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550 and 610 MPa Class High-strength Steel Plates with Excellent Toughness for Tanks and Penstocks Produced Using Carbide Morphology Controlling Technology†

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Abstract:

JFE Steel has developed 550 and 610 MPa class high strength steel plates with superior toughness and excellent weldability produced by JFE Steel's latest on-line heat-treatment technology. Excellent properties of the plates and their weldments are obtained by micro-alloying technology, and direct-quenching and on-line tempering process using Super-OLAC® (On-Line Accelerated Cooling) and HOP® (Heat-treatment On-line Process), while including low C, low weld cracking parameter (P_{CM}) value and free of B additive. Especially, rapid heating and tempering using on-line HOP temper process achieved both improvement of toughness and the extension of heat treated high-performance steel plates' production capacity. They have actual application results to many plants.

1. Introduction

Various types of steel plates are used for the construction of energy plant components such as energy storage equipment, chemical plants, and power-generation equipment. With the recent expansions in the scale of these plants, the tightening severity of operating and service conditions, and the growing demand for more efficient and economical construction methods, the materials used in these plants must be stronger, tougher, and easier to weld. And with the strong energy consumption and active energy plant construction worldwide in recent years, the demand for reliable supplies of high-performance steels and shortened construction periods has been rising.

To meet these requirements, JFE Steel has developed a series of high-performance 550 MPa class and 610 MPa class high-strength steel plates (JFE-HITEN 610U2, 610E, ASTM A841 Gr.B C1.2, and the like) with excellent weldability, for the construction of various types of tanks and penstocks in hydraulic power generation plants. These steels have been developed by taking advantage of JFE Steel's latest plate-manufacturing technologies, including an accelerated cooling device with a high cooling rate and uniform cooling capabilities, JFE Steel's *Super*-OLAC® (On-Line Accelerated Cooling), and HOP® (Heat-treatment On-line Process), an induction heating type on-line heat-treatment process performed after accelerated cooling[1–5]. The core steelmaking technologies for these steels combine a microalloying technology with JFE Steel's latest techniques for plate manufacture. These technologies have made it possible to quenching and tempering on a rolling line with improved productivity, and to upgrade performance by microstructure control and the refinement and dispersion control of carbides by rapid heating and tempering with

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HOP.

This paper describes the features and properties of the 550 MPa class and 610 MPa class high-strength steel plates developed through the application of carbide refinement and dispersion technology by the plate on-line heat treatment process.

2. JFE Steel's On-Line Heat Treatment Technology

The quenching and tempering heat treatment of plates has hitherto been performed in an off-line atmospheric furnace. Steelmakers have hoped to develop an on-line heat treatment for plates as an alternative. Thanks to the development of the thermo-mechanical controlled process (TMCP) technology, research and development of controlled rolling and controlled cooling has advanced. A method of direct quenching (DQ) after rolling has developed, and a direct quenching and tempering (DQ-T) process is widely used in the manufacture of high-strength steel plates[6]. The 550 MPa class, 610 MPa class, and higher-class high-strength steels are strengthened by improving hardenability via the application of DQ. This makes it possible to reduce the C content and P_{CM} value and improve the weldability and welded joint performance.

Direct quenching is performed by an accelerated cooling device on a rolling line. In 1980, JFE Steel became the world's first steel producer to develop and practically apply equipment for on-line accelerated cooling (OLAC). More than a decade later, the company developed an on-line accelerated cooling device, *Super*-OLAC, with a high cooling capacity approaching the theoretical limit, and a uniform cooling capability. JFE Steel introduced *Super*-OLAC in its plate mill in 1998[7,8].

For tempering, JFE Steel developed a HOP (Heat-treatment On-line Process) using an induction heating system that permits on-line tempering. This process has

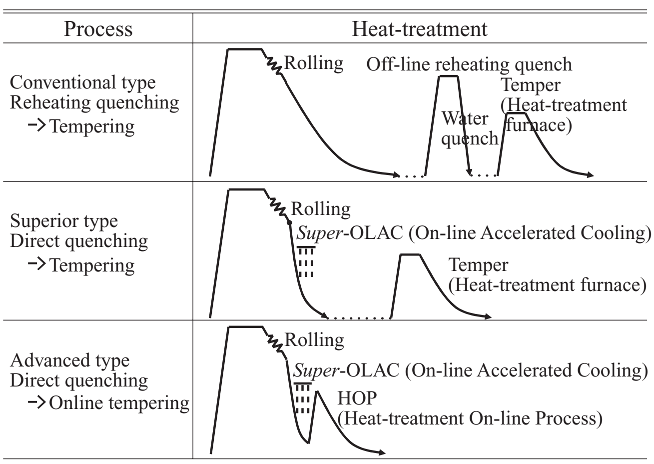


Fig.1 Development of heat treatment process

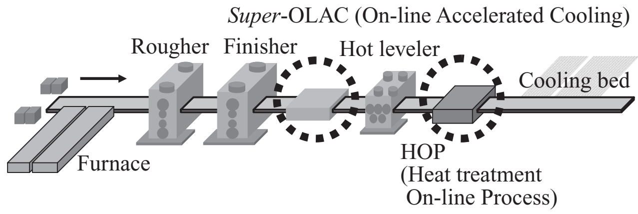


Fig.2 Layout of online heat-treatment facilities of West Japan Works (Fukuyama)

been operating on a full scale since 2004. A combination of *Super*-OLAC and HOP has permitted full on-line quenching and tempering treatment of steel plates with both improved productivity and performance[8,9]. This is a feat of steelmaking never before achieved. **Figure 1** shows a development of the quenching and tempering process. **Figure 2** shows the layout of the Fukuyama Plate Mill of West Japan Works, JFE Steel where *Super*-OLAC and HOP are in service.

3. Technology for Carbide Refinement and Dispersion by Rapid Heating and Tempering

3.1 Technology for Cementite Refinement and Dispersion in Tempering

In medium- and high-carbon steels with microstructures consisting mainly of martensite, such as those for machine structural use, an increase in the heating rate during tempering uniformly refines the dispersion of cementite[10,16]. In low-carbon steels with microstructures consisting mainly of bainite or mixed microstructures of martensite and bainite, on the other hand, the mechanism by which cementite is refined and dispersed through rapid heating has yet to be clarified[11].

This study was conducted to closely investigate how the heating rate and heating process affect the cementite precipitation behavior. The experiments were performed with 780 MPa class low-carbon steels with a mixed microstructure of martensite and bainite[4,5,12]. The results are shown in **Figs. 3** and **4**, respectively.

When the heating rate is increased from 0.3°C/s at a rate equivalent to that of furnace tempering to 3°C/s and above, cementite tends to be refined and dispersed. In steels tempered in an atmospheric furnace, relatively coarse cementite precipitates at the lath boundaries. In steels rapidly heated and tempered, on the other hand, large amounts of cementite are formed within the laths and the cementite formed is uniformly refined and dispersed.

During the heating of steel tempered in an atmospheric furnace, the cementite precipitates and grows mainly at the lath boundaries. During rapid tempering,

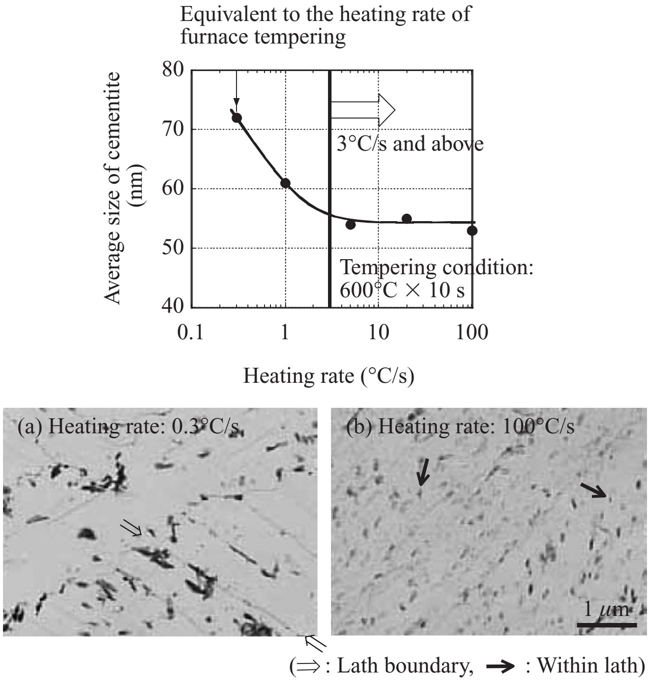


Fig. 3 Uniform dispersion of fine cementite by rapid heating and tempering

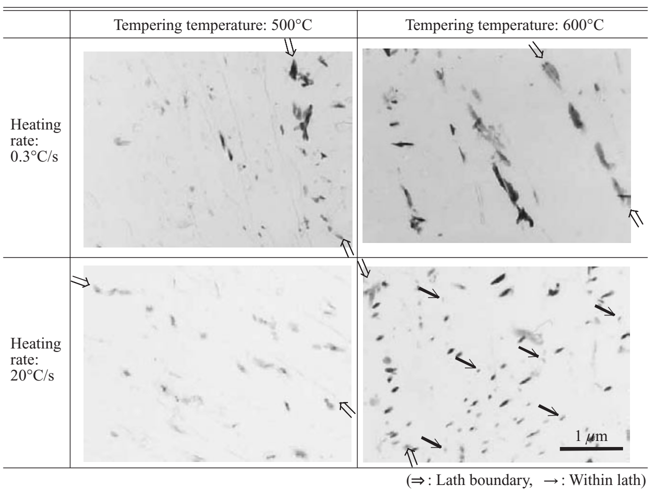


Fig. 4 Precipitation behavior of cementite during heating process

a cementite precipitates mainly at the lath boundaries in the low-temperature region, then a finer cementite precipitates from within the laths as the heating temperature climbs, bringing about uniform refinement and dispersion.

Figure 5 schematically shows the effect of the heating rate on the precipitation behavior of cementite. On the low-temperature side of the heating process, cementite begins to preferentially precipitate mainly at the lath boundaries. At a low heating rate the cementite at the lath boundaries grows as it is, assuming a coarse morphology along the lath boundaries. At a high heating rate the temperature climbs to high levels so quickly, there is no time for cementite precipitates to grow along the lath boundaries. The recovery of dislocations thus fails to

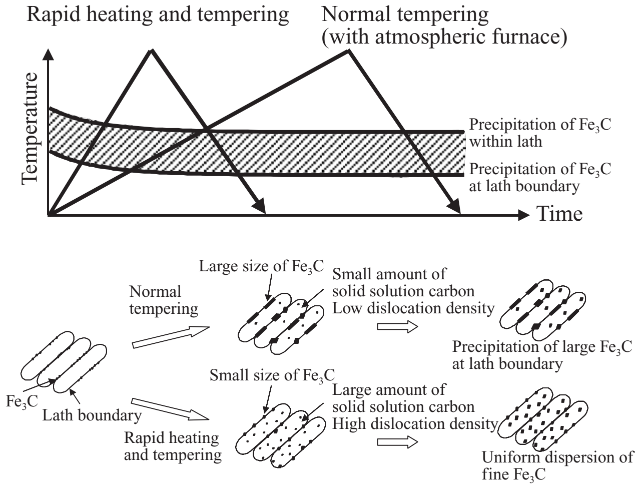


Fig. 5 Mechanism of uniform dispersion of fine cementite by rapid heating and tempering

proceed, and uniform fine cementite is obtained by the precipitation of cementite using the dislocations within the laths as nucleation sites.

Thus, the authors can identify three key factors in the refinement and dispersion of cementite: the mechanism that preserves the large number of dislocations that become precipitation sites, the mechanism by which the temperature that permits the dispersion of carbon atoms within the laths is reached, and the mechanism by which the suppression of cementite growth at the lath boundaries ensures the maximum possible amount of solid solution carbon within the laths. It is particularly important to rapidly raise both the temperature at which cementite begins to precipitate from the lath boundaries and the temperature at which cementite begins to precipitate from within the laths. The effect of alloying elements on the precipitation and growth process of cementite has been investigated[5,13], and an optimum tempering process with control of the heating rate, alloy designs, and heating process has been realized by HOP. Thus, it is now possible to manufacture high-strength steel plates with uniformly refined and dispersed cementite.

3.2 Effect of Rapid Heating and Tempering on the Strength and Toughness of High-strength Steel Plates

The strength and toughness of a 780 MPa class steel plate tempered in an atmospheric furnace and a rapidly heated and tempered 780 MPa class steel plate were rearranged using a temper parameter (T.P.) determined through considerations of the heating process and cooling process during tempering. The results are shown in **Fig 6**.

$$\text{T.P.} = T \times (\log t + C) \qquad (1)$$

where T: temperature (K), t: time (h), C: constant

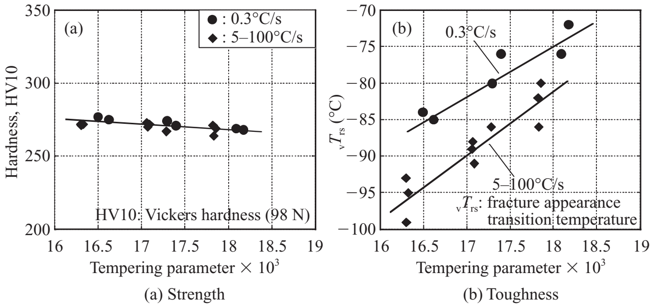


Fig. 6 Relationship between tempering parameter and mechanical properties of 780 MPa class steel

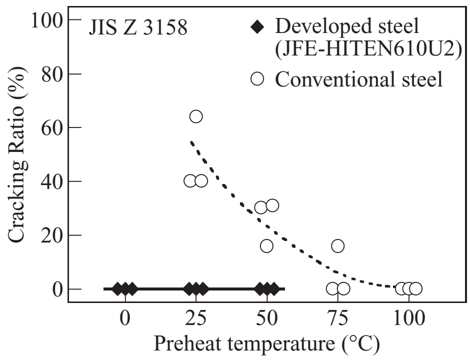


Fig. 7 Decrease of preheat temperature to avoid weld cracking of the developed steel by suppression of C and P_{CM}

Strength can be unequivocally rearranged by T.P. irrespectively of the heating rate. Toughness, on the other hand, cannot be rearranged solely by T.P. and heating rate dependence is observed. Due to rapid heating and tempering, high toughness is achieved through the uniform refinement and dispersion of cementite.

4. Development Concept for 550 and 610 MPa Class High-strength Steel Plates for Tanks and Penstocks

4.1 Applied Specifications and Heat Treatment Process

When applied for tanks and penstocks, the newly developed steel plates correspond to 610 MPa class steel plate specified as SPV490 in JIS G 3115 Steel Plates for Pressure Vessels or 550 MPa class steel plates specified as A841 Gr. B Cl. 2 in ASTM standard. For the heat treatment, direct quenching (DQ) by *Super*-OLAC and on-line rapid tempering by HOP are adopted in both steels.

4.2 Concept of Alloy Design and Microstructure Control by On-Line Heat Treatment

The 550 MPa and 610 MPa class high-strength steel plates with superior toughness have the following features, based on a heat-treatment on-line process as a precondition:

(1) Reduced C Content, Reduced Weld Cracking Parameter (P_{CM}), and No Added B

From the viewpoint of weldability, the chemical compositions of these steels are characterized by a C content of not more than 0.09 mass%, a low P_{CM} of not more than 0.20 mass%, and no added B. These conditions were made possible by applying the accelerated cooling *Super*-OLAC. Compared to conventional steels (the RQ-T type JIS SPV490 steel and ASTM A537-2 steel), the developed steel was produced at a lower preheat temperature (**Fig. 7**) and a decreased hardness of weldment (**Fig. 8**), and exhibited excellent welded joint performance.

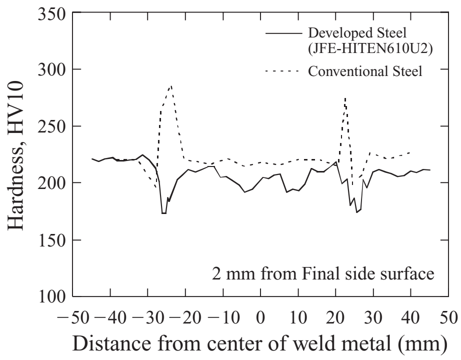


Fig. 8 Improvement of HAZ hardness distribution of the developed steel by suppression of C content and P_{CM}

(2) Optimum Use of Microalloying Elements

In the direct quenching and on-line rapid heating and tempering (DQ-HOP) process using *Super*-OLAC and HOP, the microstructure and precipitation of carbonitrides are controlled through transformation strengthening and fine-precipitation strengthening during tempering and the like[6,14] using microalloying elements. An excellent strength-toughness balance is realized as a result.

(3) Refinement and Dispersion of Carbides by HOP Rapid Heating

With the application of rapid heating and tempering using HOP, the refinement and dispersion of cementite realizes high toughness (**Fig. 9**) and the complete on-line heat treatment improves productivity.

(4) Microstructure Control of the Heat-affected Zone(HAZ)

The alloy design to ensure weldment toughness relies on the optimum use of microalloying elements, as well as the reduction of the C content, the limited P_{CM}, and the elimination of added B to reduce hardness. For JFE-HITEN610E, a steel plate for large oil storage tanks processed by high-efficiency, large-

Table 1 Chemical compositions of the developed steels

(mass%)

Grade	Thickness (mm)	C	Si	Mn	P	S	Others	C_{eq}	P_{CM}
A841B2	16, 38	0.08	0.19	1.34	0.014	0.002	Mo, V, etc.	0.33	0.16
JFE-HITEN 610U2	25	0.08	0.20	1.35	0.014	0.002	Mo, V, etc.	0.33	0.16
	40	0.09	0.25	1.46	0.008	0.001	Mo, V, etc.	0.39	0.19
JFE-HITEN 610E	12, 22	0.09	0.20	1.36	0.015	0.002	Mo, V, etc.	0.36	0.18
	32	0.09	0.20	1.22	0.008	0.002	Mo, V, etc.	0.33	0.17

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

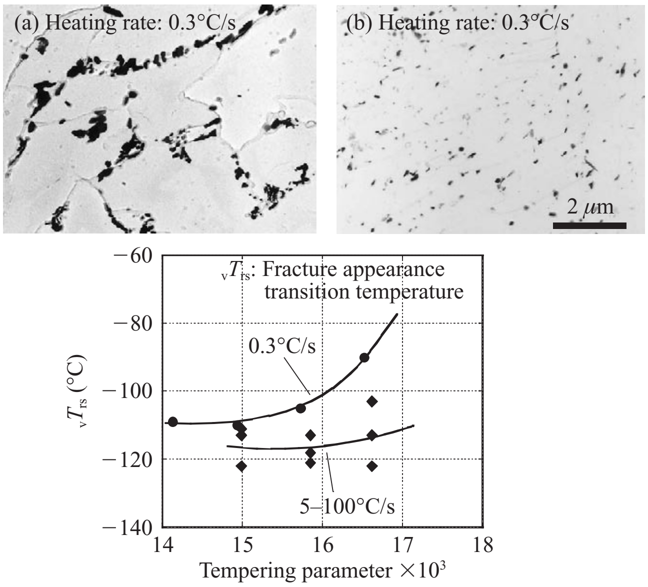


Fig.9 Cementite refinement and toughness improvement by rapid heating and tempering of JFE-HITEN610U2

heat-input electrogas arc welding (EGW), the alloy design meets the requirements for both welded joint strength and HAZ toughness during large-heat-input welding. For HAZ toughness, the alloy design avoids an upper bainite microstructure and obtains high toughness by suppressing the formation of the martensite-austenite (M-A) constituent[1,2, 15].

5. Properties of Developed Steels

5.1 Base Metal Performance of Developed Steels

The chemical compositions of the developed steels are shown in **Table 1**. In all of the steels, the C content is controlled to a low value of not more than 0.09 mass% and P_{CM} is controlled to a low value of not more than 0.20 mass%.

Tables 2 to **4** show the base metal performance of the A841 Gr.B Cl.2 steel plate, and that of the JFE-HITEN610U2 and 610E steel plates processed by

Table 2 Mechanical properties of ASTM A841 Gr.B Cl.2

Thickness (mm)	Tensile properties				Charpy impact properties		
	Position, Direction	YS (MPa)	TS (MPa)	El (%)	Position, Direction	$_vE_{-25°C}$ (J)	$_vE_{-45°C}$ (J)
16	Full-thick., C	583	669	36	1/4*t*, L 1/4*t*, C	296 236	278 140
38	Full-thick., C	522	617	50	1/4*t*, L 1/4*t*, C	320 298	263 284

A841Gr.B Cl.2 Specification: YS≧415, 550≦TS≦690MPa
$_vE$: On the purchase order, if not specified; $_vE_{-40°C}$≧20 J
YS: Yield strength, TS: Tensile strength, El: Elongation
$_vE$: Absorbed energy

Table 3 Mechanical properties of JFE-HITEN610U2

Thickness (mm)	Tensile properties				Charpy impact properties		
	Position, Direction	YS (MPa)	TS (MPa)	El (%)	Position, Direction	$_vE_{-20°C}$ (J)	$_vE_{-40°C}$ (J)
25	Full-thick., C	586	662	43	1/4*t*, L 1/4*t*, C	— —	328 324
40	Full-thick., C	564	657	52	1/4*t*, L 1/4*t*, C	337 331	321 316

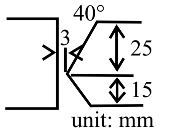
SPV490 Specification: YS≧490, 610≦TS≦740 MPa
$_vE_{-10°C}$≧47 J (L)
YS: Yield strength TS: Tensile strength El: Elongation
$_vE$: Absorbed energy

Table 4 Mechanical properties of JFE-HITEN610E

Thickness (mm)	Tensile properties				Charpy impact properties	
	Position, Direction	YS (MPa)	TS (MPa)	El (%)	Position, Direction	$_vE_{-15°C}$ (J)
12	Full-thick., C	642	702	26	1/4*t*, L 1/4*t*, C	288 273
22	Full-thick., C	613	682	41	1/4*t*, L 1/4*t*, C	309 293
32	Full-thick., C	567	642	44	1/4*t*, L 1/4*t*, C	311 255

SPV490 Specification: YS≧490, 610≦TS≦740 MPa
$_vE_{-10°C}$≧47 J (L)
YS: Yield strength TS: Tensile strength El: Elongation
$_vE$: Absorbed energy

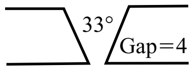
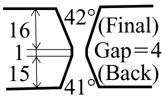
Table 5 Mechanical properties of JFE-HITEN610U2's SMAW welded joint

Thickness (mm)	Welding	
	Edge preparation	Welding conditions
40		Heat input: 4.1 kJ/mm LB-62UL (ϕ5)* Preheat: None Inter pass temp: ≦150°C

PWHT	Tensile properties		Charpy impact properties		
	TS (MPa)	Fracture position	Position		$_vE_{-20°C}$ (J)
none	664 665	Base metal Base metal	1/4*t*	Weld metal	124
				Fusion line	277
				HAZ	313
580°C×2 h, 2 times	655 653	Base metal Base metal	1/4*t*	Weld metal	143
				Fusion line	267
				HAZ	278

* Supplied by Kobe Steel, Ltd.
TS: Tensile strength $_vE$: Absorbed energy HAZ: Heat affected zone

Table 6 Mechanical properties of JFE-HITEN610E's EGW welded joints

Thickness (mm)	Welding	
	Edge preparation	Welding conditions
22		Heat input: 8.7 kJ/mm DWS-60G (ϕ1.6)* Built-up: 1 side, 1 pass Preheat: none
32		Heat input: 6.9, 6.5 kJ/mm DWS-60G (ϕ1.6)* Built-up: Both side 1 pass Preheat: None

Thickness (mm)	Tensile properties		Charpy impact properties		
	TS (MPa)	Fracture position	Position		$_vE_{-15°C}$ (J)
22	633 628	Base metal	1/4*t*	Weld metal	105
				Fusion line	121
				HAZ	240
32	628 622	Base metal Base metal	1/4*t*	Weld metal	100
				Fusion line	173
				HAZ	290

* Supplied by Kobe Steel, Ltd.
TS: Tensile strength $_vE$: Absorbed energy HAZ: Heat affected zone

DQ-HOP. The strength and low-temperature toughness meet the A841 Gr.B Cl.2 specification and SPV490 specification.

5.2 Welded Joint Performance

As examples of welded joint performance of the developed steels, **Tables 5** and **6** show the welded joint performance of DQ-HOP-processed JFE-HITEN610U2 with joints welded by shielded metal arc welding (SMAW), and DQ-HOP-processed JFE-HITEN610E with joints welded by electrogas arc welding (EGW). The joint strength and weldment toughness values meet the specifications for the base metal in both steels. Thus, both steels have excellent welded joint performance.

6. Conclusion

This paper presented the features and properties of high-performance 550 MPa and 610 MPa class steel plates produced using JFE Steel's technology for refining and dispersing carbides. These steels are to be used as steel plates for tanks and penstocks, plant components that require extremely high reliability. The features and properties of these steels were achieved by a combination of material design through microalloying technology and advanced plate manufacturing technologies such as *Super*-OLAC and HOP (Heat-treatment On-line Process). A cumulative total exceeding 80 000 t of 610 MPa class steels using HOP has already been proven in the field. The authors expect these newly developed steels to be increasingly used in the future, and thus intend to make them adaptable to diversifying needs.

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