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Development of SA-738 Gr. B High Strength Steel Plate with Excellent Toughness for Power Generating Plants†

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Abstract:

JFE Steel has developed ASME SA-738 Gr. B (ASME: The American Society of Mechanical Engineers) high strength steel plate for reactor containment vessels in response to great demand for new construction of nuclear power plants mainly in America, China, and developing countries. The developed steel has excellent toughness to meet the requirement of exemption rule of post-weld heat treatment (PWHT) in ASME with thickness 44.5 mm or less, and also has good weldability through the reduction of preheat temperature. Heavy section plate around 100 mm thickness has good toughness by redeucing impurity levels, and excellent internal qualities can be obtained through the application of a forging and plate rolling process to continuous casting slabs. These developed steels have already been adapted to some nuclear power plants.

1. Introduction

In order to prevent global warming due to CO_2 emissions and respond to increasing global energy demand, construction of a large number of new nuclear power plants is being planned, centering on the United States, China, and the emerging economies. It is generally assumed that the main stream in nuclear power plants constructed in the future will be Generation III (III+) nuclear reactors[1)]. In the new 1 000 MW class pressurized water reactor, which is one of these new reactors, SA-738 Gr. B under the ASME Code (ASME Boiler & Pressure Vessel Code, ASME: The American Society of Mechanical Engineers) has been designated as a steel plate for reactor containment vessels.

Since the volume of a reactor containment vessel is extremely large and construction involves many parts which are performed at the site, post-weld heat treatment (PWHT) of field welds increases both construction costs and the work load. On the other hand, the ASME Code, Section III, Division I, Subsection NE, Class MC Components (Rules for Construction of Nuclear Facility Components) recognizes the possibility of omitting PWHT (exemption rule) for SA-738 and certain other carbon steels with thicknesses of 44.5 mm or less based on strict toughness requirements in cases where limits on the C content and preheat temperature are applied. Accordingly, development of steel plates with excellent low temperature toughness of the base material and welded joints, which satisfy the requirement in PWHT exemption rule within the specified composition range, has been demanded.

In addition to the above-mentioned materials, heavy section plates with 100 mm class thickness are used in equipment hatches and airlocks in reactor containment vessels. When these heavy section plates are produced from continuous casting slabs by a plate rolling process, deterioration of mechanical properties due to the effects of center porosities which were not closed in the center of plate thickness is a concern. To improve the internal

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Table1 Target properties of the developed steel

	Thickness (mm)	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb	Ceq
SA-738 Gr. B	t ≤38.1	≤0.20	0.15/ 0.55	0.90/ 1.50	≤0.030	≤0.030	≤0.35	≤0.60	≤0.30	≤0.20	≤0.07	≤0.04	≤0.48
	38.1< t ≤63.5									≤0.30			
	t >63.5			0.90/ 1.60									—

Thickness (mm)	Base plate					Welded joint	
	Tensile properties			Charpy impact properties	Drop weight properties	Tensile properties	Charpy impact properties
	YS (MPa)	TS (MPa)	El (%)	$_{\mathrm{v}}E$ (J)	T_{NDT} (°C)	TS (MPa)	$_{\mathrm{v}}E$ (J)
38.1< t ≤63.5	≥414	587/703	≥20	$_{\mathrm{v}}E_{-60^{\circ}\mathrm{C}}$ ≥48 (Min.) ≥55 (Ave.)	—	≥587	$_{\mathrm{v}}E_{-40^{\circ}\mathrm{C}}$ ≥48 (Min.) ≥55 (Ave.)
t >63.5	≥414	587/703	≥20	$_{\mathrm{v}}E_{-40^{\circ}\mathrm{C}}$ ≥62 (Min.) ≥68 (Ave.)	≤−25	≥587	$_{\mathrm{v}}E_{-40^{\circ}\mathrm{C}}$ ≥62 (Min.) ≥68 (Ave.)

Ceq=C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5
YS: Yield strength TS: Tensile strength El: Elongation $_{\mathrm{v}}E$: Absorbed energy T_{NDT}: Nil-ductility transition temperature

soundness of heavy section products, JFE Steel developed a process in which forging is applied to continuous casting slabs before plate rolling[2–5], and has supplied a large number of plates for pressure vessels and other applications. In the developed steel, heavy section materials with excellent internal properties were developed using continuous casting slabs by applying the combined forging and plate rolling process.

This paper introduces the base material performance, weldability, and welded joint performance of the SA-738 Gr. B high strength steel plate which was developed as a material for reactor containment vessels.

2. Development Targets for SA-738 Gr. B for Reactor Containment Vessels

2.1 Target Properties of SA-738 Gr. B

Table 1 shows the target properties of SA-738 Gr. B high strength steel plate, which was developed for reactor containment vessels, based on the ASME Code for chemical composition and mechanical properties. SA-738 Gr. B is a 600 MPa class steel which is produced by quench-temper (Q-T) treatment. Upper limits for the contents of alloy elements and carbon equivalent Ceq are specified by plate thickness. In order to guarantee properties after applying PWHT (615°C×10 h), one target in material development was to secure the required mechanical properties with a temper temperature of 650°C or higher.

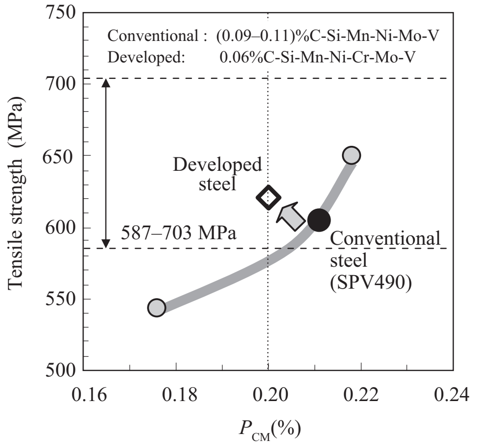
The toughness guarantee temperature was set based on the lowest service metal temperature, and was modified based on the reactor structure, location of construction, plate thickness, etc. In material development, the test temperatures for Charpy impact properties and drop weight properties were calculated based on the ASME Code, assuming construction in a cold region, and securing toughness at −60°C and −40°C was then set as a development target, also considering a safety allowance. In particular, for Charpy impact properties, when the above-mentioned PWHT exemption rule is to be applied, it is necessary to satisfy the specified absorbed energy at a temperature 5.6°C lower than the specified temperature, or to increase the absorbed energy at the specified temperature by 7 J.

2.2 Development Concept

To achieve the target properties, a study was carried out based on SPV490[6–8], which is a JIS material (JIS: Japanese Industrial Standards) of tempered 600 MPa grade steel, and has a record of use as a steel plate for reactor containment vessels at nuclear power plants in Japan.

Regarding the manufacturing method, although both SA-738 Gr. B and SPV490 are Q-T materials, if the temper temperature is set to an elevated temperature of 650°C or more, recovery of dislocations, precipitation coarsening, etc. generally proceed. As these changes reduce the strength of the material, consideration of the composition design is necessary, for example, measures to improve resistance to temper softening, etc. in order to secure the required strength when applying high temperature tempering followed by PWHT.

To satisfy the PWHT exemption rule with steel plates having thicknesses of 44.5 mm or less, it is important to prevent increased hardness of the heat affected zone (HAZ) by reducing the C content and weld-crack sensi-



P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Fig. 1 Relationship between tensile strength and P_{CM} after post weld heat treatment (PWHT)

tivity composition P_{CM}.

Figure 1 shows the results of a laboratory study of toughness after high temperature tempering (670°C) and PWHT (615°C×10 h) based on a 0.11% C conventional SPV490 and a 0.06% C steel. In order to compensate for the strength reduction due to the low C content of the developed steel in comparison with the conventional SPV490 steel, a composition design which makes it possible to secure strength with a low P_{CM} ($\leqq$ 0.20%) was adopted by optimum addition of elements with large temperature softening resistance, such as Mo, V, Cr, Si, etc.[9].

The effect of reducing impurity elements in order to improve low temperature toughness was also studied. Using the 0.06% C steel as a base, the effect of the phosphorus content on base material toughness after PWHT was studied. The results are shown in **Fig. 2**. It is possible to suppress toughness decrease in the matrix and improve base material toughness after PWHT by reducing the phosphorus content.

With heavy thickness materials with thicknesses of 100 mm class, securing toughness in the center of thickness area using continuous casting slabs is an issue. Therefore, a combined forging and plate rolling process which had been established previously by JFE Steel was applied. As in the study of plates of 40 mm class thickness described above, the optimum amounts of alloy elements such as Mo, V, Cr, etc., which have large resistance to temper softening, were also added to secure strength after PWHT, and in addition, reduction of the impurity elements P and S was reflected in the composition design as a measure to improve low temperature toughness.

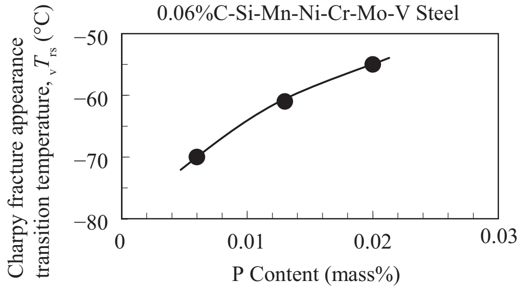


Fig. 2 Effect of P content on toughness after post weld heat treatment (PWHT)

3. Properties of Developed SA-738 Gr. B Steel

3.1 Base Material and Welded Joint Properties of Developed Steel (Thickness: 47.6 mm)

The chemical composition of the developed steels (also including steels with thicknesses of 44.5 mm and under to which the PWHT exemption rule under ASME Sec. III is applicable) are shown in **Table 2**. Weldability is improved by holding the C content to a low level and reducing P_{CM} to 0.20% or less. To suppress the strength drop due to PWHT, the composition design actively uses elements (Mo, V, Cr, Si, etc.) which increase resistance to temper softening, and to improve low temperature toughness, the impurity elements P and S are reduced in the steelmaking process.

The mechanical properties of the base plate of the developed steel, which is manufactured by the quench-temper (Q-T) process, are shown in **Table 3**. Strength satisfying the requirement of SA-738 Gr. B and excellent low temperature toughness at −60°C are obtained before and after PWHT.

The results of a maximum hardness test and the results of a y-groove weld cracking test, which were performed to evaluate weldability, are shown in **Table 4** and **Table 5**, respectively. Because P_{CM} was reduced to no more than 0.20%, maximum hardness is low, at 275

Table 2 Chemical compositions of the developed steels

(mass%)

Thickness (mm)	C	Si	Mn	P	S	Others	Ceq	P_{CM}
47.6	0.05	0.39	1.44	0.003	0.001	Cu, Ni, Cr, Mo, V, etc.	0.46	0.20
103.1	0.12	0.30	1.54	0.003	0.001	Ni, Cr, Mo, V, etc.	0.52	0.25

Ceq=C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5
P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Table 3 Mechanical properties of base plate of the developed steel

Thickness (mm)	Position	Direction	PWHT	Tensile properties			Charpy impact properties		
				YS (MPa)	TS (MPa)	El (%)	$_vE_{-40°C}$ (J)	$_vE_{-60°C}$ (J)	$_vT_{rs}$ (°C)
47.6	1/4t	T	—	573	642	28	431	380	−97
			615°C×10 h	565	642	27	343	303	−80

Tensile test specimen: ASME SA-370, Φ12.7 mm (GL 50.8 mm)
Charpy impact test specimen: ASME SA-370, Full-size
ASME: The American Society of Mechanical Engineers
PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation
$_vE_{-40°C}$: Absorbed energy at −40°C $_vE_{-60°C}$: Absorbed energy at −60°C $_vT_{rs}$: Fracture appearance transition temperature

Table 4 Results of maximum hardness test (Thickness: 47.6 mm)

Preheat temperature (°C)	Maximum hardness, HV10
R.T. (25)	275
50	266
100	275
150	260

Test method: JIS Z 3101 (JIS: Japanese Industrial Standards)
Welding condition: SMAW SMAW: Shielded metal arc welding Heat input: 1.7 kJ/mm R.T.: Room temperature

Table 5 Results of y-groove weld cracking test

Thickness (mm)	Welding condition	Preheat temperature (°C)	Cracking ratio (%)		
			Surface	Section	Root
47.6	SMAW Welding consumable: LB-62UL* Heat input: 1.7 kJ/mm Atmosphere: 30°C-80%	R.T. (25)	0	0	0
		50	0	0	0
		75	0	0	0
		100	0	0	0

Test method: JIS Z 3158 (JIS: Japanese Industrial Standards)
*Supplied by Kobe Steel, Ltd.
SMAW: Shielded metal arc welding R.T.: Room temperature SMAW: Shielded metal arc welding

Table 6 Welding condition and mechanical properties of welded joints of the developed steel

Thickness (mm)	Groove configuration	Welding condition	PWHT	Tensile properties		Charpy impact properties		
				TS (MPa)	Fracture position	Position		$_vE_{-40°C}$ (J)
47.6	X	GMAW Welding consumable: MG-S3N* Heat input: 3.8 kJ/mm	—	638	WM	1/4t	WM	147
							FL	176
							HAZ	289
			615°C×10 h	619	WM	1/4t	WM	144
							FL	176
							HAZ	244

*Supplied by Kobe Steel, Ltd. GMAW: Gas metal arc welding PWHT: Post weld heat treatment TS: Tensile strength
WM: Weld metal FL: Fusion line HAZ: Heat-affected zone $_vE_{-40°C}$: Absorbed energy at −40°C

points, even under a condition of no preheating, and the plate possesses excellent weldability, having a cracking prevention preheat temperature of room temperature or less.

The mechanical properties of welded joints of the developed steel are shown in **Table 6**. Welded joint strength satisfying the specification of the base material and excellent weld toughness were obtained before and after PWHT. In case the PWHT exemption rule is applied, it is necessary to satisfy the specified toughness value at a temperature 5.6°C lower than the lowest service metal temperature, or to increase the absorbed

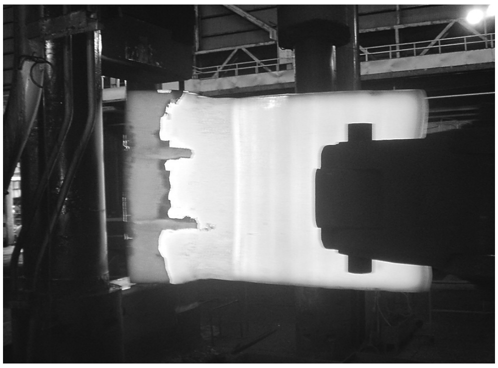


Photo 1 Forging reduction in widthwise of continuous casting slab

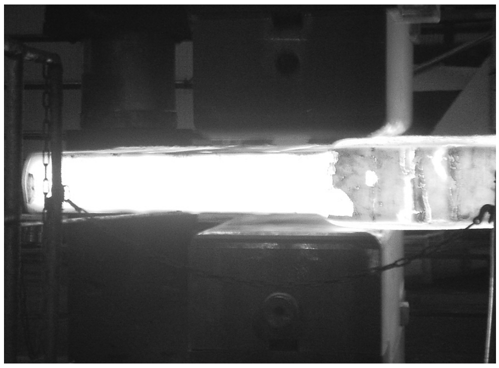


Photo 2 Forging reduction in thicknesswise of continuous casting slab

Table 7 Mechanical properties of base plate of the developed steel

Thickness (mm)	Position	Direction	PWHT	Tensile properties			Charpy impact properties			Drop weight properties
				YS (MPa)	TS (MPa)	El (%)	$_{v}E_{-20°C}$ (J)	$_{v}E_{-40°C}$ (J)	$_{v}T_{rs}$ (°C)	T_{NDT} (°C)
103.1	1/4t	T	—	591	674	28	271	242	−69	−50
			615°C×10 h	566	663	28	295	258	−69	−40
	1/2t		—	551	651	22	187	199	−43	—
			615°C×10 h	536	646	24	219	174	−38	—

Tensile test specimen: ASME SA-370, Φ12.7 mm (GL 50.8 mm) Charpy impact test specimen: ASME SA-370, Full-size
ASME: The American Society of Mechanical Engineers
Drop weight test specimen: ASTM E208 type P-3 ASTM: The American Society for Testing and Materials
PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation $_{v}E$−20°C: Absorbed energy at −20°C
$_{v}E_{-40°C}$: Absorbed energy at −40°C $_{v}T_{rs}$: Fracture appearance transition temperature T_{NDT}: Nil-ductility transition temperature

Table 8 Results of y-groove weld cracking test

Thickness (mm)	Welding condition	Preheat temperature (°C)	Cracking ratio (%)		
			Surface	Section	Root
103.1	SMAW Welding consumable: LB-62UL* Heat input: 1.7 kJ/mm Atmosphere: 30°C-80%	75	15	23	94
		100	0	17	67
		125	0	0	0

Test method: JIS Z 3158 (JIS: Japanese Industrial Standards) *Supplied by Kobe Steel, Ltd. SMAW: Shielded metal arc welding

energy at the specified temperature by 7 J. However, the developed steel has excellent low temperature toughness which amply exceeds the specified value at −40°C even without PWHT. The above-mentioned base material toughness and welded joint toughness results confirmed that the developed steel has excellent low temperature toughness satisfying the PWHT exemption rule.

3.2 Base Material and Welded Joint Properties of Developed Steel (Thickness: 103.1 mm)

The chemical composition of the heavy thickness plate used as a material for equipment hatches and air-locks of reactor containment vessels is shown in Table 2. As shown in **Photos 1** and **2**, forging is applied to continuous casting slabs in the width and thickness directions, followed by plate rolling. The mechanical properties of the base plate of the developed steel, which is manufactured by the quench-temper (Q-T) process, are shown in **Table 7**. The heavy thickness plate assumes PWHT. Before and after PWHT, this plate possesses strength amply satisfying the specified value at both the 1/4t and 1/2t positions and excellent low temperature toughness at −40°C.

The results of the y-groove weld cracking test with a 103.1 mm full thickness test specimen of the developed steel are shown in **Table 8**. The crack prevention preheat temperature is 125°C, and the plate displays sufficiently high weldability as a heavy section plate of 600 MPa class steel.

The mechanical properties of welded joints of the developed steel are shown in **Table 9**. Before and after PWHT, the plate possesses welded joint strength satisfying the specification of the base material and excellent low temperature toughness in the weld at −40°C.

Table 9 Welding condition and mechanical properties of welded joints of the developed steel

Thickness (mm)	Groove configuration	Welding condition	PWHT	Tensile properties		Charpy impact properties		
				TS (MPa)	Fracture position	Position		$_{v}E_{-40^{\circ}C}$ (J)
103.1	X	GMAW Welding consumable: MG-S3N* Heat input: 3.8 kJ/mm	—	678	WM	1/4*t*	WM	118
							FL	124
							HAZ	303
			615°C×10 h	623	WM	1/4*t*	WM	162
							FL	172
							HAZ	303

*Supplied by Kobe Steel, Ltd. GMAW: Gas metal arc welding PWHT: Post weld heat treatment TS: Tensile strength
WM: Weld metal FL: Fusion line HAZ: Heat-affected zone $_{v}E_{-40^{\circ}C}$: Absorbed energy at −40°C

4. Conclusion

A steel plate with high weldability and excellent low temperature toughness satisfying the PWHT exemption rule specified for thicknesses of 44.5 mm and under in ASME Sec. III was developed as an SA-738 Gr. B high strength steel plate for reactor containment vessels. A heavy section plate of 100 mm class thickness with excellent internal properties was also developed by applying a combined forging and plate rolling process to continuous casting slabs.

Application of the developed steel as a steel plate for reactor containment vessels in new-type nuclear reactor plants has already begun, and adoption in newly-constructed plants in other countries is also expected in the future.

In comparison with SA-537 Cl. 2, which is widely used as a steel plate for tanks and pressure vessels under ASME Sec. VIII, a high allowable stress is set for SA-738 Gr. B. Accordingly, application of the SA-738 Gr. B in pressure vessel plates is expected in the future, responding to needs such as weight reduction by use of thinner plates, etc.

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