Development of 780 N/mm²-Class Structural Steel for Building Structures Suitable for High Heat Input Welding

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Abstract

As steel building structures become taller, there are high hopes for the use of 780 N/mm²-class steel for welded box columns. However, it has been difficult to ensure the strength and toughness of welded joints when using high-heat input welding. To counter this, Kobe Steel has developed a steel plate that improves the toughness of the heat-affected zone in high-heat input welding by suppressing the formation of the M-A constituent (island martensite), a brittle hard phase, through increased Cr and Mo and reduced C, Si, and Mn. Evaluation of the mechanical properties of the base material, electroslag, and submerged arc welded joints confirmed favorable results in terms of strength, toughness, and weldability, making this plate suitable for high-efficiency construction.

Introduction

Recent years have seen a trend toward larger and taller steel building structures. As such, we anticipate the expanded application of 780 N/mm²-class steel to welded box columns. For the sake of efficiency, the convention in box column fabrication is to use electroslag welding (ESW) for inner diaphragms and submerged arc welding (SAW) for the corners. These are high-efficiency, high-heat input welding processes performed in a single pass, traditionally applied to box columns using 590 N/mm²-class steel or lower. Employing high-heat input welding with conventional 780 N/mm²-class steel makes it difficult to ensure the necessary strength and toughness of the welding joint. As such, low-heat input multi-pass welding is generally used, which is relatively inefficient. The high number of labor hours required for steel frame fabrication involving 780 N/mm²-class steel means that this class of steel is rarely used for said application.

This drove Kobe Steel to develop steel plate capable of maintaining strength and toughness during high-heat input welding to improve the efficiency of welding 780 N/mm²-class steel for box column fabrication.

This paper describes technology for ensuring high toughness of the heat-affected zone (HAZ) in the high-heat input welding of 780 N/mm²-class steel. It also introduces the properties of the base material of the developed steel plate and the properties of ESW joints intended for inner diaphragms and SAW joints at corners.

1. Development objectives

Tables 1 and **2** show the chemical composition and base material properties of Kobe Steel's 780 N/mm²-class steel that is designed for high-heat input welding in building construction applications (KBSA630C; see Note). The mechanical properties of the developed steel are designed to improve the toughness of high-heat input welds, including the HAZ of the inner diaphragm and corners, while meeting the specifications of Kobe Steel's high-performance 780 N/mm²-class steel for building construction.

There is concern regarding brittle fracture originating from the area where toughness is reduced in the HAZ of the inner diaphragm. Past research into preventing brittle fracture in 490 N/mm²-class steel reports that the weld should have a Charpy impact test result of at least 47 J to meet the standard strength specification (325 N/mm²) for 490 N/mm²-class steel used for the inner diaphragm.[1)] Studies[1), 2)] to confirm the necessary performance characteristics of ESW areas when using steels above a strength class of 490 N/mm² provide notable results: Assuming 780 N/mm²-class steel for the columns and 590 N/mm²-class high-performance steel for building structures for the beams (SA440), even columns made from 780 N/mm²-class steel

Table 1 Specification for chemical composition of KBSA630C

Steel	Chemical compositions (%)					P_{CM} (%)
	C	Si	Mn	P	S	
KBSA630C	≦0.13	≦0.55	≦2.50	≦0.015	≦0.008	≦0.30

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

Table 2 Mechanical properties of KBSA630C

Steel	Tensile properties				Impact properties
	YP or 0.2%YS (N/mm²)	TS (N/mm²)	El. (%)	YR (%)	$_vE_0$ (J)
KBSA630C	630-750	780-930	17≦	≦85	47≦

Tensile test specimen: JIS Z2241 No.4-1/4t-Transverse
Charpy impact test specimen: JIS Z2242 Full size-1/4t-Longitudinal

Note) KBSA is a trademark of Kobe Steel, Ltd. (4936432).

Table 3 Base chemical composition of conventional steel

(%)

C	Si	Mn	P	S	Others	P_{CM}
0.05	0.27	2.00	0.008	0.002	Cr, Mo,etc.	0.28

yield similar trends as for columns made of 490 N/mm^2-class steel or SA440. Therefore, to ensure the standard strength of the inner diaphragm in the ESW areas of columns made of 780 N/mm^2-class steel, we set a target of 47 J or greater for the Charpy impact test result of the welds of the developed steel.

2. Technology for high HAZ toughness in the high-heat input welding of 780 N/mm^2-class steel

The HAZ becomes a single-phase austenite (γ) structure near the boundary of the weld metal when exposed to high temperatures. Higher welding heat input results in a longer duration of exposure to a high temperature and a decrease in the cooling rate. Consequently, the final microstructure in the HAZ of high-heat input welds tends to be coarser due to the transformation from the coarsened γ phase. Furthermore, during cooling, the concentration of C stabilizes untransformed γ due to a slow cooling rate, promoting the formation of island martensite (MA), a brittle hard phase, and thereby reducing the toughness of the HAZ.

However, it has been reported that dispersing oxides finely within the steel suppresses γ coarsening in the HAZ due to pinning by the oxides.[3] It has also been reported that reducing the Si content can suppress MA formation[4], which is being applied to steels suitable for high-heat input welding in strength classes of 590 N/mm^2 and under.

Furthermore, for 590 – 780 N/mm^2-class steels in which the microstructure of the HAZ is bainite, a fine low-carbon bainite technique (low-carbon multi-orientation bainite) has been reported.[5] This technique suppresses the formation of MA by using weak carbide-forming elements to cause multi-orientation of the bainite structure in the HAZ, thereby refining the microstructure and reducing the amount of C added.

The welding heat input of electroslag-welded box columns is as high as 1,000 kJ/cm, so the HAZ cools more slowly than with the heat input conventionally applied to 780 N/mm^2-class steel. Furthermore, compared with steel plates of strength classes 590 N/mm^2 or lower, where ESW has traditionally been applied, a higher alloy content is required with 780 N/mm^2-class steel to ensure the required strength of the base material. Consequently, the γ phase in the HAZ stabilizes more readily. This effect combined with the slower cooling rate of high-heat input welding further promotes the formation of MA.

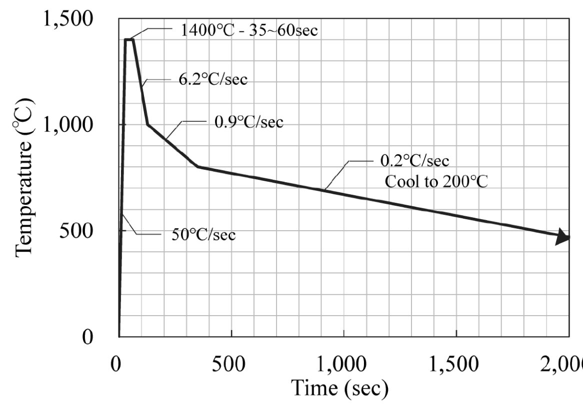


Fig. 1 Thermal history assumed for ESW

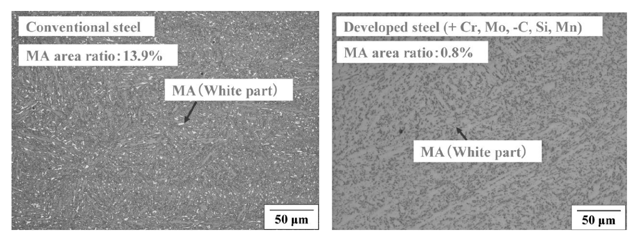


Fig. 2 Effect of increased Cr and Mo and reduced C, Si, and Mn on MA suppression

Therefore, in this development, we investigated the chemical composition of a steel sheet that would further suppress MA formation in the ESW of 780 N/mm^2-class steel. Using the base chemical composition of conventional steel (**Table 3**), square test specimens measuring 12.5 mm × 33 mm × 55 mm were taken from steel samples with varying amounts of Cr, Mo, C, Si, and Mn. To uniformly reproduce the microstructure of the HAZ during high-heat input welding, we used a thermal cycling device to apply a single cycle (**Fig. 1**) simulating the thermal history of an ESW bond area. We observed the microstructure after thermal cycling to determine how the amount of each element added affects the formation of MA. The results confirm that MA formation is suppressed in compositions in which Cr and Mo are increased and C, Si, and Mn are reduced (**Fig. 2**). As mentioned at the beginning of Section 2, MA is said to form when γ stabilizes due to the concentration of C in untransformed γ during the transformation from γ. It is hypothesized that increasing Cr and Mo inhibits the formation of MA by forming a low-temperature transformation structure without thermally stabilizing γ. It is further hypothesized that reducing C, Si, and Mn not only reduces the amount of C that concentrates in the untransformed γ, but also promotes the formation of iron carbides, thereby inhibiting the formation of MA from the untransformed γ.

3. Properties of the developed steel

3.1 Composition and base material properties

Table 4 shows the chemical composition of the developed steel. Based on the results detailed in Section 2, we increased the Cr and Mo and decreased the C, Si, and Mn from their amounts in the test steel to yield the developed steel.

We used TMCP (thermomechanical control processing) technology to produce this steel. **Table 5** shows the results of tensile and Charpy impact testing of the developed steel, which meet the target standards of 780 N/mm^2-class steel (KBSA630).

3.2 Weldability

We performed Y-groove weld cracking tests on the developed steel. **Tables 6** and **7**, respectively, show the welding conditions and test results. The evaluation using welding consumables of both the 780 N/mm^2 and 590 N/mm^2 classes revealed that both exhibit good weldability.

3.3 Welding joint properties

3.3.1 ESW joint properties

We evaluated the properties of a high-efficiency, high-heat input, single-pass ESW joint intended for an inner diaphragm. **Table 8** shows the welding

Table 4 Representative chemical composition of the developed steel

(%)

Steel	C	Si	Mn	P	S	Others	P_{CM}
Developed steel	0.04	0.03	1.42	0.004	0.002	Cr, Mo, etc.	0.28

Table 5 Mechanical properties of the developed steel

Thickness (mm)	YS (N/mm^2)	TS (N/mm^2)	EL (%)	YR (%)	vE_0 (J)
25	712	886	23	80	238
50	708	889	22	80	219
85	690	869	21	79	254
KBSA630C	630-750	780-930	17≦	≦85	47≦

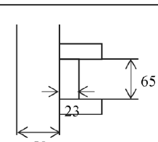
Table 6 Welding conditions for Y-groove weld cracking test

Thickness (mm)	85
Welding consumables	JIS Z3312 G59JA1UC3M1T MG-60(1.2φ) JIS Z3312 G78A2UCN4M4T MG-80(1.2φ) JIS Z3312 G78A2UCN4M4T MG-82(1.2φ)
Heat input (kJ/cm)	17.0
Preheating temperature (°C)	5
Testing atmosphere	5°C, humidity-60%

Table 7 Results of Y-groove cracking test

Welding consumables	Cracking ratio (%)	
MG-60(1.2 ϕ)	Surface	0
	Section	0
	Root	0
MG-80(1.2 ϕ)	Surface	0
	Section	0
	Root	0
MG-82(1.2 ϕ)	Surface	0
	Section	0
	Root	0

Table 8 Condition of ESW

Thickness (mm)	Groove shape	Welding consumables	Welding conditions
Skin plate: 50 mm (developed steel) Diaphragm: 65 mm (590 N/mm^2 steel)		Wire: JIS Z3353 YES602-M Flux: JIS Z3353 FES-CS	380 A-52 V Welding speed: 1.02 cm/min Heat input: 1,146 kJ/cm

conditions. The inner diaphragm was made of 590 N/mm^2-class steel.

After construction, we collected tensile test specimens from the weld joints per JIS Z 3111 A1 of the Manual for Standard Mechanical Tests of Weld Zone in Steel Building Structures.[6] Charpy impact test specimens, prepared as JIS Z 2242 V-notch specimens, were taken from the weld metal (bond -1 mm), bond, and HAZ (bond +1 mm). **Fig. 3** shows the specimen collection locations.

Fig. 4 shows the macrostructure of the joint, which confirms sufficient penetration. As **Table 9** shows, the weld metal of the ESW meets the minimum standard for a base material of 590 N/mm^2-class steel for the inner diaphragm (0.2% offset yield strength ≥ 440 N/mm^2, tensile strength ≥ 590 N/mm^2). The Charpy impact test results ranged from 84 to 193 J. This is an improvement over the conventional steel welded via the same method (Table 3) and confirms that the development target of ≥ 47 J at 0℃ is satisfied.

3.3.2 SAW joint properties

We evaluated the properties of a high-efficiency, high-heat input single-pass SAW joint intended as a corner joint. **Table 10** shows the welding consumable specifications and welding conditions. The welding consumable is the developed SAW material.[7]

Fig. 5 shows the macrostructure of the cross-section, which confirms good penetration. **Fig. 6** depicts the specimen sampling locations. In accordance with the Manual for Standard

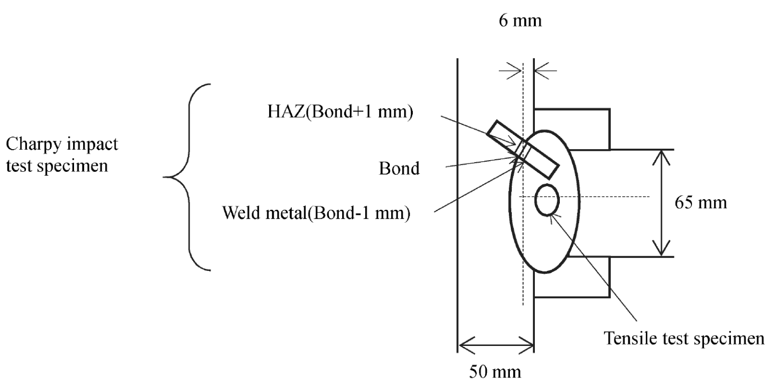


Fig. 3 Test specimen sampling position (ESW)

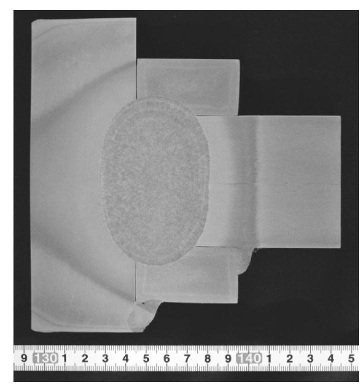
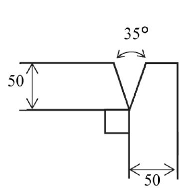


Fig. 4 Cross-sectional macrostructure (ESW)

Table 9 Mechanical properties of ESW joint

Steel	Tensile test of weld metal		Charpy impact test, vE_0		
	YS (N/mm²)	TS (N/mm²)	Weld metal (Bond-1 mm) (J)	Bond (J)	HAZ (Bond+1 mm) (J)
Developed steel	497	698	84	86	193
Conventional steel	-	-	-	15	-
590 N/mm^2 steel	440≦	590≦	47≦	47≦	47≦

Table 10 Condition of SAW

Thickness (mm)	Groove shape (mm)	Welding consumables	Welding conditions
Skin plate: 50 mm (developed steel)		Wire: JIS Z3351 YS-NM6 6.4 mmΦ Flux: JIS Z3352 SACG-I1	L: 2050A-40V T: 1500A-48V Welding speed: 20 cm/min Heat input: 462 kJ/cm

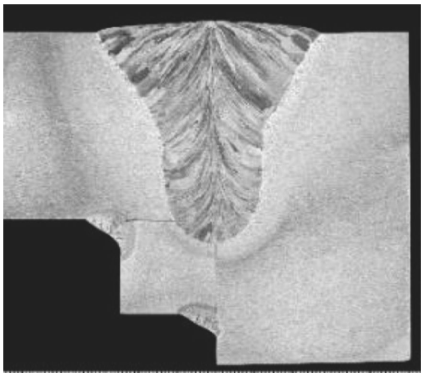


Fig. 5 Cross-sectional macrostructure (SAW)

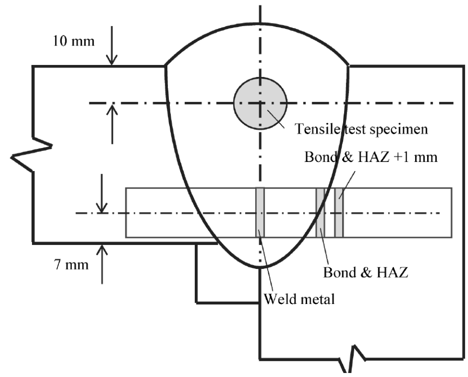


Fig. 6 Test specimen sampling position (SAW)

Table 11 Mechanical properties of SAW joint

Steel	Tensile test of weld metal		Charpy impact test, vE_0		
	YS (N/mm^2)	TS (N/mm^2)	Weld metal (J)	Bond&HAZ (J)	Bond&HAZ+1 mm (J)
Developed steel	652	829	46	55	51
Conventional steel	-	-	-	20	-

Mechanical Tests of Weld Zone in Steel Building Structures[6], we prepared tensile test specimens collected from the center of the deposited material, 10 mm from the surface of the base metal, per JIS Z 3111 A1. Charpy impact test specimens were prepared as JIS Z 2242 V-notch specimens. The designations and sample locations are “Weld metal,” which is 7 mm from the rear face of the base metal; “Bond&HAZ” on the flange side; and “Bond&HAZ+1 mm,” which is 1 mm into the HAZ as measured from “Bond&HAZ.”

Table 11 shows the mechanical properties of the SAW joint. The tensile properties of the weld metal meet the lower limits for a base material of 780 N/mm^2-class steel (0.2% offset yield strength ≥ 630 N/mm^2, tensile strength ≥ 780 N/mm^2). The Charpy impact test results ranged from 46 to 55 J, confirming an improvement over conventional steel fabricated using the same welding method (Table 3).

Conclusions

We validated that our developed steel has excellent base material properties and welding joint properties. In this way, we solved the challenge of uniting construction efficiency with performance characteristics in a way that even applies to the high-heat input, single-pass welding of 780 N/mm^2-class steel. Our next steps are to validate our developed steel in actual structures and to promote its use as a material that enhances performance and efficiency in steel building structures.

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