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High Strength Steel Plates with Excellent Toughness for Tanks and Penstocks Applying Thermo-Mechanical Control Process (TMCP)†

1. Introduction

Various types of steel plates are used in the energy plant field, which includes energy storage facilities, chemical plants, power generating equipment, and similar facilities. In recent years, large-scale equipment has been used in these facilities, operating conditions and use environments have become more severe, and higher efficiency in construction has been demanded with the aim of reducing construction costs. Strict performance requirements are also applied to the steel materials used in these plants, such as high strength, improved toughness, improved weldability, etc., and cost reduction has been demanded. Moreover, active construction of energy plants is now underway in response to growing energy demand worldwide, heightening the need for high performance steels. Thus, it is also necessary to secure adequate supplies of these steel products, shorten construction period, etc.

Using the accelerated cooling device, *Super*-OLAC™ (On-Line Accelerated Cooling), which features a high cooling capacity and uniform cooling performance, the induction heating-type online heat treatment process HOP™ (Heat-Treatment On-Line Process) after accelerated cooling, and other advanced plate manufacturing technologies[1], in combination with advanced material property design technology, JFE Steel has developed high performance, high strength steels with excellent weldability[2,3] for various types of tanks and penstocks for hydro power plants in order to meet the needs outlined above. These products are already used in a large number of plants.

This report introduces thermo-mechanical control process (TMCP)-type steel plates conforming to ASME SA-841/ASTM A841/EN 10028-5 (ASME: The American Society of Mechanical Engineers, ASTM: The American Society for Testing and Materials, EN: European Norm), which can be used as substitutes for heat-treated steels under conventional standards (ASME SA-537, etc.) that are widely applied to tanks and penstocks.

2. Features and Concept of Developed Steels

2.1 Applicable Standards

2.1.1 ASME SA-841/ASTM A841

Thermo-mechanical control process-type SA-841/A841 steels have been standardized as steel plates that can be substituted for heat-treated SA-537/A537 steels produced by heat treatment processes such as normalizing (N) or quenching and tempering (Q-T), and were formally registered in Section VIII, Div. 1, 2 in 2011 through a process of registration in the Code Case of the ASME Boiler & Pressure Vessel Code. As their tensile property requirements are the same as those of SA-537/

Table 1 Thermo-mechanical control process (TMCP) standard with respect to ordinal standard

TS Grade	Standard	Conventional standard		Recommended standard	
		Grade	Heat treatment	Grade	Heat treatment
450–500	ASME	SA-537-1	N	SA-841A-1	TMCP
	EN 10028	P355N, NL1, NL2	N or NR	P355M, ML1, ML2	TMCP
		—	—	P420M, ML1, ML2	TMCP
530–550	ASME	SA-537-2	Q-T	SA-841B-2	TMCP
	EN 10028	P460Q, QL1, QL2	Q-T	P460M, ML1, ML2	TMCP

ASME: The American Society of Mechanical Engineers EN: European Norm
N: Normalizing NR: Normalizing rolling Q-T: Quenching and tempering

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A537, wide application as TMCP steels is expected in the future. The strength classes of these steels are SA-841 Gr. A Cl. 1 steel (TS of 480 MPa class; TS: Tensile strength) and SA-841 Gr. B Cl. 2 steel (TS of 550 MPa) (**Table 1**).

2.1.2 EN 10028-5

Thermo-mechanical control process-type steels are also registered in the EN standard as EN 10028-5, and it is possible to omit heat treatment of N type steel (EN 10028-3) and Q-T type steel (EN 10025-6) (Table 1).

2.2 Omission of Heat Treatment by Application of TMCP

A comparison of TMCP and the conventional heat treatment process is shown in **Fig. 1**. Application of TMCP makes it possible to omit conventional heat treatment processes such as N and Q-T. Under the EN standard, normalizing rolling (NR) is recognized as a process that enables omission of N (EN 10028-3).

2.3 Features and Concept of Developed Steels

The features of the developed steels applying TMCP are shown in **Fig. 2**. Use of the *Super*-OLAC™ and microalloying technology makes it possible to reduce the C content and P_{CM} (Weld cracking parameter), and improves weldability and reliability, for example, by improving weldability (Decrease of preheat temperature to avoid weld cracking: **Fig. 3**) and improving welded joint performance (Decrease of hardness: **Fig. 4**; Increase of toughness), etc. In addition, application of TMCP also realizes an online process, as it is possible to omit the conventional off-line heat treatment processes, and thereby makes it possible to shorten production lead time, save costs associated with heat treatment, and increase production capacity. As a result, with TCMP, it is possible to enjoy large merits, even based on the same design conditions as in the past.

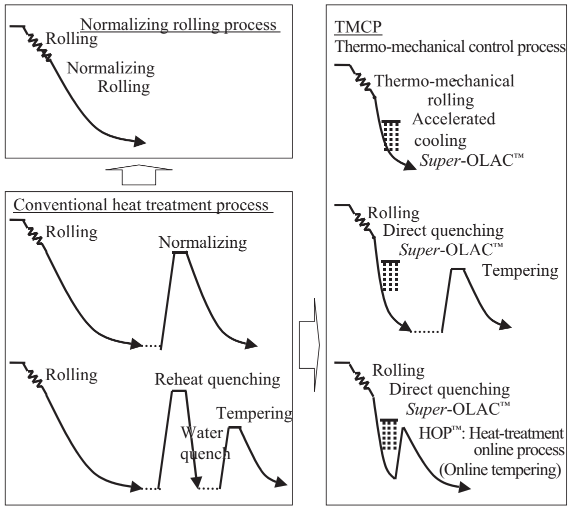
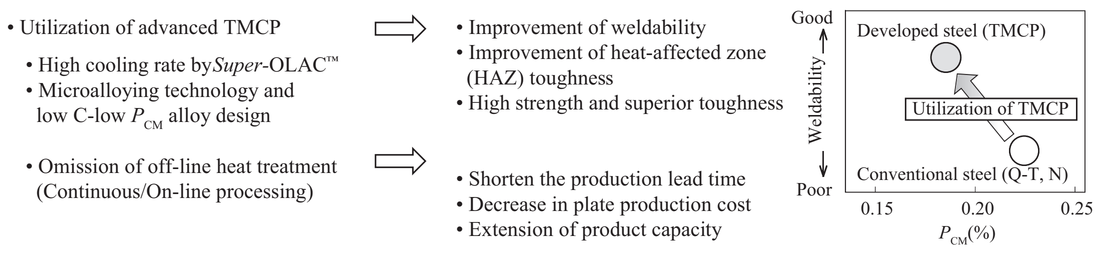
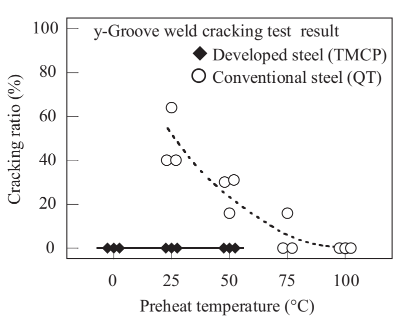


Fig. 1 Comparison of production process between thermo-mechanical control process (TMCP) and conventional heat treatment process



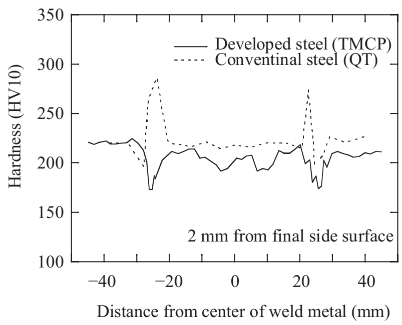
P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Fig. 2 Feature of high strength steel plates applying thermo-mechanical control process (TMCP) for tanks and pen-stocks



TMCP: Thermo-mechanical control process
P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Fig. 3 Decrease of preheat temperature to avoid weld cracking of the developed steel by suppression of C content and P_{CM}



TMCP: Thermo-mechanical control process
P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Fig. 4 Improvement of heat affected zone (HAZ) hardness distribution of the developed steel by suppression of C content and P_{CM}

Table 2 Chemical compositions of ASME SA-841 Gr.A Cl.1

(mass%)

Grade	Thickness (mm)	C	Si	Mn	P	S	Others	C_{eq}	P_{CM}
SA-841A-1 (EN P355ML2)	12	0.09	0.39	1.47	0.004	0.001	Ti, etc.	0.34	0.18
	40	0.10	0.40	1.46	0.010	0.002	Ti, etc.	0.35	0.19

ASME: The American Society of Mechanical Engineers EN: European Norm
C_{eq}=C+Mn/6+Cu/15+Ni/15+Cr/5+Mo/5+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 ASME SA-841 Gr.A Cl.1

Grade	Thickness (mm)	Tensile properties				Charpy impact properties		
		Position, Direction	YS (MPa)	TS (MPa)	El (%)	Position, direction	${}_{V}E_{-40°C}$ (J)	${}_{V}E_{-60°C}$ (J)
SA-841A-1 (EN P355ML2)	12	Full-thickness, C	445	533	24	1/4*t*, C	399	345
	40	Full-thickness, C	420	536	32	1/4*t*, C	426	424

ASME: The American Society of Mechanical Engineers EN: European Norm
SA-841Gr.B Cl.2 Specification: YS≥345, 480≤TS≤620 MPa
${}_{V}E$: On the purchase order, if not specified; ${}_{V}E_{-40°C}$≥20 J
YS: Yield strength TS: Tensile strength El: Elongation ${}_{V}E$: Absorbed energy

Table 4 Chemical compositions of ASME SA-841 Gr.B Cl.2

(mass%)

Grade	Thickness (mm)	C	Si	Mn	P	S	Others	C_{eq}	P_{CM}
SA-841B-2 [Type I] (EN P460M)	16 and 38	0.08	0.19	1.34	0.014	0.002	Mo,V, etc.	0.33	0.16
	60	0.09	0.26	1.45	0.011	0.001	Mo,V, etc	0.39	0.20
SA-841B-2 [Type II] (EN P460ML2)	40 and 60	0.06	0.20	1.47	0.009	0.003	Cu, Ni, Cr, Mo, V, etc.	0.40	0.17

ASME: The American Society of Mechanical Engineers EN: European Norm
C_{eq}=C+Mn/6+Cu/15+Ni/15+Cr/5+Mo/5+V/5 P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Table 5 Mechanical properties of ASME SA-841 Gr.B Cl.2

Grade	Thickness (mm)	Tensile properties				Charpy impact properties				
		Position, Direction	YS (MPa)	TS (MPa)	El (%)	Position, Direction	${}_{V}E_{-25°C}$ (J)	${}_{V}E_{-40°C}$ (J)	${}_{V}E_{-45°C}$ (J)	${}_{V}E_{-50°C}$ (J)
SA-841B-2 [Type I] (EN P460M)	16	Full-thickness, C	583	669	36	1/4*t*-C	236	—	140	—
	38	Full-thickness, C	522	617	50	1/4*t*-C	298	—	284	—
	60	1/4*t*-C	553	641	30	1/4*t*-C	276	—	170	—
SA-841B-2 [Type II] (EN P460ML2)	40	1/4*t*-C	500	595	30	1/4*t*-C	—	282	—	310
	60	1/4*t*-C	504	573	31	1/4*t*-C	—	288	—	345

ASME: The American Society of Mechanical Engineers EN: European Norm
SA-841Gr.B Cl.2 Specification : YS≥415, 550≤TS≤690 MPa, ${}_{V}E$: On the purchase order, if not specified; ${}_{V}E_{-40°C}$≥20 J
YS: Yield strength TS: Tensile strength El: Elongation ${}_{V}E$: Absorbed energy

3. Properties of Developed Steels

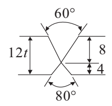
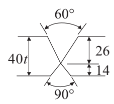
3.1 Properties of Base Materials

The chemical compositions and mechanical properties of the developed steels SA-841 Gr. A Cl.1 and SA-841 Gr. B Cl. 2 are shown in **Tables 2–5**, respectively. SA-841 Gr. A Cl.1 satisfies EN 10028 P355ML2, SA-841 Gr. B Cl. 2 Type I (Target of minimum design temperature: −20°C) satisfies EN 10028 P460M, and Type II (Target of minimum design temperature: −50°C) also satisfies EN 10028 P460ML2. These steels possess strength amply satisfying the respective specifications, as well as excellent low temperature toughness.

3.2 Welded Joints Properties of Developed Steels

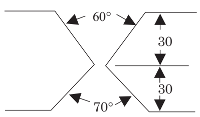
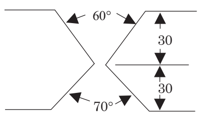
As an example of the welded joint performance of the developed steels SA-841 Gr. A Cl.1 and SA-841 Gr. B Cl. 2, the mechanical properties of shielded metal arc welding (SMAW) joints are shown in **Tables 6** and **7**,

Table 6 Typical mechanical properties of ASME SA-841 Gr.A Cl.1's SMAW weldments

Grade	Thickness (mm)	Welding		PWHT	Tensile properties	Charpy impact properties			
		Edge preparation	Welding condition		TS (MPa)	Position		$_{v}E_{-40°C}$ (J)	$_{v}E_{-60°C}$ (J)
SA-841A-1 (EN P355ML2)	12		Welding consumable: NB-1SJ (3.2φ)* Heat input: 4.0 kJ/mm	—	526 529	1/4 t	WM	65	45
							FL	162	59
							HAZ	321	228
	40		Welding consumable: NB-1SJ (4.0φ)* Heat input: 4.3 kJ/mm	—	550 552	1/4 t	WM	66	49
							FL	126	56
							HAZ	239	196

*Supplied by Kobe Steel, Ltd.
ASME: The American Society of Mechanical Engineers EN: European Norm SMAW: Shielded metal arc welding
PWHT: Post weld heat treatment TS: Tensile strength $_{v}E$: Absorbed energy WM: Weld metal FL: Fusion line HAZ: Heat-affected zone

Table 7 Typical mechanical properties of ASME SA-841 Gr.B Cl.2's SMAW weldments

Grade	Thick-ness (mm)	Welding		PWHT	Tensile properties	Charpy impact properties					
		Edge preparation	Welding condition		TS (MPa)	Position		$_{v}E_{-25°C}$ (J)	$_{v}E_{-30°C}$ (J)	$_{v}E_{-45°C}$ (J)	$_{v}E_{-50°C}$ (J)
SA-841B-2 [Type I] (EN P460M)	60		Welding consumable: LB-62UL (5.0φ)* Heat input: 2.3 kJ/mm	—	679 677	1/4t	WM	158	—	99	
							FL	178	—	126	
							HAZ	300	—	224	
				580ºC ×5 h	681 683	1/4t	WM	141	—	68	
							FL	126	—	84	
							HAZ	209	—	193	
SA-841B-2 [Type II] (EN P460ML2)	60		Welding consumable: NB-1SJ (5.0φ)* Heat input: 2.3 kJ/mm	—	620 622	1/4t	WM		125		106
							FL		237		260
							HAZ		274		241
				580ºC ×4.5 h	598 605	1/4t	WM		147		127
							FL		177		117
							HAZ		281		170

*Supplied by Kobe Steel, Ltd.
ASME: The American Society of Mechanical Engineers EN: European Norm SMAW: Shielded metal arc welding
PWHT: Post weld heat treatment TS: Tensile strength $_{v}E$: Absorbed energy WM: Weld metal FL: Fusion line HAZ: Heat-affected zone

respectively. In all cases, joint strength satisfying the specified values of the base material under the ASME standard and the corresponding EN standards (P355ML2 and P460M, P460ML2) and high welded joint toughness are obtained, and the steels display excellent welded joint performance.

4. Conclusion

Steel plates for tanks and penstocks manufactured using state-of-the-art TMCP technology provide excellent weldability and base material/welded joint properties, while also reducing costs, shortening production lead time, and increasing supply capacity. Wide-ranging application of these steel plates as a substitute for conventional heat-treated products is expected in the future.

References

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2) Hayashi, Kenji; Araki, Kiyomi; Abe, Takashi. JFE Technical Report. 2005, no. 5, p. 66–73.
3) Hayashi, Kenji; Nagao, Akihide; Matsuda, Yutaka. JFE Technical Report. 2008, no. 11, p. 19–25.

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