JFE TECHNICAL REPORT
No. 18 (Mar. 2013)

Heat-Treated Steel Plates with Heavy Section and Large Product Weight†

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Abstract:

Recently, the demand for extra heavy plates (i.e., is thicker, wider, and/or longer plates), thinner plates with high tensile strength, and plates with high toughness property in low temperature is increasing to accommodate the trend of larger plant structures, to cut installation cost by reducing weld line and to improve the reliability of the plant itself. JFE Steel has started operating a new production line that consists of a batch-type heat treatment furnace and water dip tank, in which higher temperature heating is available. By taking advantage of these newly constructed facilities, JFE Steel is capable of manufacturing a quenched and tempered heavy section steel plate with improved material properties, which is approximately twice as much weight as former products. By using an ingot casting process in West Japan Works (Kurashiki District) of JFE Steel has capability of manufacturing a large ingot of 120 t and forging press of 6 000 t capacity. JFE Steel manufactures heat-treated steel plates with heavy section and large weight by the optimum combination of these processes with a number of actual plant applications and steadily respond to the demands in the energy field, which would continue to expand.

1. Introduction

In recent years, with rising global energy demand, steel plates with large product weight, which is realized by thicker, wider, and longer plates, have been strongly demanded in plates used in energy-related plants in order to cope with the upscaling of equipment and reduce construction costs and time by reducing welding lines. At the same time, rational design and improved reliability are also needed in plants, with an orientation to use of thinner plates by application of high strength materials and to satisfy low temperature specifications. In particular, large product weight has become important in heat treated steel plates, i.e., quenched and tempered materials, which is superior from the viewpoint of improving the properties of extra heavy section plates.

JFE Steel manufactures high quality, extra heavy steel plates by effectively utilizing the forging process, using large-scale ingots produced from high purity steels refined by the LD furnace-RH vacuum degassing process[1]. On the other hand, from the viewpoints of energy saving and shortening the manufacturing process and delivery time, JFE Steel began manufacturing extra heavy plates through combined forging and plate rolling process[2–5] with the aim to improve center porosities and centerline segregation, using slabs produced by the vertical-bending-type (after solidification) continuous casting machine, which secures excellent material cleanliness properties, and already has a production record of more than 220 000 t. Responding to the demand for plates with larger unit product weight, JFE Steel also started operation of a new line that consists of a batch-type heat treatment furnace enabling high temperature heat treatment, dip-type water quenching pit, etc. with the aims of further increasing product weight and improving plate properties. This new production line was installed at West Japan Works (Kurashiki District), which is equipped with an ingot-making process capable of producing large-scale 120 t ingots and a 6 000 t free forging press, and thereby established an integrated system for the manufacture of extra heavy plates.

† Originally published in *JFE GIHO* No. 29 (Feb. 2012), p. 54–60

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This paper introduces the various properties of extra heavy steel plates manufactured using this new production equipment.

2. Production Equipment

2.1 Specifications of New Production Line

Table 1 shows the specifications of the main equipment enabling production of large product weight heat-treated plates accompanying the trend toward thicker, wider, and heavier plates. The effective height of the batch type heat treatment furnace is 400 mm, and improved temperature uniformity in the furnace and the material being heat-treated in comparison with the conventional heat treatment furnace is achieved by adoption of a high speed gas burner and pulse combustion for the furnace. The main purpose of the automatic surface grinder is to adjust the surface conditions of products. As a feature of this device, the grinder is also equipped with a rough grinding whetstone.

In heat treatment of extra heavy section steel plates, the cooling rate when cooling from the austenite region of plates is extremely slow, and it is also necessary to secure satisfactory strength before post weld heat treatment (PWHT), as strict PWHT conditions are required according to thickness enlarged. Therefore, the quenching pit was designed to secure a fully satisfactory cooling rate over the full length and full width of steel plates by optimizing the pit diameter and the cooling water feed and discharge positions. **Figure 1** shows the average cooling rate from 800°C to 400°C at the 1/2t position for various plate thicknesses. The cooling rate for the 202 mm thickness (carbon steel) is somewhat fast in comparison with other Cr-Mo and Mn-Mo-Ni steels. As the thermal conductivity of the respective chemical composition is the dominant factor for cooling at the 1/2t position in extra heavy section steel plates, this appears to show the effect using actual measurements using carbon steel plates, which have comparatively high thermal conductivity.

Table 1 Capacity of main equipment

Equipment	Capacity
Batch type heat treating furnace	Capacity: 150 t Max. 1 050°C Effective height: 400 mm
Quenching pit	Dipping type
Surface grinder	Max. 450Tmm Rough and fine whetstone
Flame cutter	Max. 400Tmm

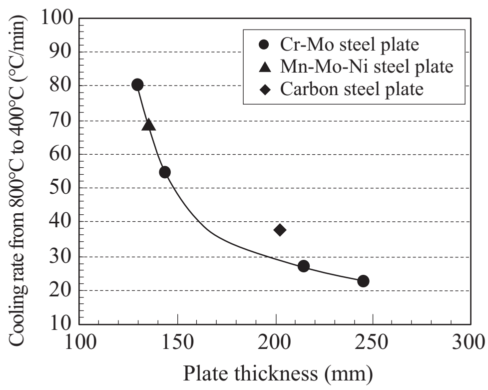


Fig. 1 Relation between cooling rate and plate thickness of 1/2t

3. Results of Application

3.1 Application to Steel Plates for Nuclear Power Plants

The following presents the actual results of application to JIS G 3120 (JIS: Japanese Industrial Standard) SQV2A steel plates, which have low temperature toughness and are used in reactor pressure vessels. A slab was produced by the ingot-making process using a chemical composition design that considered reduction of manganese sulfide by reducing the S content and obtaining a fine grain effect in AlN by nitrogen dissolution into molten steel as measures to improve toughness[6)]. The chemical composition is shown in **Table 2**. Using the forging press, which has superior performance in improving the internal properties of extra heavy steel plates, an ingot

Photo 1 Forged slab using ingot (Removed surface scale)

Table 2 Chemical composition of SQV2A steel plate

(mass%)

C	Si	Mn	P	S	Ni	Mo	Others	Ceq	ΔG
0.18	0.25	1.43	0.003	0.0011	0.66	0.51	Cr, N	0.591	−0.21

Ceq = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14
ΔG = Cr + 3.3Mo + 8.1V −2

Table 3 Mechanical properties of SQV2A steel plate

Forged slab dimension (mm)	Product dimension (mm)	PWHT	Direction	Position		Tensile test YS (MPa)	Tensile test TS (MPa)	Tensile test El (%)	Tensile test RA (%)	Tensile test RA_Z (%)	Charpy impact test $_vE_{-23}$ (J)	Charpy impact test $_vE_{-40}$ (J)	Charpy impact test $_vT_{rs}$ (°C)	Fracture toughness test T_{NDT} (°C)	Fracture toughness test Pre-Strain (5.1%) Ageing T_{NDT} (°C)
320× 3 600× 4 250	130× 4 650× 6 500	—	C	Top	1/4*t*	479	618	27	73	55	—	—	—	—	—
					1/2*t*	494	637	25	72	62	—	—	—	—	—
				Bottom	1/4*t*	491	628	28	75	—	—	—	—	—	—
					1/2*t*	485	623	28	73	—	—	—	—	—	—
		625°C ×30 h		Top	1/4*t*	466	605	27	73	64	148	113	−31	−33	−33
					1/2*t*	471	619	28	72	61	139	82	−26	−33	−28
				Bottom	1/4*t*	466	607	28	74	—	—	—	—	—	—
					1/2*t*	466	608	29	74	—	—	—	—	—	—
Specification (1/4*t*, C)						≥345	550–690	≥18	—	—	≥40	—	—	≤−12	

PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation RA: Reduction of area
RA_Z: Reduction of area in through thickness tensile test (*Z* direction) $_vE_{-23}$: Absorbed energy at −23°C
$_vE_{-40}$: Absorbed energy at −40°C $_vT_{rs}$: Charpy fracture appearance transition temperature T_{NDT}: Nil-ductility transition temperature

Table 4 Elevated temperature tensile property of SQV2A steel plate

Test temperature (°C)	PWHT	Direction	Position	Elevated temperature tension test YS (MPa)	TS (MPa)	El (%)	RA (%)
100	625°C ×30 h	C	1/4*t*	443	573	22	73
			1/2*t*	437	565	21	73
200			1/4*t*	410	553	22	74
			1/2*t*	410	554	21	72
291			1/4*t*	417	572	22	73
			1/2*t*	418	573	21	72
360			1/4*t*	403	557	24	79
			1/2*t*	399	550	25	77
425			1/4*t*	381	497	25	82
			1/2*t*	379	490	24	80
Specification (360°C, 1/4*t*, C)				≥298	≥485	—	—

PWHT: Post weld heat treatment YS: Yield strength
TS: Tensile strength El: Elongation RA: Reduction area

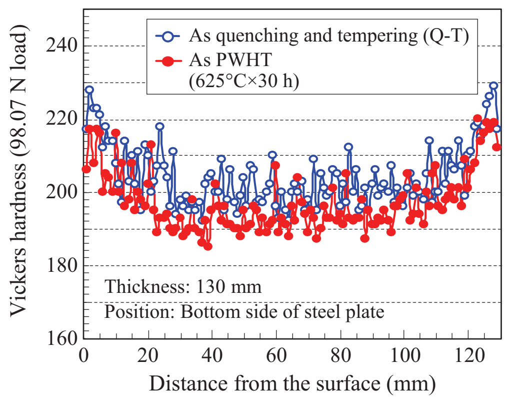


Fig. 2 Section hardness distribution before and after post weld heat treatment (PWHT)

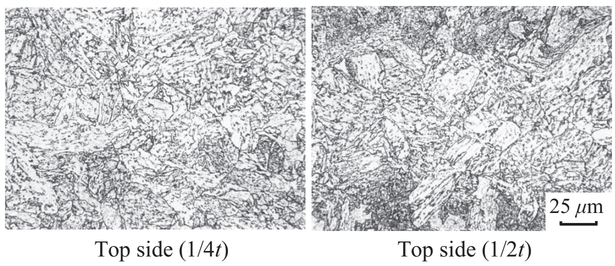


Photo 2 Microstructure of SQV2A steel plate

with an average thickness of 1 228 mm was reduced to a thickness of 320 mm. The unsteady both ends of the ingot were then properly cut off and discarded, producing the forged slab shown in **Photo 1** before plate rolling. This slab was rolled to a thickness of 130 mm and width of 4 650 mm by plate rolling, followed by quenching at 885°C and tempering at 660°C using the newly-constructed batch type heat treating furnace and water quenching pit.

The mechanical properties of the steel plate are shown in **Tables 3** and **4**. Property deviations are small at the top and bottom sides of the plate and also at the 1/4*t* and 1/2*t* thickness positions, and the steel plate has homogeneous properties fully satisfying the standard values. **Figure 2** shows the all section hardness distribution before and after PWHT. Hardness deviations before and after PWHT were also minimized by setting the tempering temperature 35°C higher than the PWHT temperature. **Photo 2** shows the microstructure of the top side of the steel plate. At the 1/4*t* position, the microstructure consists of tempered bainite. Although a tempered martensite microstructure, which is caused by segregation of the components, can be observed partially at the 1/2*t* position, low temperature toughness and drop weight properties are fully satisfied, as shown in Table 3, and it can be said that the amount of discard from the top end of the ingot was appropriate. **Photo 3** shows the results of a bend test of the surface layer under conditions of bending angle: 180° and bending inner diameter

Bend test (Surface) Side bend test (All thickness)

Photo 3 Results of bend test and side bend test

radius: 20 mm, and the results of an all-thickness side bend test. In both cases, no crack can be observed on the outside of the curved portion, demonstrating satisfied formability.

3.2 Application to Steel Plates for Process Equipment

3.2.1 2.25Cr-1Mo-V Steel plates

In the field of desulfurization reactor devices used in petroleum refining plants, there is an orientation toward higher efficiency by adopting high temperature-high pressure operating conditions and upscaling the equipment. To meet this need, 2.25Cr-1Mo-V steel plates with high elevated temperature strength and excellent resistance to hydrogen attack[7)] in comparison with the conventional 2.25Cr-1Mo steel plates has been applied in commercial plants. These properties are secured by compound addition of V, Nb, and other alloying elements. Moreover, allowable stress was greatly increased under the revision of the code in ASME Sec. VIII, Div. 2, 2007 (ASME: The American Society of Mechanical Engineers), and a further expansion of demand is expected, as users can now enjoy the design advantage of weight reduction accompanying a remarkable reduction in plate thickness[8)].

A forged slab with a thickness of 385 mm and weight of 32.9 t was produced using the forging press from an ingot with an average thickness of 1 053 mm produced by the ingot-casting process. The chemical composition is shown in **Table 5**. In order to prevent temper embrittlement, a composition design was adopted in which the Si content was reduced and impurity elements such as P, Sb, As, Sn, etc. were decreased as much as possible. As a result, the temper embrittlement sensitivity, index *J*-factor and *x*-bar are on sufficiently low, satisfactory levels. When necessary, Ca is added from the viewpoint

Table 5 Chemical composition of SA-542 Type D-4a steel plate

(mass%)

C	Si	Mn	P	S	Cr	Mo	V	Nb	Others	*J*-factor (%)	*x*-bar (ppm)
0.14	0.04	0.55	0.009	0.0010	2.41	1.07	0.322	0.031	Cu, Ni, Ti, B	56.7	9.8

J-factor = (Si + Mn) (P + Sn) $\times 10^4$
x-bar = (10P + 5Sb + 4Sn + As) $\times 10^{-2}$

Table 6 Mechanical properties of SA-542 Type D-4a steel plate

Forged slab dimension (mm)	Product dimension (mm)	PWHT	Direction	Position		Tensile test					Charpy impact test	
						YS (MPa)	TS (MPa)	El (%)	RA (%)	RA_Z (%)	$_vE_{-29}$ (J)	$_vE_{-50}$ (J)
385× 2 145× 5 070	210× 3 200× 5 100	—	C	Top	1/4*t*	597	710	26	77	68	—	—
					1/2*t*	608	721	25	75	68	—	—
				Bottom	1/4*t*	585	699	25	77	—	—	—
					1/2*t*	597	710	25	76	—	—	—
		698°C ×7 h		Top	1/4*t*	570	688	25	78	70	192	121
					1/2*t*	581	702	24	76	69	87	51
				Bottom	1/4*t*	565	683	25	78	—	—	—
					1/2*t*	568	692	25	76	—	—	—
		712°C ×34 h		Top	1/4*t*	503	633	27	76	69	213	73
					1/2*t*	516	644	26	75	66	153	96
				Bottom	1/4*t*	502	633	26	78	—	—	—
					1/2*t*	512	645	25	77	—	—	—
Specification (1/4*t* and 1/2*t*, C)						≥415	585–760	≥18	—	—	≥55	—

PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation RA: Reduction of area
RA_Z: Reduction of area in through thickness tensile test (*Z* direction)
$_vE_{-29}$: Absorbed energy at −29°C $_vE_{-50}$: Absorbed energy at −50°C

Table 7 Elevated temperature tensile property of SA-542 Type D-4a steel plate

Test temperature (°C)	PWHT	Direction	Position	Elevated temp.tension test			
				YS (MPa)	TS (MPa)	El (%)	RA (%)
370	712°C×34 h	C	1/2*t*	435	529	20	72
435				424	506	21	75
454				421	497	21	76
482				411	479	22	76
Specification (454°C, 1/2*t*, C)				≥338	≥453	—	—

PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation RA: Reduction of area

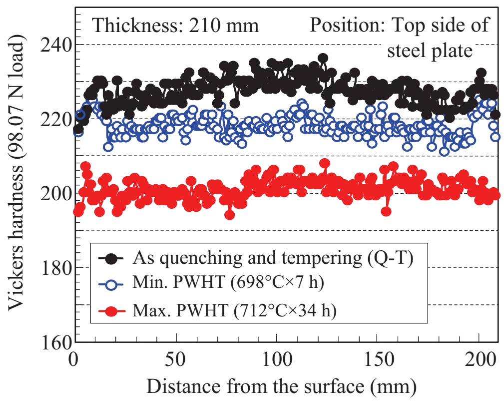


Fig. 3 Section hardness distribution before and after post weld heat treatment (PWHT)

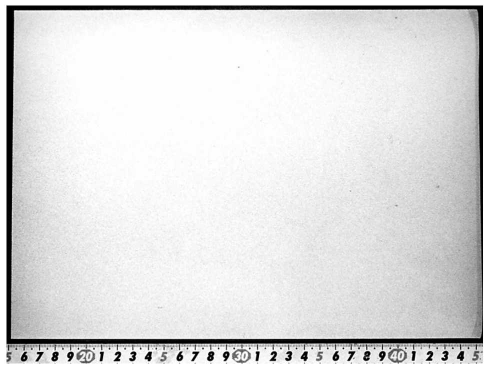
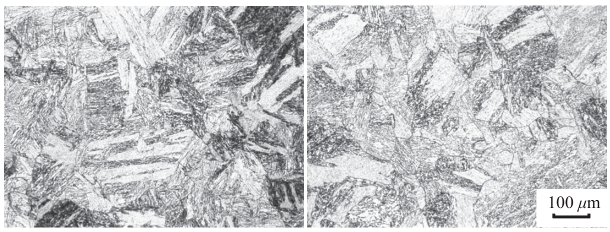


Photo 4 Macrostructure of SA-542 Type D-4a steel plate



Top side (1/4*t*) Top side (1/2*t*)

Photo 5 Microstructure of SA-542 Type D-4a steel plate

of preventing reheat crack.

A steel plate with a thickness of 210 mm, width of 3 200 mm, and weight of 26.9 t was produced from this slab by plate rolling. This was followed by preheating treatment at 1 000°C and quenching at 1 050°C and tempering at 725°C. The mechanical properties of the plate are shown in **Tables 6** and **7**. To obtain the standard values of room temperature strength and high elevated temperature strength in extra heavy section steel plates with thicknesses exceeding 200 mm at the 1/2*t* position under severe PWHT conditions (e.g., 712°C×34 h) as required in 2.25Cr-1Mo-V steel plates, high temperature heat treatment at 1 000–1 050°C was adopted, and satisfied strength properties were confirmed. Heat treatment in this temperature range had been impossible with the conventional heat treatment equipment. Accordingly, it is possible to manufacture plates with the required heavy section and large product weight by setting the proper preheating temperature and quenching temperatures considering the balance of strength and toughness, corresponding to the plate thickness, PWHT conditions, elevated temperature strength, etc. **Figure 3** shows the all section hardness distribution in the as-delivered condition (as-quenched and tempered), and after the minimum and maximum PWHT conditions. There are also cases in which tempering is performed under high temperature (725°C) and sufficient holding time (0.5 h or more per inch (25.4 mm) at the 1/2*t* position), and internal hardness deviations are slight. The Brinell hardness obtained as the average of 3 points at positions 1.6 mm under the surface was 212 points in the as-quenched and tempered condition and 203 and 192 points after the same minimum and maximum PWHT conditions as in Fig. 3, respectively.

Photo 4 shows the macrostructure of the steel plate across the all thickness. No clear centerline segregation can be observed. **Photo 5** shows the microstructure, which is a homogeneous bainite microstructure.

3.2.2 1.25Cr-0.5Mo Steel

1.25Cr-0.5Mo Steel plates is used in high temperature pressure vessels. The strength of this material is greatly influence of cooling rate at the quenching, and the critical cooling rate at which ferrite, which is a soft phase, begins to form is high in comparison with other Cr-Mo steels[9]. Accordingly, in the manufacture of extra heavy section steel plates, quenching (normalizing + accelerated cooling) and tempering are frequently essen-

Table 8 Chemical composition of SA-387 GR. 11–2 steel plate

(mass%)

C	Si	Mn	P	S	Cr	Mo	Other	J-factor (%)	x-bar (ppm)
0.15	0.58	0.60	0.006	0.0007	1.42	0.61	Ni	75.5	6.7

J-factor = (Si + Mn) (P + Sn) $\times 10^4$
x-bar = (10P + 5Sb + 4Sn + As) $\times 10^{-2}$

Table 9 Mechanical properties of SA-387 GR. 11–2 steel plate

Rolled slab dimension (mm)	Product dimension (mm)	PWHT	Direction	Position		Tensile test					Charpy impact test	
						YS (MPa)	TS (MPa)	El (%)	RA (%)	RA_Z (%)	$_vE_0$ (J)	$_vE_{-10}$ (J)
420× 1 925× 4 775	243× 1 825× 7 100	—	C	Top	1/4t	435	601	30	75	74	—	—
					1/2t	393	569	29	72	65	—	—
		691°C ×4 h			1/4t	415	585	29	75	74	163	186
					1/2t	383	569	30	73	73	208	120
		691°C ×20 h			1/4t	390	559	30	75	74	136	76
					1/2t	364	549	30	76	70	89	51
Specification (1/4t and 1/2t, C)						≥310	515–690	≥22	—	—	≥33	—

PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation RA: Reduction of area
RA_Z: Reduction of area in through thickness tensile test (Z direction) $_vE_0$: Absorbed energy at 0°C $_vE_{-10}$: Absorbed energy at −10°C

tial as plate heat treatment in order to improve both tensile strength and toughness.

A steel plate with a thickness of 243 mm was manufactured by plate rolling using a slab 385 mm in thickness that was produced by slabbing mill from the ingot-casting process. The chemical composition of the ladle is shown in **Table 8**. For quenching treatment of this plate thickness, which had not been possible with the conventional heat treatment equipment, quenching at 940°C and tempering at 715°C were performed using the heat treatment equipment which was put into operation recently. The mechanical properties of the steel plate are shown in **Table 9**. After the assumed maximum PWHT conditions of 691°C×20 h, tensile strength at the 1/2t position amply satisfied the standard value, showing that it is possible to manufacture steel plates with Charpy impact properties to meet 0°C level customer requirements with no problems.

3.2.3 Carbon steel plate for pressure vessels

In the manufacture of carbon steel plates for pressure vessels for moderate and lower temperature services (ASME standard: SA-516), which have comparatively high Charpy impact properties, the upper limit of the carbon equivalent is specified. When low temperature toughness is required in extra heavy section steel plates, such as those with thicknesses exceeding 100 mm, it is necessary to perform quenching (normalizing + accelerated cooling) and tempering as plate heat treatment.

Table 10 shows the chemical composition of the ladle in the ingot-casting process. A slab with a thickness of 420 mm was produced from an ingot by slabbing

Table 10 Chemical composition of SA-516 GR. 70 steel plate

(mass%)

C	Si	Mn	P	S	Others	Ceq (%)
0.20	0.29	1.15	0.012	0.0028	Cu, Ni, Mo, V, Nb	0.454

Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15

Table 11 Results of microscopic test for non-metallic inclusions in steel

Method: JIS G 0555, d_{60}×400 (%)							
Position		Type inclusion					
		A_1	A_2	B	C_1	C_2	Total
Top	1/4t	0.01	0	0	0	0	0.01
	1/2t	0.02	0	0	0	0	0.02

A_1: Viscous deformation (Sulphides) A_2: Viscous deformation (Silicates)
B : Granular inclusions discontinuously (Alumina, etc.)
C_1: Irregular dispersion without viscous deformation (Oxide) C_2: Irregular dispersion without viscous deformation (Carbo-nitride)

Table 12 Mechanical properties of SA-516 GR. 70 steel plate

Rolled slab dimension (mm)	Product dimension (mm)	PWHT	Direction	Position		Tensile test					Charpy impact test		
						YS (MPa)	TS (MPa)	El (%)	RA (%)	RA_Z (%)	$_vE_0$ (J)	$_vE_{-20}$ (J)	$_vE_{-40}$ (J)
400× 2 150× 4 500	202× 2 300× 6 500	—	C	Top	1/4t	373	530	33	68	63	215	139	59
					1/2t	352	513	33	70	66	149	113	37
		625°C ×10 h			1/4t	361	520	34	71	68	180	136	77
					1/2t	340	503	33	71	64	166	99	40
Specification (1/4t, C)						≥260	485–620	≥21	—	—	≥28	—	—

PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation RA: Reduction of area
RA_Z: Reduction of area in through thickness tensile test (Z direction)
$_vE_0$: Absorbed energy at 0°C $_vE_{-20}$: Absorbed energy at −20°C $_vE_{-40}$: Absorbed energy at −40°C

Table 13 Elevated temperature tensile property of SA-516GR.70 steel plate

Test temperature (°C)	PWHT	Direction	Position	Elevated temp.tension test			
				YS (MPa)	TS (MPa)	El (%)	RA (%)
225	625°C ×10 h	C	1/4t	284	473	28	70
			1/2t	324	518	27	58
300			1/4t	283	499	27	65
			1/2t	329	546	23	50
350			1/4t	270	491	33	72
			1/2t	318	527	27	64
Specification (300°C, 1/4t, C)				≥175	—	—	—

PWHT: Post weld heat treatment YS: Yield Strength TS: Tensile Strength El: Elongation RA: Reduction of area

mill, and a plate 202 mm in thickness and 2 300 mm in width was produced from this slab by plate rolling. This was followed by quenching at 910°C and tempering at 660°C.

Table 11 shows the results of a microscopic test for non-metallic inclusions, which was performed in accordance with JIS G 0555. The steel plate showed satisfied cleanliness at both 1/4t and 1/2t positions. **Table 12** shows the mechanical properties of the steel plate before and after PWHT under conditions of 625°C×10 h. Satisfied results were obtained, that the standard values for tensile strength and toughness not only at the 1/4t position, but also at the 1/2t position.

The results of tests of elevated temperature strength properties, which were performed using samples taken from the bottom end of the steel plate, are shown in **Table 13**. It can be understood that the steel plate possesses excellent properties.

4. Conclusion

The current state of production of heat-treated steel plates with heavy sections and large product weights at JFE Steel was introduced. In all cases, it is possible to manufacture steel plates with excellent internal quality and stable mechanical properties using a combination of equipment that includes an ingot-casting process for large-scale steel ingots and a free forging press, together with a newly-installed batch type heat treating furnace with high temperature specification and quenching pit. It is also possible to satisfy standards for steel forgings products, preconditioned on production of rectangle size with a forging process. Active use in expanding the applications of large product weight heat-treated steel plates is expected in the future.

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