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High Performance Steel Plates for Tank and Pressure Vessel Use —High Strength Steel Plates with Excellent Weldability and Superior Toughness for the Energy Industry—†

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Abstract:

JFE Steel has developed a series of high performance 610 MPa class HSLA steel plates with excellent weldability (consisting of JFE-HITEN610U2 with high weldability, JFE-HITEN610U2L for low temperature use, and JFE-HITEN610E for high heat input welding) for the energy industry. Excellent properties of the plates and their weldments are brought about by the microalloying technology, and a direct-quenching and tempering process using Super-OLAC (on-line accelerated cooling) while including low C content, low weld cracking parameter (P_{CM}) value and free of B additive. JFE Steel has also developed a process for manufacturing high reliability heavy section steel plates with excellent internal quality by a combined forging and plate rolling process using high quality continuous casting slabs. Excellent internal properties can be obtained in the manufacture of heavy section SQV2B for pressure vessels and 200 mm thickness class steel plates. All of these products have been applied in numerous plants.

1. Introduction

Various types of steel plates are used in the energy industry in energy storage tanks, chemical plants, power plants, and other applications. In recent years, accompanying the construction of large-scale facilities, more severe operating and service conditions, and high efficiency in welding, which contributes to reduced construction costs, increasingly difficult performance requirements have also been placed on materials, such as improved weldability and enhanced reliability, including welded joints, where high strength, welded joint toughness, and other features are demanded.

To meet these requirements, JFE Steel has developed a series of high performance 610 MPa class high strength low alloy (HSLA) steel plates with excellent weldability (JFE-HITEN610U2, 620U2L, 610E) utilizing advanced material design and manufacturing technologies[1)]. These products have already been applied in a large number of actual plants, including tanks, penstocks, and other facilities, and achieve a broad improvement in welding efficiency by reducing the preheating temperature for welding and relaxing heat input restrictions of welding, and simultaneously contribute to enhanced reliability in welded structures by suppressing hardening of weldments and improving heat affected zone (HAZ) toughness.

JFE Steel also possesses a manufacturing technology for high quality heavy section steel plates, in which high reliability is required, by a combined forging and plate rolling process using continuous casting slabs[2,3)]. The

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products manufacturing by this process are applied as plates for pressure vessels and similar applications. This paper describes the features and properties of the series of high performance 610 MPa class HSLA steel plates with excellent weldability (JFE-HITEN610U2, 620U2L, 610E) and the manufacturing technology for high quality heavy section steel plates by the combined forging and plate rolling process using continuous casting slabs.

2. High Performance 610 MPa Class HSLA Steel Plate Series

2.1 Alloy Design Concept and Manufacturing Technology for High Performance 610 MPa Class HSLA Steel Plate Series

The features and alloy design concept of the high performance 610 MPa class HSLA steel plate series are shown in **Table 1** and **Fig. 1**, respectively. The developed steels all assume conformance with SPV490 of JIS G 3115, Steel plates for pressure vessel, as a precondition, and have the following features.

(1) Reduction of C Content and Weld Cracking Parameter (P_{CM}) and Free of B Additive Alloy Design

From the viewpoint of weldability, the chemical composition adopted for these steels features a low C content below 0.09 mass%, P_{CM} limited below 0.20 mass%, and free of B additive alloy design. This was made possible by application of JFE Steel's advanced on-line accelerated cooling device, *Super*-OLAC[4], which has the world's highest cooling rate / emperature controllability. In comparison with the conventional steels, this technology realizes a reduction in the preheating temperature (**Fig. 2**) and reduction in the maximum hardness of weldment (**Fig. 3**), together with excellent welded joint perfor-

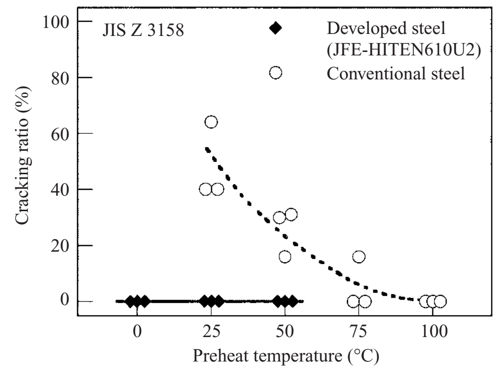


Fig. 2 Decrease of preheat temperature to avoid weld cracking of the developed steel by suppression of C and P_{CM}

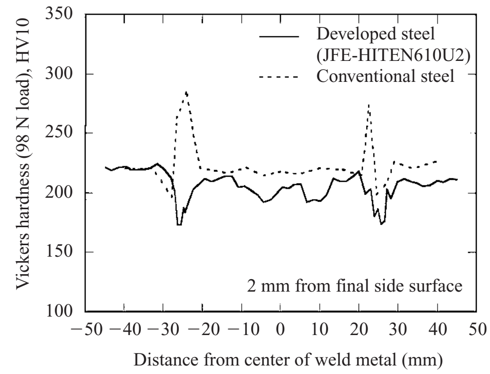
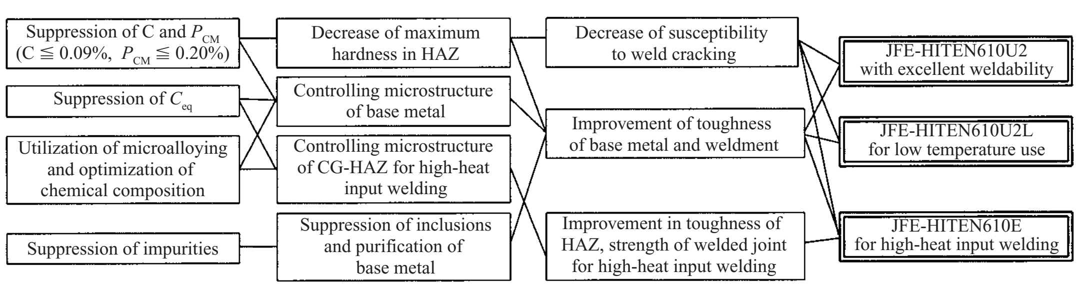


Fig. 3 Improvement of HAZ hardening in hardness distribution of the developed steel by suppression of C content and P_{CM}

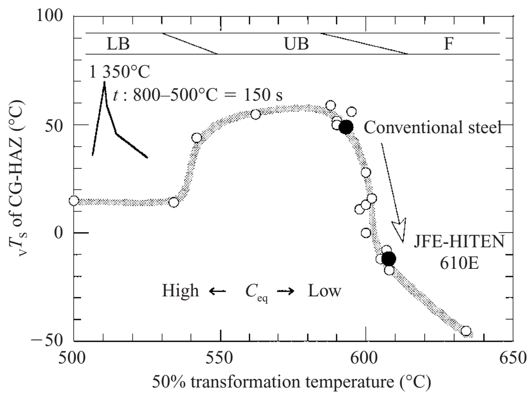
Table 1 JFE Steel's high performance 610 MPa class steel plate series for pressure vessel use

Grade	Thickness, *t* (mm)	Feature	Typical application
JFE-HITEN610U2	6–75	Excellent weldability Superior toughness	Tank, Penstock
JFE-HITEN610U2L	6–75	Excellent weldability Superior toughness at low temperature	Spherical tank for low temperature use
JFE-HITEN610E	6–75	Excellent weldability Superior properties for high heat input welding	Oil storage tank



C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14, P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B, CG-HAZ : Coarse grain HAZ

Fig. 1 Alloy design concept of JFE Steel's high performance 610 MPa class steel plate series



LB : Lower bainite, UB : Upper bainite, F : Ferite

Fig. 4 Influence of microstructure and its transformation temperature on toughness ($_{\mathrm{V}}T_{\mathrm{S}}$) of simulated CG-HAZ for high heat input welding

mance.

(2) Optimum Use of Microalloying Elements

An excellent strength-toughness balance is realized by controlling the microstructure and precipitation of carbonitrides through transformation strengthening and fine-precipitation strengthening during tempering, etc.[5,6] by utilizing microalloying elements in a direct-quenching and tempering (DQ-T) process using *Super*-OLAC.

JFE-HITEN610U2 secures high strength/toughness in addition to greatly improved weldability in comparison with the conventional steel, and is applicable to a wide range of applications such as tanks, penstocks, etc.

JFE-HITEN610U2L, which is based on 610U2, was developed as a high toughness steel for low temperature use, which offers the features of 610U2 combined with excellent low-temperature toughness at −50°C. Refinement of the microstructure is achieved by applying further ingenuity to the material design and controlling the manufacturing conditions in the DQ-T process, satisfying the requirements of both high weldability and guaranteed high toughness at −50°C.

JFE-HITEN610E with improved welded joint strength and heat affected zone (HAZ) toughness for high heat input welding was developed for use in the shell plates of large oil storage tanks, in which high efficiency high heat input electro gas arc welding (EGW) is applied. In addition to the features of 610U2, this steel has an alloy design (**Fig. 4**) which avoids the upper bainite (UB) microstructure that forms at a temperature around 550–600°C and deteriorates HAZ toughness in the coarse grain HAZ (CG-HAZ) for high heat input welding. High HAZ toughness[7] is achieved by suppressing formation of the martensite-austenite constituent (M-A) (**Photo 1**). In order to secure welded joint strength above 610 MPa for high heat input welding, the hardness of the HAZ softened region was increased and the width of the softened region was reduced (**Fig. 5**) by optimum use of microalloying elements, while absolutely minimizing deterioration of HAZ toughness, thereby enhancing welded joint strength without causing deterioration of HAZ toughness. As a result, both excellent weldability and enough properties of weldment for high heat input welding are obtained.

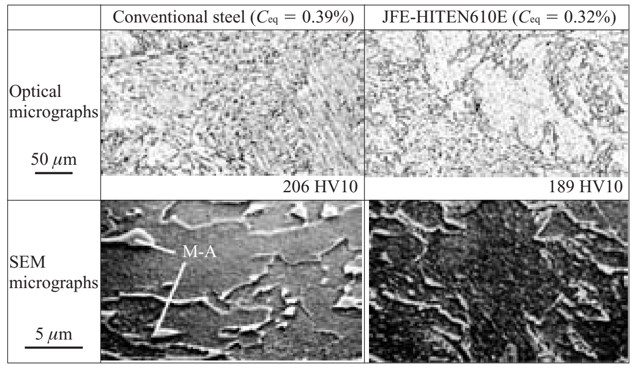


Photo 1 Microstructure of simulated CG-HAZ for high heat input welding

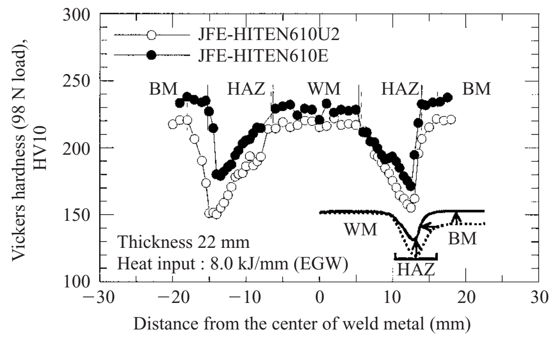


Fig. 5 Improvement of HAZ softening in hardness distribution for high heat input welding by utilization of micro-alloying

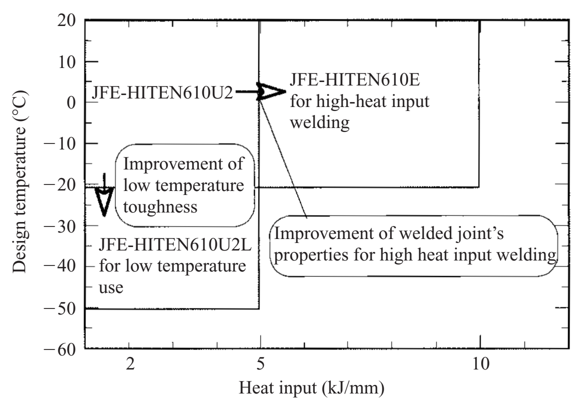


Fig. 6 Applicable design temperature and heat-input limits of the developed steels

The applicable range of the developed steels judged from the viewpoints of the design temperature and heat input limits of welding is shown in **Fig. 6**.

2.2 Properties of High Performance 610 MPa Class HSLA Steel Plate Series

The chemical compositions of the developed steels are shown in **Table 2**. In all the steels, the C content

Table 2 Chemical compositions of the developed steels

(mass%)

Grade	Thickness, t (mm)	C	Si	Mn	P	S	Others	C_{eq}	P_{CM}
JFE-HITEN610U2	38	0.08	0.21	1.34	0.006	0.001	Mo, V, etc.	0.33	0.17
	75	0.08	0.26	1.44	0.005	0.002	Mo, V, etc.	0.39	0.18
JFE-HITEN610U2L	50	0.07	0.20	1.32	0.007	0.001	Cu, Ni, Cr, Mo, V, etc.	0.41	0.19
JFE-HITEN610E	22	0.09	0.20	1.37	0.010	0.002	Mo, V, etc.	0.35	0.18
	45	0.09	0.20	1.37	0.010	0.002	Mo, V, etc.	0.35	0.18
JFE Specification 610U2, U2L, E	6–75	0.09 max.	0.15–0.55	1.00–1.60	0.020 max.	0.010 max.	Cu, Ni, Cr, Mo : 0.30 max., V : 0.06 max., Nb : 0.03 max.	0.44 max.	0.20 max.
JIS G 3115 SPV490	6–75	0.18 max.	0.15–0.75	1.60 max.	0.030 max.	0.030 max.	Alloying elements other than those listed may be added.	0.45* max.	0.28* max.

$C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$

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

*$50 < t \leqq 75$ mm : C_{eq} : 0.47 max., P_{CM} : 0.30 max.

is 0.09 mass% or less, and P_{CM} is controlled below 0.20 mass%.

2.2.1 610 MPa class steel plate with excellent weldability for tanks and penstocks "JFE-HITEN610U2"

The mechanical properties of JFE-HITEN610U2 steel plates are shown in **Table 3**. Tensile strength and Charpy impact properties satisfying the JIS SPV490 specification can be obtained.

As an example of weldability, the results of a maximum hardness test are shown in **Fig. 7**. Under all welding conditions, a low HAZ hardness of no more than 300 points (HV10) is obtained as the Vickers hardness, greatly reducing weld hardening in comparison with the conventional steel. As a result of this hardness reduction, low temperature weld cracking is suppressed, while the sulfide stress corrosion cracking (SSC) sensitivity of welds is reduced, and even better SSC resistance than in the conventional steel is obtained. From the results of a y-groove weld cracking test (SMAW, LB-62UL (4ϕ), 1.7 kJ/mm, 20°C-60%), it can be understood that this steel possesses extremely good low temperature cracking resistance, showing no cracking under a 0°C plate temperature condition in either 38 mm or 75 mm thickness.

Table 4 shows the mechanical properties of welded joint by submerged arc welding (SAW) as a representative example of the welded joint performance of JFE-HITEN610U2. As the welded joint has high strength, satisfying the specification for the base metal, combined with high HAZ toughness, it can be understood that the

Table 3 Mechanical properties of JFE-HITEN610U2

Thickness, t (mm)	Position	Direction	YS (MPa)	TS (MPa)	El (%)	$_VE_{-10°C}$ (J)	$_VE_{-25°C}$ (J)	$_VT_S$ (°C)
			Tensile properties			Charpy impact properties		
38	1/4t	L	541	633	32	332	344	−67
		C	547	637	31	318	326	−63
75	1/4t	L	531	621	33	313	334	−64
		C	531	624	31	267	237	−57

SPV490 Specification : YS ≧ 490, 610 ≦ TS ≦ 740 MPa, $_VE_{-10°C}$ ≧ 47 J (L)

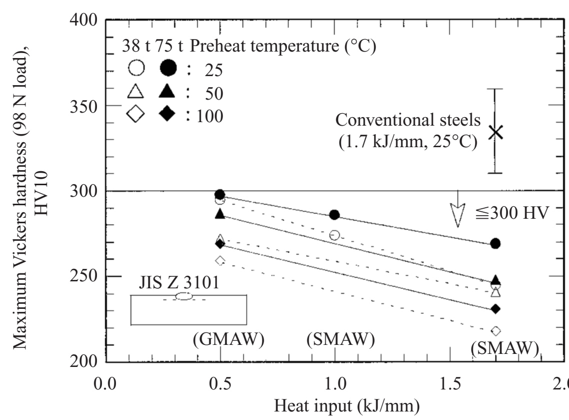
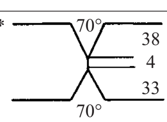


Fig. 7 Maximum hardness of JFE-HITEN610U2

Table 4 Mechanical properties of JFE-HITEN610U2's SAW welded joints

Thickness, t (mm)	Welding condition	TS (MPa)	Fracture position	Position		$_VE_{-15°C}$ (J)	$_VT_S$ (°C)
		Tensile properties		Charpy impact properties			
75	Welding consumabl : US-40 (ϕ4.0)*/MF-38* Preheat : None Inter pass temperature : ≦150°C Heat input : 4.6 kJ/mm PWHT : None 	630	HAZ–BM	$\frac{1}{4}t$	WM	68	−32
					FL	117	−42
					HAZ	225	−59

* Supplied by Kobe Steel, Ltd.

developed steel provides excellent welded joint performance.

2.2.2 610 MPa class steel plate with superior toughness for low temperature tank use "JFE-HITEN610U2L"

The mechanical properties of JFE-HITEN610U2L steel plate, which was developed for use in low temperature applications, and its welded joint produced by shielded metal arc welding (SMAW) are shown in **Tables 5** and **6**, respectively. No reduction in strength by post weld heat treatment (PWHT) was observed, and in all cases, plate and welded joint strength which amply satisfied the JIS SPV490 specification was obtained.

Furthermore, in both the plate and the welded joint, sufficient absorbed energy at −50°C was obtained, indicating that the developed steel has satisfactory performance for use in low temperature tanks.

2.2.3 610 MPa class steel plate for high heat input welding "JFE-HITEN610E"

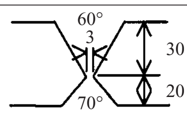
The mechanical properties of JFE-HITEN610E for high heat input welding, and high heat input electro gas arc welding (EGW) welded joints are shown in **Tables 7** and **8**, respectively. Excellent performance of plate and welded joint satisfying the JIS SPV490 specification have been obtained. These EGW welded joint properties were obtained under high heat input welding conditions of 1-pass welding for 22 mm thick plate and 1-pass for both side welding for 45 mm thick plate. In both cases, welded joint strength satisfying the specification of the plate and good Charpy impact properties at −15°C were obtained, showing satisfactory performance for use in the shell plates of large oil storage tanks.

Table 5 Mechanical properties of JFE-HITEN610U2L

Thickness, t (mm)	PWHT	Direction	Tensile properties			Charpy impact properties		
			YS (MPa)	TS (MPa)	El (%)	$_{\mathrm{V}}E_{-50°\mathrm{C}}$ (J)	$_{\mathrm{V}}T_{\mathrm{S}}$ (°C)	$_{\mathrm{V}}T_{\mathrm{E}}$ (°C)
50	–	L	569	659	29	278	−71	−75
		C	567	660	28	238	−67	−72
	580°C 2 h × 2	L	558	652	30	243	−65	−71
		C	569	660	28	198	−55	−68

Position : 1/4t

Table 6 Mechanical properties of JFE-HITEN610U2L's SMAW welded joint

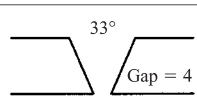
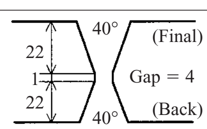
Thickness, t (mm)	Welding condition	Tensile properties		Charpy impact properties			
		TS (MPa)	Fracture position	Position	$_{\mathrm{V}}E_{-50°\mathrm{C}}$ (J)	$_{\mathrm{V}}T_{\mathrm{S}}$ (°C)	$_{\mathrm{V}}T_{\mathrm{E}}$ (°C)
50	LB-62L (ϕ5)* Heat input = 2.3 kJ/mm Preheat : None Inter pass temp : ≦150°C PWHT : 580°C × 2 h × 2 times 	676 681	WM WM	WM	133	−63	−58
				FL	183	−63	−64
				HAZ	208	−62	−74

* Supplied by Kobe Steel, Ltd.

Table 7 Mechanical properties of JFE-HITEN610E

Thickness, t (mm)	Position	Direction	Tensile properties			Charpy impact properties		
			YS (MPa)	TS (MPa)	El (%)	$_{\mathrm{V}}E_{-15°\mathrm{C}}$ (J)	$_{\mathrm{V}}E_{-30°\mathrm{C}}$ (J)	$_{\mathrm{V}}T_{\mathrm{S}}$ (°C)
22	Full thickness	L	605	678	42	–	–	–
		C	605	677	40	358	350	<−48
45	Full thickness	L	539	638	55	–	–	–
		C	538	640	53	–	–	–
	1/4t	L	526	624	30	–	–	–
		C	528	621	30	347	326	−48

Table 8 Mechanical properties of JFE-HITEN610E's EGW welded joints

Thickness, t (mm)	Welding condition	Tensile properties		Charpy impact properties	
		TS (MPa)	Fracture position	Position	$_{\mathrm{V}}E_{-15°\mathrm{C}}$(J)
22	DWS-60G (ϕ1.6)* Heat input = 8.0 kJ/mm Built-up : 1 side 1 pass Preheat : None 	620 623	HAZ HAZ	WM	69
				FL	159
				HAZ	254
45	DWS-60G (ϕ1.6)* Heat input = 9.3, 8.5 kJ/mm Built-up : Both side 1 pass Preheat : None 	639 642	HAZ HAZ	WM	56
				FL	129
				HAZ	248

* Supplied by Kobe Steel, Ltd.

2.3 Practical Application of High Performance 610 MPa Class HSLA Steel Plate Series

These developed steels have received Japan Welding Engineering Society (JWES)'s quality certification under the applicable standards specified in WES 3001-1996, "Weldable High Strength Steel Plates," WES 3009-1998, "Supplementary Requirements for High Strength Steel Plates with Low Susceptibility to Cold Cracking," and WES 3003-1995, "Evaluation Criterion of Rolled Steels for Low Temperature Application." These steels already have a large record of application results in China, which has achieved remarkable economic growth in recent years and is actively constructing large-scale tanks and penstocks, and JFE-HITEN610U2, 610U2L, and 610E have all received general approval in material ratings by the China Standardization Committee on Boilers and Pressure Vessels.

JFE Steel began mass production of high performance 610 MPa class steel plates in 1996, and since that time, has developed a complete series of products by expanding the available plate thickness range and further improving performance, making it possible to meet the requirements of larger-scale tanks and more severe service conditions. This product line is making an important contribution to improved weldability and enhanced reliability in large-scale tanks, penstocks, and other energy infrastructure, and has actual results exceeding a cumulative total of 90 000 t since 2000.

3. Combined Forging and Plate Rolling Process Using Continuous Casting Slabs

3.1 Outline of Combined Forging and Plate Rolling Process

The purpose of this process, in which continuous casting slabs are forged before plate rolling when manufacture heavy section steel plates, is to increase the soundness of internal qualities and improve mechanical properties at the plate center-of-thickness (1/2*t*) position annihilating center porosities. Actual results of use in various applications exceed 85 000 t. This process has been formally approved as special practices mitigating the reduction ratio limitation on the ASTM Standard A 20/A 20M-02 and the ASME Boiler and Pressure Vessel Code 2002 Addenda SA-20/SA-20M (Standard Specification for general requirements for pressure vessel steel plates).

The general outline of the forging reduction work using continuous casting slabs is illustrated in **Photos 2** and **3**. In order to secure large plastic strain in the direction of compression at the slab center position with a small reduction ratio in forging and improve properties

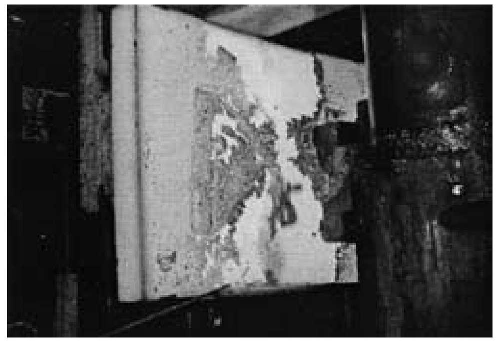


Photo 2 Forging reduction in widthwise of continuous casting slab

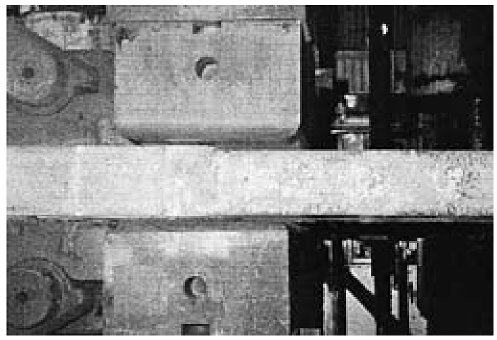


Photo 3 Forging reduction in thicknesswise of continuous casting slab

by annihilating center porosities, JFE Steel have newly developed the bi-directional forging reduction process in which reduction is performed first in the slab width direction, followed by reduction in the slab thickness direction. This forging reduction process has made it possible to manufacture heavy section steel plates with excellent internal qualities with product thicknesses as large as 240 mm using 310 mm thick continuous casting slabs (reduction ratio of thickness from strand cast slab to plate: 1.29).

3.2 Properties of High Strength Heavy Section Steel Plates by Conbined Forging and Plate Rolling Process

With the production of larger-scale boilers and pressure vessels, the thickness required in the steel products for these applications has also increased. Consequently, the soundness of the internal properties of the steel plates now has a large influence on the safety of the plant itself. The following presents examples of application of products produced by this manufacturing process as high strength heavy section plates.

3.2.1 Application to JIS G 3120 SQV2B steel plates

The following presents the properties of JIS G 3120 SQV2B, which has excellent low temperature toughness and is used in nuclear reactors and other

Table 10 Mechanical properties of SQV2B

Thickness, t (mm)	Position (1/4W)		Tensile properties				Charpy impact properties		
			YS (MPa)	TS (MPa)	El (%)	RA (%)	$_{V}E_{-12°C}$ (J)	$_{V}E_{-23°C}$ (J)	$_{V}T_{S}$ (°C)
120	Top	1/4t	533	664	26	80	266	265	−62
		1/2t	519	653	24	79	253	227	−51
	Bottom	1/4t	547	678	27	81	260	237	−67
		1/2t	515	641	25	80	265	262	−60
Specification (1/4t, C)			≧485	620–790	≧16	–	Aiming : $_{V}E_{-12°C}$ ≧ 47		–

Plate size : 120 × 4 160 × 4 570, PWHT : 615°C × 15 h, Direction : C

Table 11 Through-thickness tensile test results of SQV2B

Thickness, t (mm)	Position (1/4W)		Direction	PWHT	Tensile properties			
					YS (MPa)	TS (MPa)	El (%)	RA (%)
120	Bottom	1/4t	Z	615°C × 15 h	520	647	22	69
		1/2t			524	651	22	69

Table 12 Impact and drop weight properties of SQV2B

Pre-strain (Direction)	Aging	Position (1/4W)		Direction	Charpy impact properties			DWT
					$_{V}E_{-12°C}$ (J)	$_{V}E_{-23°C}$ (J)	$_{V}T_{S}$ (°C)	T_{NDT} (°C)
2.5% (L)	250°C × 1 h	Top	1/4t	C	274	277	−64	−38
			1/2t		276	267	−60	−33
2.5% (C)			1/4t		269	259	<−70	−33
			1/2t		255	218	−61	−33

PWHT : 615°C × 15 h

Table 9 Chemical compositions of SQV2B

(mass%)

C	Si	Mn	P	S	Ni	Cr	Mo
0.17	0.25	1.44	0.005	0.001	0.66	0.13	0.55

pressure vessels. The chemical composition of a sample steel plate is shown in **Table 9**. Tensile test and Charpy impact test results are shown in **Table 10**. These results show no large differences in properties at any position in the plate, including the longitudinal direction (top and bottom sides) and plate thickness direction positions, and amply exceed the standard values. **Table 11** shows the results of a through-thickness tensile test. As can be understood from these results, properties which are virtually identical with those at the 1/4t position can be obtained at the 1/2t position, demonstrating that soundness at the plate center position and homogeneity in the thickness direction have been secured.

Table 12 shows the results of Charpy impact test and drop-weight test after pre-strain, aging, and PWHT. The toughness level is sufficiently high, being similar to that when no pre-strain was applied, as shown in Table 10, and the nil-ductility transition temperature (NDT temperature) shows a satisfactory value of −33°C or less.

As evaluations of plant safety from the viewpoint of fracture toughness, a static fracture toughness (K_{IC}) test and crack arrest fracture toughness (K_{Ia}) test were performed. As examples of the results, the relationship T-RT_{NDT} (RT_{NDT}: reference temperature established by drop-weight test and Charpy impact test) is shown for

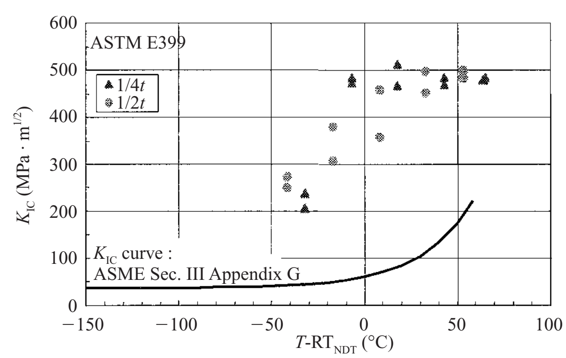


Fig.8 Static fracture toughness properties of SQV2B

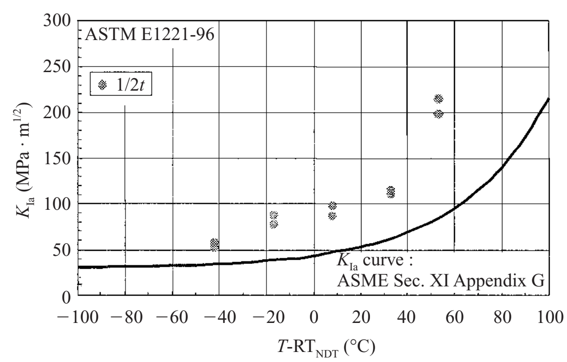


Fig.9 Crack arrest fracture toughness properties of SQV2B

Table 14 Mechanical properties of HT610moderate

Thickness, t (mm)	Position (1/2W)		Direction	Tensile properties				Charpy impact properties	
				YS (MPa)	TS (MPa)	El (%)	RA (%)	$_{V}E_{0°C}$ (J)	$_{V}E_{-20°C}$ (J)
168	Top	1/4t	L	583	687	22	72	145	137
			C	583	689	22	71	167	95
		1/2t	L	572	681	21	71	193	132
			C	577	687	22	67	101	96
208		1/4t	L	566	671	23	72	204	152
			C	564	670	23	70	145	114
		1/2t	L	554	665	20	73	190	142
			C	555	670	20	70	110	98
Aiming				≧530	≧640	≧16	–	≧30	–

PWHT : 560°C × 8 h, G.L. of tensile test specimen : $5.65\sqrt{A}$

Table 13 Chemical composition of HT610modified

(mass%)

C	Si	Mn	P	S	Others
0.14	0.24	1.44	0.009	0.001	Cu, Ni, Cr, Mo, V, Ca

Table 15 Through-thickness tensile test results of HT610modified

Thickness, t (mm)	Position (1/2W)		Direction	PWHT	TS (MPa)	RA (%)
168	Top	1/4t	Z	560°C × 8 h	689	69
		1/2t			675	64
208		1/4t			672	70
		1/2t			672	68

the two tests in **Figs. 8** and **9**, respectively. All of the obtained fracture toughness values exceed the values obtained from the ASME's K_{IC} and K_{Ia} curves.

3.2.2 Application to 200 mm thickness class heavy section steel plates

An example of the manufacturing results of 200 mm thickness class heavy section steel plates is presented in the following. **Table 13** shows the chemical composition of sample plates, and **Table 14** shows tensile test and Charpy impact test results. The results of a through-thickness tensile test are shown in **Table 15**. The plates possess satisfactory properties in terms of soundness at the thickness center position and homogeneity in the thickness direction.

4. Conclusion

JFE Steel has developed a series of high performance 610 MPa class HSLA steel plate as steel products for high reliability pressure vessels and a manufacturing technology for high quality heavy section steel plates, as described in this report. These high performance plates were realized by a fusion of material design technology using microalloying technology and advanced plate manufacturing technologies, including JFE Steel's *Super*-OLAC, advanced on-line accelerated cooling technology and a conbined forging and plate rolling technology for heavy section steel plates. In the future, JFE Steel will continue to respond to diverse needs and hopes that its customers will take advantage of these newly-developed steels.

References

1) Yuga, M.; Hayashi, K.; Takahashi, K.; Suzuki, S.; Maeda, T.; Murakami, Y.; Kojima, T. 610 N/mm^2 class high performance steel plates for pressure vessel. Yousetsu-Kozou Symp. 2002, p. 303.
2) Araki, K.; Kohriyama, T.; Nakamura, M. Development of heavy section steel plates with improved internal properties through forging and plate rolling process using continuous casting slabs. Kawasaki Steel Technical Report. no. 40, 1999, p. 80.
3) Araki, K.; Deshimaru, S.; Kondou, H.; Kohriyama, T. Manufacture of heavy section steel plates with improved internal properties through combined forging and plate rolling process using continuous casting slabs. Atsuryoku-Gijutsu. vol. 41, 2003, p. 20.
4) Omata, K.; Yoshimura, H.; Yamamoto, S. Leading high performance steel plate with advanced manufacturing technologies. NKK Technical Review. no. 88, 2003, p. 73.
5) Kozasu, I. Controlled rolling and controlled cooling (ISIJ). 1997.
6) Maeda, T.; Omori, T. Study on transformation behavior of Nb bearing HSLA steels through DQ process. CAMP-ISIJ. vol. 10, 1997, p. 1378.
7) Murakami, Y.; Takahashi, K.; Kojima, T. Yousetsu-Kozou Symp. 1996, p. 49.