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Development of High Strength H-Shapes with Excellent Toughness Manufactured by Advanced Thermo-Mechanical Control Process (TMCP)†

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Abstract:

JFE Steel has developed high performance H-shapes applying an advanced thermo-mechanical control process (TMCP). To obtain high strength H-shapes with excellent toughness, it is important to obtain refined bainite microstructure, through suitable alloy design, hot rolling under the optimum rolling conditions, and accelerated cooling after hot rolling. This paper introduces examples of recently developed high performance H-shapes, such as 520 MPa grade (in tensile strength) H-shapes for high-rise building construction application with excellent toughness, weldability and earthquake-resistant properties, and 490 MPa grade (in tensile strength) H-shapes with superior low temperature toughness. Alloy designing to obtain refined microstructure under the specific hot rolling conditions to H-shapes, and the accelerated cooling facilities for shapes (Super-OLAC S: On-line Accelerated Cooling for Shapes. OLAC is a registered trademark in Japan.) are essential for the development of high performance H-Shapes.

1. Introduction

H-shapes are widely used in buildings, factories, and various types of plants. In recent years, structures have been characterized by progressively greater height, larger scale, and larger spans. In high rise buildings, there is a tendency toward more complex structural types such as composite structures which include shopping centers and other commercial space, offices, and hotels[1]. Under these circumstances, larger sizes have been required in rolled H-shapes. JFE Steel developed and manufactures large-section constant-outer-size H-shapes with a web height of 1 000 mm (Super HISLEND H-Shape) to meet this need[2].

On the other hand, increases in specified design strength due to higher strength requirements for structural members have heightened the need for high strength steel in order to expand the range of choices for economical and efficient design, such as the reduction of thickness, weight reduction of steel structures by size reductions, etc.

Giant earthquakes such as the Hanshin-Awaji Earthquake caused widespread damage to beam-end connections in structures. Learning from this, high performance steels with a low yield ratio (yield strength/tensile strength), excellent toughness including the welding portion, and weldability have been demanded[3].

Thick plates are used in box columns, other columns, and steel pipes which are applied as structural columns. These plates are manufactured by the thermo-mechanical control process (TMCP). High performance plates with higher strength have developed in tandem with progress in hot rolling and accelerated cooling technologies[4–6].

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The thermo-mechanical control process is also an effective technology for realizing high strength in H-shapes. However, it is necessary to construct a TMCP technology specifically for H-shapes, which is different from that used with plates, as H-shapes of complex and diverse sizes are formed in the hot rolling process.

This paper introduces the study of TMCP technology which was considered in a manufacturing technology for H-shapes, together with the base material performance, weldability, and weld joint property of a low yield ratio SM520 grade (in tensile strength) constant-outer-size H-shape and a −40°C low temperature specification SM490Y grade (in tensile strength) H-shape which are produced using that technology.

2. TMCP Technology for H-shapes

2.1 Features of H-shape Rolling and Austenite Recrystallization Behavior

In the rolling process for H-shapes, the material is heated to a temperature of 1 250°C or more, which is higher than that used in plate rolling, in order to secure formability during caliber rolling and universal rolling. At these high temperatures, austenite (hereinafter, *γ*) undergoes rapid austenite grain growth (**Photo 1**). Furthermore, in the H-shape hot rolling process, the rolling reduction per pass and total reduction ratio are relatively small in comparison with the plate rolling. Therefore, in order to secure ductility and toughness, adequate refinement of the coarse initial *γ* grain size in the hot rolling process becomes important.

Photo 2 shows optical microscope images of Si-Mn steel and Nb bearing steel when heated at 1 300°C for 0.5 h, hot rolled at 10%/pass at 970°C or higher for a maximum of 7 passes (total reduction: 52%), and quenched in water. In the Si-Mn steel (Nb free), fine recrystallized *γ* can be observed. On the other hand, the Nb bearing steel displays a mixed microstructure consisting of coarse *γ* and fine *γ*. This is because the recrystallization of *γ* is suppressed by added Nb. If accelerated cooling is performed from this state, coarse bainite will form, reducing ductility and toughness.

An effective means of achieving further refinement of *γ* is refinement in which stable, fine precipitates are dispersed in the steel in order to suppress the *γ* grain growth. **Photo 3** (b) shows the *γ* microstructure when steel containing dispersed TiN was heated at 1 300°C for 0.5 h. This microstructure is fine in comparison with that of the conventional steel shown in Photo 3 (a). Thus, a finer *γ* microstructure is obtained through hot rolling by dispersion of TiN in the steel (**Photo 4**).

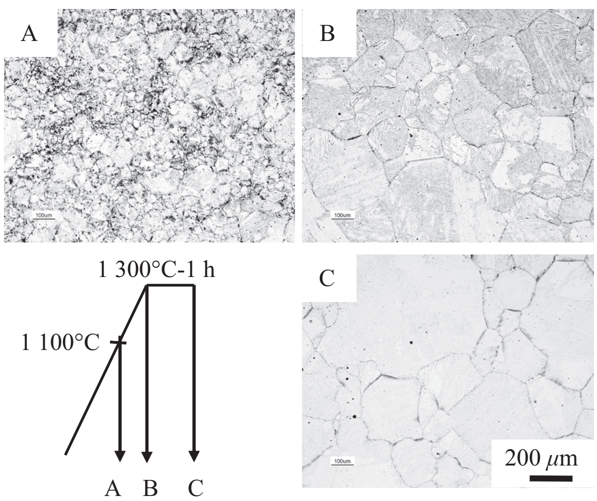


Photo 1 γ grain growth behavior during reheating

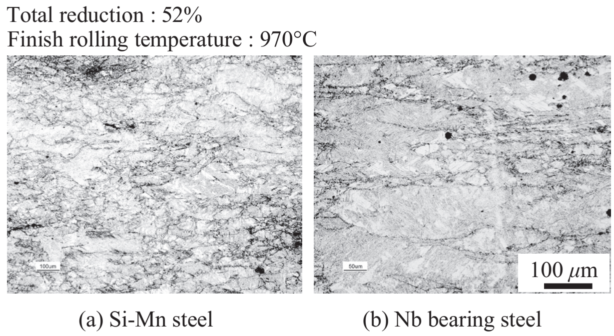


Photo 2 Optical microstructures after hot rolling; (a)Si-Mn steel and (b)Nb bearing steel

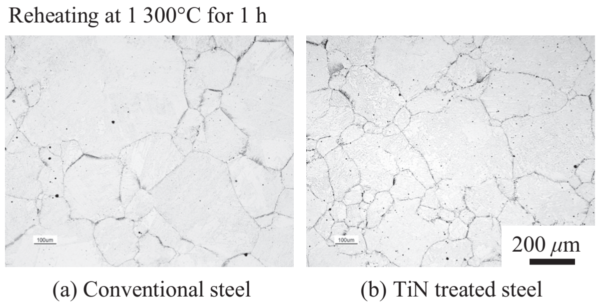


Photo 3 γ grain structures after reheating at 1 300°C for 0.5 h; (a) Conventional steel and (b) TiN treated steel

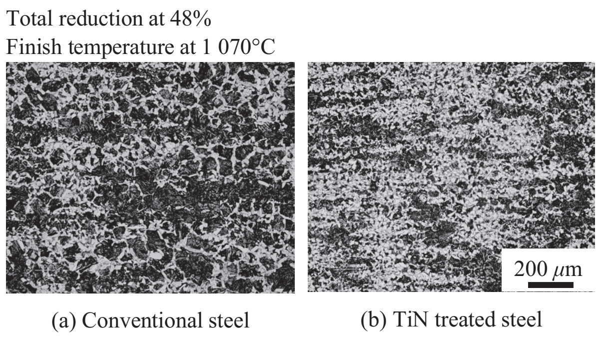


Photo 4 γ grain structures after hot rolling; (a) Conventional steel and (b) TiN treated steel

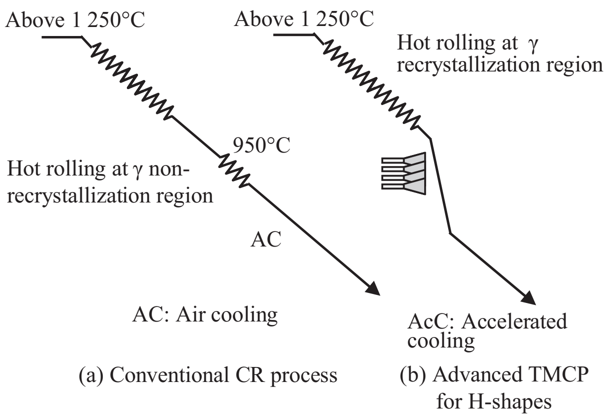


Fig. 1 Schematic illustration of Thermo-mechanical control process (TMCP) for H-shapes; (a)Conventional controlled rolling (CR) process and (b)Advanced TMCP for H-shapes

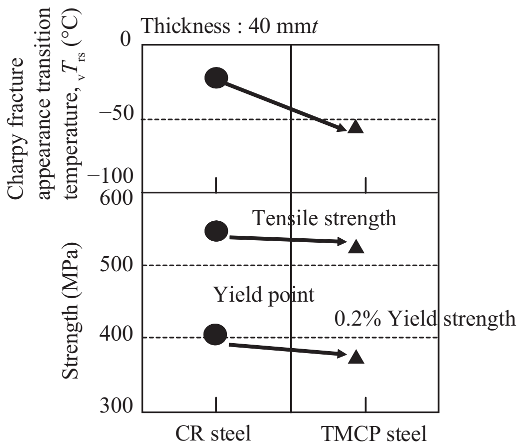


Fig. 2 Strength and toughness of thermo-mechanical control process (TMCP) steel compared with conventional controlled rolling (CR) steel

2.2 TMCP Technology Suitable for H-shapes

A schematic diagram of an advanced TMCP process which considers a manufacturing technology specifically for H-shapes is shown in **Fig. 1** in comparison with conventional controlled rolling (CR). It is necessary to perform composition design properly in order to promote refinement of the initial γ grain size and recrystallization of γ during hot rolling. In particular, although Nb is a useful element in TMCP steels, with H-shapes, the amount of addition and the rolling schedule must be carefully selected. In hot rolling, H-shapes with high strength and excellent ductility and toughness can be manufactured by securing the amount of reduction in the high temperature region necessary to ensure adequate recrystallization of the coarse initial γ grain size, followed by accelerated cooling.

The strength and toughness of conventional CR steel and TMCP steel were investigated by performing rolling which simulated the H-shape manufacturing process in the laboratory. The conventional CR steel is a 0.15%C-1.45%Mn steel with microalloying of Nb and V. The TMCP steel is a 0.13%C-1.55%Mn steel without addition of Nb and V microalloys. With the TMCP steel, accelerated cooling by water cooling from the γ region was performed after hot rolling. The microstructure of the TMCP steel is shown in **Photo 5** in comparison with that of the CR steel[7].The CR steel has a ferrite + pearlite structure, whereas the TMCP steel has a fine bainite structure. A comparison of strength and toughness is shown in **Fig. 2**[7]. Although the strengths of the CR steel and TMCP steel are on the same level, the TMCP steel possess superior toughness.

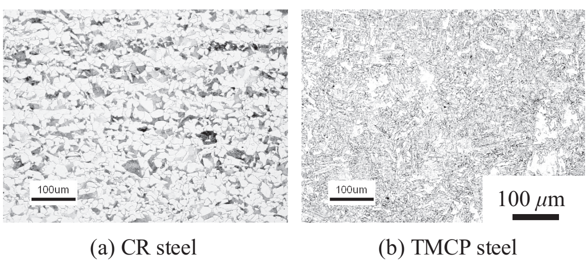


Photo 5 Microstructures of controlled rolling (CR) steel and thermo-mechanical control process (TMCP) steel; (a) CR steel, (b)TMCP steel

3. High Strength H-shapes by Application of Advanced TMCP

A low yield ratio SM520 grade (in tensile strength) wide-width constant-outer-size H-shape (hereinafter Super Hislend H-shape), which is applied to beam materials for high rise buildings and large-scale factories, and a low temperature toughness specification H-shapes were manufactured in the steel works by applying advanced TMCP technology, and the base material properties, weldability, and weld joint property of these H shapes were investigated.

3.1 Low Yield Ratio SM520 Grade Super Hislend H-shape for Buildings

3.1.1 Chemical composition and manufacturing condition

The typical chemical composition of the steel is shown in **Table 1**. This steel has the same carbon content and carbon equivalent as general-purpose 490MPa grade (in tensile strength) steel. After heating

Table 1 Typical chemical composition of steel used

(mass%)

C	Si	Mn	P	S	Others	C_{eq}
0.17	0.33	1.28	0.020	0.003	Ti	0.40

C_{eq}(%)=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14 to a temperature in excess of 1 250°C, hot rolling was performed considering the high temperature reduction ratio and heating temperature, followed by accelerated cooling using JFE Steel's accelerated cooling facilities for shapes (*Super*-OLAC S. OLAC is a registered trademark in Japan.). The sizes of the H-shapes manufactured in this study were H900×400×19×40 mm and H1000×400×16×32 mm constant-outer-size H-shapes.

3.1.2 Mechanical properties of base material

As shown in **Photo 6**, the microstructure of the Super Hislend H-shape with a 40 mm flange thickness in the flange 1/6 width-1/4*t* portion is fine bainite. The tensile test results and Charpy impact test results are shown in **Tables 2** and **3**, respectively. High strength satisfying the product standard was obtained in the flange 1/6 width portion, fillet, and web, and the yield ratio was less than 80%. Charpy absorbed energy was 200 J or higher, indicating that the developed H-shape possesses satisfactory base material strength and toughness.

3.1.3 Weldability

A y-groove weld cracking test in accordance with JIS Z 3158 (JIS: Japanese Industrial Standards) was performed by CO_2 welding in an environment with a humidity of 60% and a preheating temperature of 5°C. The welding electrode used MG-56 (1.2 mm in diameter). The results are shown in **Table 4**. The product displayed excellent weldability with no weld cracks observed in the 5°C preheating environment.

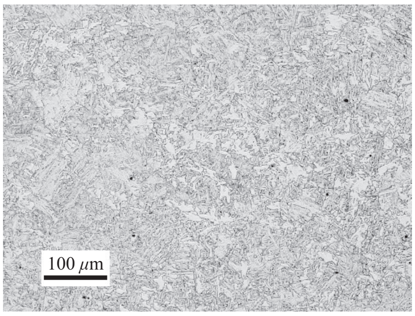


Photo 6 Microstructure of developed H-shape(Flange portion)

Table 4 Results of y-groove weld cracking test in accordance with JIS Z 3158

Welding electrode	Humidity (%)	Pre-heat temperature (°C)	Surface (%)	Root section (%)	Cross section (%)
MG-56 (1.2 mφ)	60	5	0	0	0
			0	0	0
			0	0	0
		25	0	0	0
			0	0	0
			0	0	0

Table 2 Tensile test results of developed H-shapes

Size	Position	YP or 0.2% YS (MPa)	TS (MPa)	YR (%)	El (%)
Spec.		355–(475)	520–640	(<80)	(>21)
H900×400×19×40	F1/6	409	553	74	31
	Fillet	446	573	78	29
	W1/6	402	531	76	27
H1000×400×16×32	F1/6	401	543	74	32
	Fillet	414	566	73	30
	W1/6	442	562	79	25

YP: Yield point YS: Yield strength TS: Tensile strength YR: Yield ratio El: Elongation

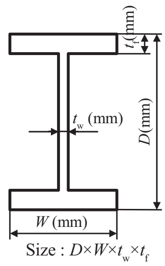
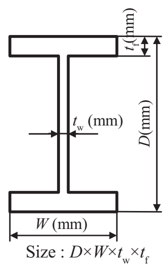


Table 3 Charpy impact test results of developed H-shapes

Size	Position		Dimension	$_vE_0$ (J)	$_vT_{rs}$ (°C)
Spec.				>27	
H900×400×19×40	F1/6	Outer surface	L	237	−45
		Inner surface	L	248	−42
	Fillet		L	208	−33
	W1/6		L	214	−53
H1000×400×16×32	F1/6	Outer surface	L	232	−23
		Inner surface	L	232	−35
	Fillet		L	187	−32
	W1/6		L	225	−68

$_vE_0$: Charpy absorbed energy at 0°C $_vT_{rs}$: Charpy fracture appearance transition temperature



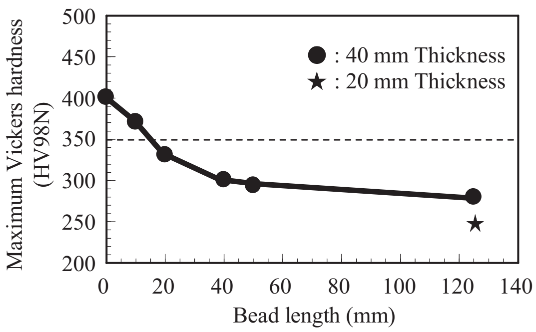


Fig. 3 Maximum hardness test results for developed H-shape

A maximum hardness test in the weld heat-affected zone (HAZ) in short-bead welding was performed in accordance with JIS Z 3101. **Figure 3** shows the maximum hardness test results for developed H-shape. When the weld length was 20 mm or more, the maximum hardness in the HAZ was less than HV350. Thus, the developed H-shape possesses good weldability satisfying the Japan Architectural Standard Specification (JASS 6)[8].

3.1.4 Properties of multi-pass welded joints

Multi-pass welding of Super Hislend H-shape with a 40 mm flange thickness was performed by CO_2 welding, and the resulting weld joint properties were investigated. Using MG-56 (1.2 mm in diameter) as the welding electrode, 9-layer, 16-pass welding was performed without preheating and with a maximum interpass temperature of 250°C or less. The heat input was 3 kJ/mm. The macrostructure of a welded joint is shown in **Photo 7**. No harmful welding defects such as lack of fusion or weld cracking were observed in the welding portion. The tensile test results of the welded joint are shown in **Table 5**. Fracture strength exceeds 550 MPa,

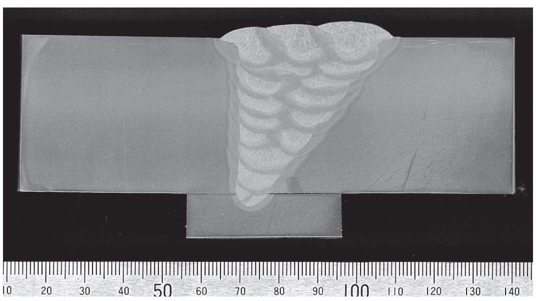
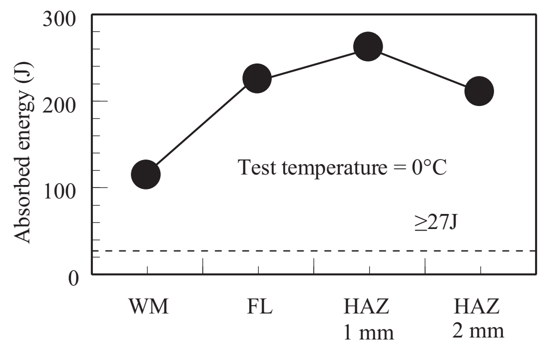


Photo 7 Macro-structure of CO_2 welded joint

Table 5 Tensile test results of CO_2 welded joint

Weld material	Heat input	TS (MPa)	Break position
MG-56 1.2 mφ	30 kJ/cm	552	Base metal
		575	Base metal

TS : Tensile strength



WM: Weld metal FL: Fusion line
HAZ: Heat affected zone

Fig. 4 Charpy impact test results of CO_2 welded joint

and fracture occurred in the base metal, confirming satisfactory weld jointed strength.

The Charpy impact test results of the welded joint are shown in **Fig. 4**. Satisfactory Charpy absorbed energy values exceeding 100 J were obtained in all parts, including the weld metal (WM), fusion line (FL), and HAZ.

3.2 H-shapes with Excellent Low Temperature Toughness

3.2.1 Chemical composition and manufacturing condition

The typical chemical composition of the steel is shown in **Table 6**. In order to satisfy low temperature toughness, including the welding portion, the composition design was performed using a proprietary HAZ high toughness technology (JFE EWEL®)[9,10]. H918×303×19×37 mm, which is the largest size of H-shape, and H900×400×19×40 mm, which is the maximum flange thickness of the Super Hislend H-shape, were manufactured using the advanced TMCP process, and these specimens were compared with CR type H-shapes (flange thickness: 24 mm) with added Nb, V, Ni, etc.

3.2.2 Mechanical properties of base material

The strength and toughness of the CR steels and TMCP steels are shown in **Table 7**[7]. With the TMCP steels, high strength of the SM490Y grade (in tensile

Table 6 Typical chemical compositions of steels used

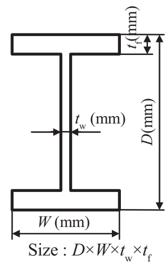
(mass%)

	C	Si	Mn	P	S	Others
CR type	0.15	0.35	1.45	0.015	0.005	Ni, Nb, V
TMCP type	0.13	0.27	1.56	0.017	0.003	TiN treated

CR: Controlled rolling
TMCP: Thermo-mechanical control process

Table 7 Mechanical properties of H-shapes

Process	Size	YP, 0.2% YS (MPa)	TS (MPa)	El (%)	Temp. (°C)	Absorbed energy (J)	$_vT_{rs}$ (°C)
Controlled rolling (CR)	700×300×13×24	394	551	27	−20	166	−20
Thermo-mechanical control process (TMCP)	903×300×19×37	411	536	29	−40	215	<−50
	900×400×19×40	427	538	28	−40	200	−67



YP: Yield point YS: Yield strength TS: Tensile strength El: Elongation
$_vT_{rs}$: Charpy fracture appearance transition temperature

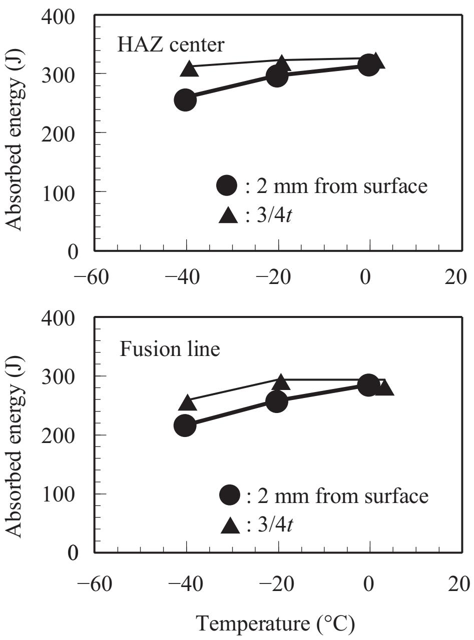


Fig. 5 Charpy impact test results of welded joint

strength) was obtained in spite of the thicker flange. The Charpy absorbed energy values at −40°C were 200 J or higher, and the material possessed excellent low temperature toughness, displaying a fracture appearance transition temperature ($_vT_{rs}$) of −50°C or less.

3.2.3 Toughness of multi-pass welded joint

Using a YGW-23 grade (wire diameter of 1.2 mm) welding electrode, 7-layer, 13-pass welding was performed by MAG welding (shield gas: Ar-20% CO_2). The maximum heat input was 3 kJ/mm, and the interpass temperature was 350°C or less. The welded joint toughness is shown in **Fig. 5**. High Charpy absorbed energy exceeding 200 J was obtained at a low temperature of −40°C in the fusion line (FL) and HAZ, confirming excellent low temperature toughness, including the welding portion.

4. Conclusion

Using an advanced TMCP technology which considers the H-shape manufacturing process, low yield ratio SM520 grade (in tensile strength) Super Hislend H-shape (maximum flange thickness: 40 mm) for use in building structures was developed. This product features an excellent anti-earthquake property and high weldability. An SM490Y grade (in tensile strength) H-shape with excellent low temperature toughness in multi-pass welds was also developed using a proprietary HAZ microstructure control technology (JFE EWEL®) developed. The low yield ratio SM520 grade (in tensile strength) Super Hislend H-shape has already been used in high rise buildings in Japan.

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