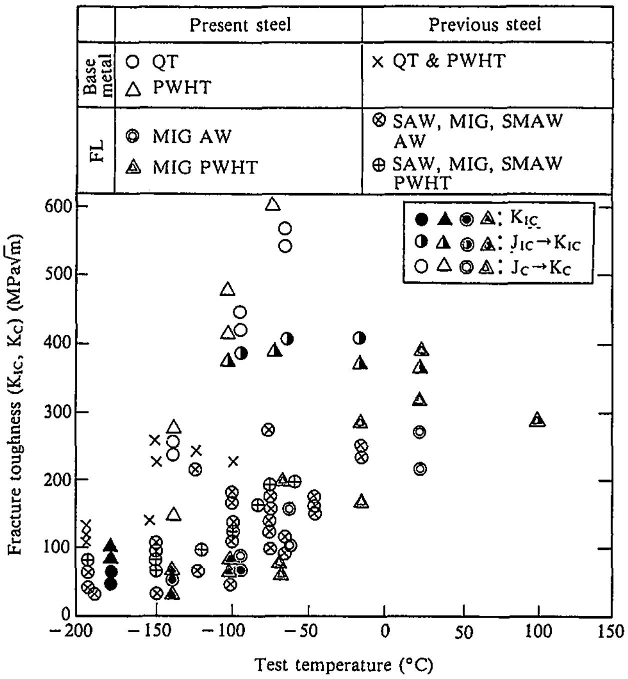


Fig. 7 Relationship between test temperature and static fracture toughness of ASTM A 543 Type B Class 1 steel plates and weld fusion line

5.6 Dynamic fracture toughness and brittle crack arrest toughness

Fig. 8 summarizes the dynamic fracture toughness test results and brittle crack arrest test results of the base metal and fusion line. The minimum toughness value at the lowest operating temperature of −13°C was $124 \mathrm{MPa}\sqrt{m}$ in the K_{Id} test. The previous A543B1 steel plate was not subjected to the dynamic fracture toughness test, and the test results shown are only from the ESSO test. Therefore, it can be said that the toughness properties of the present A543B1 steel plate are similar to those of the previous A543B1 steel plate.

5.7 Discussion on safety

The Charpy impact properties of the base metal and weld joint satisfy the requirements of the JEAC and ASME, and so does the NDT temperature in the drop weight test. It was confirmed that these properties are equal to or better than those of the previous A543B1 steel plate. The static and dynamic fracture toughness values of the base metal fall in the upper shelf region at the lowest design temperature of −13°C and indicates that the base metal is safe from brittle fracture. The minimum fracture toughness value of the fusion line in the as-welded condition and PWHT condition at the lowest design temperature of −13°C was about $124 \mathrm{MPa}\sqrt{m}$ (as obtained in the K_{Id} test).

The fracture toughness of the present A543B1 steel plate was compared with the K_{IR} and K_{IC} curves of ASME Sec. III and Sec. XI specified for primary system nuclear reactor pressure vessels. **Fig. 9** comparatively shows the static fracture toughness test results and K_{IC} curves of the base metal and fusion line. In **Fig. 10**, the dynamic fracture toughness test results and brittle crack arrest test results of the base metal and fusion line are compared with the K_{IR} curve. It is indicated that the lower limit envelope

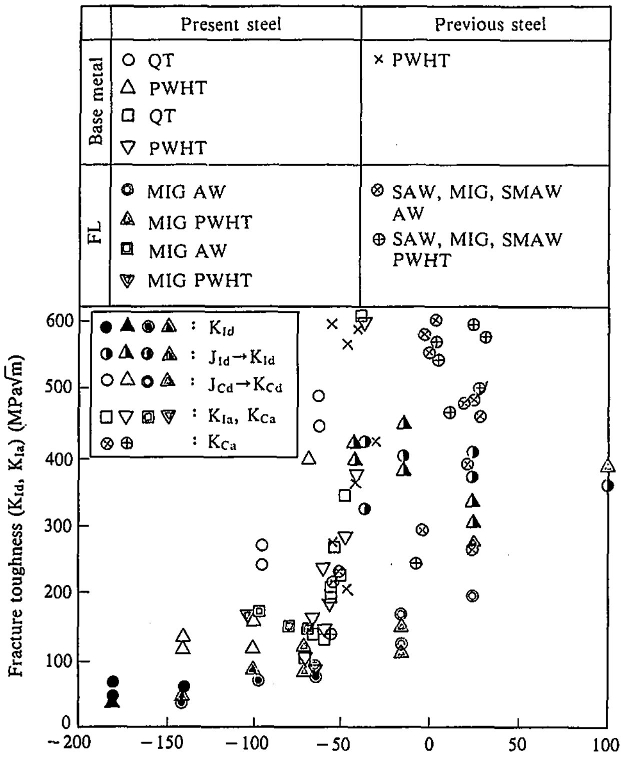


Fig. 8 Relationship between test temperature and dynamic fracture toughness and crack arrest toughness of ASTM A 543 Type B Class 1 steel plates and weld fusion line

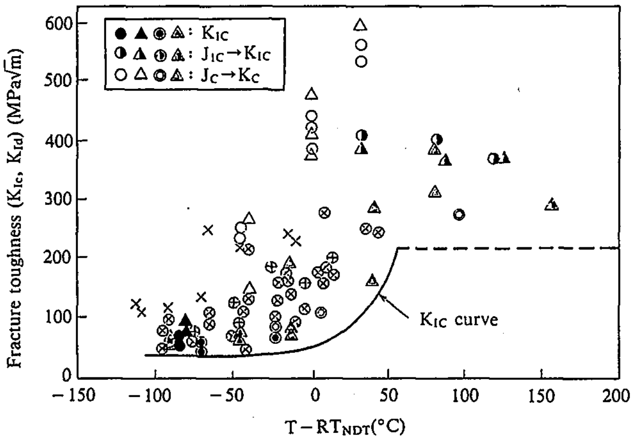


Fig. 9 Relationship between K_{IC} curve and static fracture toughness of ASTM A 543 Type B Class 1 steel plates and welded joints (for legend, refer to Fig. 7)

lines of the static and dynamic fracture toughness values are higher than the K_{IC} and K_{IR} curves.

As can be seen from **Fig. 10**, the fracture toughness values are slightly lower for the test results of the as-welded specimens with respect to T-RT_{NDT}, but none of the fracture toughness values falls below the K_{IR} curve. In other words, the lower limit of toughness is defined by the K_{IR} curve. This means that the A543B1 steel can be evaluated from the RT_{NDT} temperature, using the fracture toughness curves given in ASME Sec. III and Sec. XI.

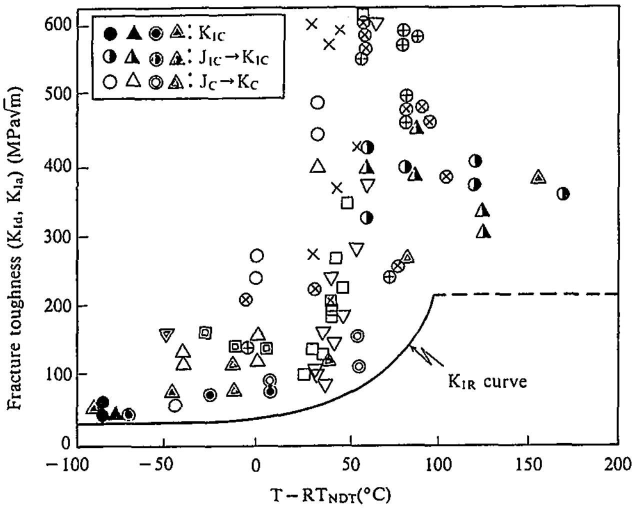


Fig. 10 Relationship between K_{IR} curve and dynamic fracture toughness and brittle crack arrest toughness of ASTM A 543 Type B Class 1 steel plates and welded joints (for legend, refer to Fig. 8)

The relationship between the critical fracture stress and temperature is obtained from the lower limit envelope line of fracture toughness values by linear fracture mechanics. The flaw assumed here is a semi-elliptic surface crack of 1/4t depth and of 1.5t length at the surface according to ASME Sec. III Appendix G. A uniform tensile stress is assumed to act on the surface crack. The K value of the surface crack is given by

$$K = \sigma_m M_m \sqrt{[\pi a/Q]} \quad ....(1)$$

where σ_m is the tensile stress; a is the crack depth; Q is the shape factor of the elliptic crack; and M_m is a correction coefficient for the tensile stress.

The value of M_m is calculated from Newman's equation[19], and the effect of temperature on the critical fracture stress is obtained accordingly. The results are given in **Fig. 11**. The critical stress curves are extremely high as compared with the design condition range (lowest operating temperature of −13°C and allowable stress of 180 N/mm^2) and indicate that the A543B1 steel plate

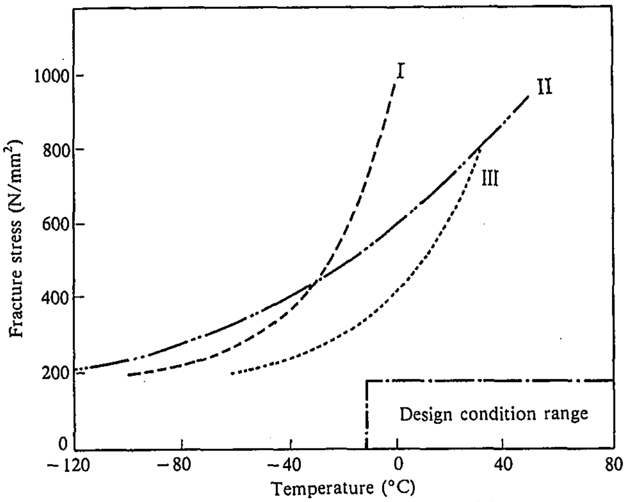


Fig. 11 Relationship between temperature and critical fracture stress

I: Fracture stress curve estimated from K_{IC} curve (NDT = −55°C)
II: Fracture stress curve estimated from toughness lower limit line
III: Residual stress curve estimated from K_{IR} curve (NDT = −55°C)

is safe from brittle fracture.

Next, whether the 50 mm thick A543B1 steel plate can be safely used against brittle fracture without PWHT is examined on the basis of its fracture toughness values at the lowest design temperature of -13°C. The fracture toughness values of the fusion line at -13°C are obtained from the RT_{NDT} temperature (-75°C in the as-welded condition and -55°C in the PWHT condition), according to the ASME K_{IR} and K_{IC} curves and the minimum values of test results. If there is welding residual stress in the as-welded condition, the evaluation is made by the K value additive law that substitutes $\sigma_m + \sigma_R$ (where σ_R is the welding residual stress) for σ_m in Eq. (1).

If a surface flaw of 1/4t depth and 1.5t length is present along the weld line, $\sigma_R = \sigma_Y/3 = 196$ N/mm^2 (where σ_Y is the yield stress) can be assumed. As can be seen in **Table 12**, the critical stress of the present A543B1 steel plate is much higher in the as-welded condition than the allowable stress of the A543B1 steel. This means that the present A543B1 steel plate can be safely used in the as-welded condition.

Table 12 Critical stress for brittle fracture

		Fracture toughness value		
		K_{IR} curve	K_{IC} curve	Minimum measured value
PWHT $RT_{NDT} = -55$°C	K_{crit} (MPa$\sqrt{m}$)	70	140	124
	σ_{crit} (N/mm^2)	338	674	589
AW $RT_{NDT} = -75$°C	K_{crit} (MPa$\sqrt{m}$)	90	215	124
	σ_{crit} (N/mm^2)	276	1000	392

$\sigma_{crit} = K_{crit}/M_m\sqrt{[\pi a/Q]}) - \sigma_R$, $\sigma_R = 196$ N/mm^2

6. Conclusions

With the object of practically applying 720-N/mm^2 high strength steel plates (former ASTM A 543 Type B Class 1) to hybrid high strength steel containment vessels, steel plates manufactured by the BOF process were tested for basic service performance, weldability and stress-relief cracking as well as for static and dynamic fracture toughness of base metal and weld fusion lines. The steel plates tested fully satisfied the applicable specifications in the quenched and tempered condition and in the postweld heat treated condition, were totally free from stress-relief cracking, and exhibited excellent static and dynamic fracture toughness properties. The use of improved welding materials further enhanced their weldability with the critical preheating temperature being lowered by 50°C. From these results, it is concluded that the steel plate under review is safely applicable to hybrid high-strength steel containment vessels.

In the near future, 720-N/mm^2 high-strength Ni-Cr-Mo high-strength steel plates (former ASTM A 543 Type B Class 1) will be used to fabricate nuclear reactor containment vessels.

Acknowledgments

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