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Development of 590N/mm^2 Steel with Good Weldability for Building Structures

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Abstract

A low-P_{cm}-type BT-HT440 (SA440) steel for building structure has been developed. As a result of precipitation hardening with Cu and other alloying elements on the basis of B-free low-C chemical composition, the developed steel allows welding at low preheating temperature or even without preheating. While the steel is characterized by significantly improved weldability over that of conventional SA440 steels, it conforms to the specifications of the high-performance 590N/mm^2 steels (SA440B and C) for building structure accredited by the Minister of Construction, and as a consequence, its properties other than the improved weldability are the same as those of conventional SA440B and C.

1. Introduction

Heavy steel plates for building structures having tensile strength of a 400 and 490N/mm^2 class are widely used for low to high-rise buildings; the steel plates include those such as SN 400 and 490 by JIS and BT-HT325 and 355 by Nippon Steel Corporation's standard (trade name BUILTEN-HT®, accredited by the Minister of Construction (now, the Minister of Land, Infrastructure and Transport) for general building structural applications)[1)]. As for steels having tensile strength of a 590N/mm^2 class, in 1996, the 590N/mm^2-class high-performance steels SA440B and C for building structure (BT-HT440 by Nippon Steel's standard) obtained accreditation from the then Minister of Construction after evaluation by the Steel Structure Evaluation Committee of the Building Center of Japan. These steels have been applied to tubular steel columns, welded rectangular-hollow-section columns and the like for high-rise to super-high-rise buildings such as the Yokohama Landmark Tower.

Table 1 shows the main specifications of SA440. It is a standard denomination of steels for building structure having high strength of a 590N/mm^2 class and the properties necessary for securing anti-seismic performance of buildings specified through the general technical development project "High-Performance Steel" under the auspices of the then Ministry of Construction. The SA440 steels have the following characteristics:

(1) Low yield ratio (YR), small fluctuation of yield point (YP) and excellent weldability for building structural applications
(2) Specified design strength, or F-value, of 440 N/mm^2, higher than that of conventional SN 490 (F = 325 N/mm^2) or similar
(3) High strength maintained even in plates more than 40 mm in thickness.

The carbon equivalent (C_{eq}) and chemical composition for susceptibility to welding crack (P_{cm}) of SA440 (BT-HT440) steels were controlled to low levels to enhance weldability. On the other hand, their strength and contents of alloying elements were higher than those of commonly used building structure steels of a 400 to 490N/mm^2 class, and they had been actually used only for a short period of time. For this reason, much care was required to realize good quality welded joints. In view of this, in order to prevent welding cracks, the Subcommittee for Utilization of High-performance Steels of the then Kozai Club (now the Japan Iron & Steel Federation) proposed preheating temperature guidelines for welding of SA440 steels, as shown in **Table 2**, in the Recommendations for Design and Welding of SA440 Steels. However, since the occurrence of welding cracks is affected by factors such as the chemical composition and thickness

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Table 1 Specification for SA440 steel

Chemical composition (mass%)

Specification	Plate thickness (mm)	C	Si	Mn	P	S
SA440B	19 - 100	≤ 0.08	≤ 0.55	≤ 1.60	≤ 0.030	≤ 0.008
SA440C					≤ 0.020	

Carbon equivalent (C_{eq}) and weld cracking parameter (P_{cm})

Specification	Plate thickness (mm)	C_{eq} (%)	P_{cm} (%)
SA440B	≤ 40	≤ 0.44	≤ 0.28
SA440C	> 40	≤ 0.47	≤ 0.30

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

Mechanical properties

Specification	Plate thickness (mm)	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Yield ratio (%)	Elongation* (%)	Charpy absorbed energy [0°C] (J)	Reduction of area through-thickness direction (%)
SA440B	19 - 100	440 - 540	590 - 740	≤ 80	≥ 20 (26)	≥ 47	–
SA440C							≥ 25

*Test piece: JIS Z 2201 - No.4 (No.5)

Table 2 Guideline of preheating temperatures in welding for SA440 steels

Welding method	Plate thickness: t (mm)		
	19 ≤ t ≤ 50	50 < t ≤ 75	75 < t ≤ 100
SMAW	≥ 100°C	≥ 100°C	≥ 125°C
GMAW	≥ 60°C	≥ 80°C	≥ 100°C
SAW	≥ 60°C	≥ 80°C	≥ 100°C
ESW	–	–	–

of steel, the hydrogen content of deposited metal and the intensity of restraint on the joint, the preheating temperatures in Table 2 were considered to include a certain safety margin. In addition, it was deemed desirable to determine actual preheating temperature by confirmation through the Y-groove cracking test according to JIS Z 3158 employing the steel and welding consumables that would be used for the welding work in question.

In the above situation, development of a superior weldability steel in accordance with the specifications of SA440 that allows welding without preheating was awaited. In response to such demands and on the basis of optimum steel chemistry and the latest steel plate production technologies, Nippon Steel has developed a superior weldability steel of a $590N/mm^2$ class having a low value of P_{cm} for building structure. This paper presents the developed low-P_{cm}-type BT-HT440 (SA440) steel.

2. Basic Concept of Development

Nippon Steel's steel plates for welded structure having the trade name of WEL-TEN® series are widely used for applications such as bridges, penstocks, buildings, construction and industrial machinery and various kinds of storage tanks. Among these, the steel plates of WEL-TEN590 and 610 series that have tensile strength of a $590N/mm^2$ class enables welding without preheating; this has been achieved as a result of R&D activities for lowering C_{eq} and P_{cm} form the viewpoint of cold weld cracking properties. Low yield ratio is required for steels for building structure in order to improve anti-seismic properties, but from the metallurgical viewpoint, the measures to control metallographic structure to lower yield ratio have not always been considered compatible with good weldability.

Nippon Steel has developed the superior weldability type of BT-HT440 steel, in which optimum steel chemistry and plate production technologies are combined, on the basis of B-free low-C steel combined with precipitation hardening, which was the basic concept of WEL-TEN super-crack-free (SCF) steel, the latest good weldability steel.

Initially, in order to enable welding without preheating, the authors defined the target value of P_{cm} as 0.22% or less, the range in which preheating is considered unnecessary in common welding work. Decrease in C content is most effective in lowering P_{cm}, however, it is necessary not simply to decrease C content but to appropriately control it in order to realize both a strength of a $590N/mm^2$ class and a low YR (resulting from separation of two phases during an α/γ dual-phase heat treatment) that are required for building structure steels. To solve the problem, the authors made the most of findings that had been obtained through the development of 590 and $780N/mm^2$-class high-weldability steels (SCF steels) for applications other than building structure[2,3].

In addition, in order to realize a strength of a $590N/mm^2$ class with B-free low-C low-P_{cm} chemical composition, precipitation hardening was indispensable. Thus, the authors selected suitable precipitation hardening elements in consideration of low YR required for building structure steels and toughness at welding under very large heat input such as electroslag welding, which is often employed for the diaphragms joints of welded rectangular-hollow-section columns made of very thick plates. It had been known that Cu, when added by a certain amount or more, remarkably enhanced steel strength through aging precipitation treatment without significantly deteriorating weldability and the properties of welded joints; a classic example of such a steel is ASTM A710 steel[4,5] developed by INCO, U.S.A. Nippon Steel had made the most of the effect in the development of a high-strength linepipe steel[6] and the $780N/mm^2$-class high-weldability steel for bridge structure[3] that was used in the Akashi Strait Bridge. Solute Cu in α-Fe precipitates coherently in the first place in the form of bcc-Cu through aging treatment, then forms an intermediate phase of a 9R structure having twin crystals, and as a result of over-aging, precipitates in the form of ε-Cu in fcc crystals having a special crystal orientation relationship (the Kurdjumov-Sachs relationship) with the parent α-Fe phase[7]. Copper contributes to precipitation hardening of steel in each of the above precipitation stages, and the intermediate phase is considered to have the largest effect.

3. Principal Properties of Developed Steel

Based on the fundamental development concept delineated in the preceding section, the authors produced steel plates using a 300-t converter through to a plate rolling mill. **Fig. 1** shows the manufacturing processes. In order to realize various properties required for building structure steels, the latest technologies were employed such as secondary refining for degassing and precise composition control and soft reduction of slabs in continuous casting as a countermeasure against center segregation. In the plate rolling process, the conditions of reheating and rolling were appropriately controlled and an α/γ dual-phase heat treatment was applied so as to realize an excellent strength/toughness balance and a low YR.

Table 3 shows the ladle analysis results of the chemical compositions of the newly developed steels. Although the steels contained

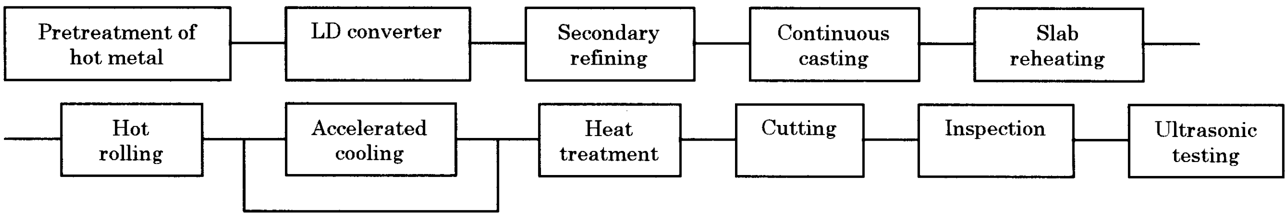


Fig. 1 Manufacturing processes

Table 3 Chemical composition of developed steels

(mass %)

Steel	Plate thickness (mm)	C	Si	Mn	P	S	Others	C_{eq}	P_{cm}
A	50	0.06	0.25	1.40	0.006	0.003	Cu,Ni,Cr,Mo,Nb,V,Ti	0.40	0.21
B	100								
C	19	0.08	0.23	1.45	0.006	0.002	Cu,Ni,Cr,Nb,V,Ti	0.37	0.21
D	28								
E	45								
F	50	0.06	0.36	1.47	0.010	0.001	Cu,Ni,Cr,Mo,Nb,V,Ti	0.41	0.22
G	80								

C_{eq}=C+Si/24+Mn/6+Ni/60+Cr/5+Mo/4+V/14

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

Table 4 Mechanical properties of developed steels

Steel	Plate thickness (mm)	Direction	Position in thickness	Tensile properties			
				Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Yield ratio (%)
A	50	Transverse	1/4-thickness	471	610	30	77
B	100			470	604	33	78
C	19			453	611	43	74
D	28			476	643	30	74
E	45			492	647	29	76
F	50			497	638	30	78
G	80			485	644	31	75

Steel	Plate thickness (mm)	Direction	Position in thickness	Charpy impact properties	
				Absorbed energy $_vE_0$ [min./av.] (J)	Fracture appearance transition temperature (°C)
A	50	Longitudinal	1/4-thickness	195 / 227	–24
B	100			247 / 250	–40
C	19			278 / 285	–85
D	28			287 / 297	–73
E	45			256 / 260	–58
F	50			266 / 292	–33
G	80			329 / 336	–50

Steel	Plate thickness (mm)	Reduction of area through-thickness direction (%)	
		Each	Av.
C	19	70, 72, 71	71
D	28	76, 76, 77	76
E	45	72, 72, 76	73
F	50	74, 73, 71	73
G	80	74, 72, 73	73

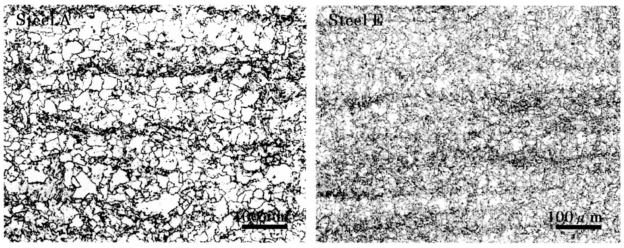


Fig. 2 Examples of optical micrographs

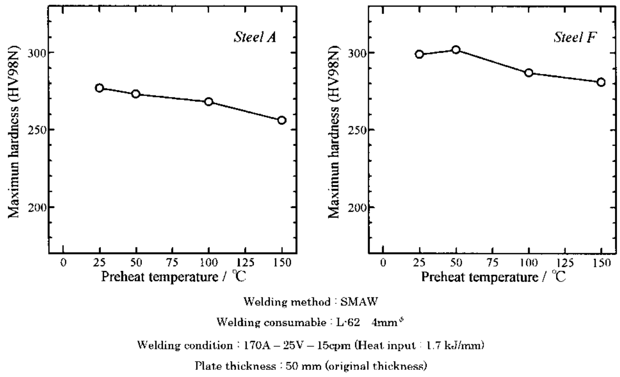


Fig. 3 Results of maximum HAZ hardness test

slightly different amounts of C and Cu depending on the final plate thickness, all of them had low P_{cm} values as a result of the low C content.

Table 4 shows the mechanical properties of the steel plates. Strength, toughness and other fundamental property items fully satisfied the specification of SA440. Generally, a precipitation hardening steel tends to have a high YR, but the YR of any of the steels was 80% or less regardless of plate thickness, satisfying the specification of SA440.

As seen with the typical examples shown in **Fig. 2**, the microstructure of the developed steels is characterized by a bainitic microstructure containing fine ferrite as a result of the α/γ dual-phase heat treatment for lowering YR.

4. Performance of Developed Steel

The authors investigated the properties of the developed steel plates for actual application focusing on weldability, which constituted the main characteristic of the steel.

4.1 Weldability

The maximum hardness test in weld heat-affected zones (HAZs) specified under JIS Z 3101 is one of the test methods for evaluating the weldability of steels; the higher the hardness at the test, the higher the susceptibility to cold weld cracking. As seen in **Fig. 3**, the maximum HAZ hardness of steels A and F, in which C contents and P_{cm} values were controlled to low levels, at the test was only slightly above HV 300 at the highest. In view of the fact that the maximum HAZ hardness of conventional SA440 steels is higher than HV 300 even at a preheating temperature of 100˚C, the weld cracking susceptibility of the developed steels, which showed low HAZ hardness values, is low.

Next, as a more direct evaluation of weld cracking susceptibility, the authors conducted Y-groove cracking test of steels A, E and F. **Table 5** shows the welding conditions and test results. In all the specimen joints welded by shielded metal arc welding (SMAW) at preheating temperature of 0˚C, cracks occurred in the weld metal; this was presumably because of high hydrogen content of the welding consumables and water condensation on the surfaces of the test pieces as a result of cooling with dry ice. Table 5 includes the test results of steel E welded by semi-automatic CO_2 gas metal arc welding (GMAW) in a constant-temperature/humidity chamber the atmosphere of which was controlled at 0˚C; no cracking was observed either in HAZs or in weld metal.

Judging from the above test results, the developed steel having a low P_{cm} value is excellent in resistance to cold weld cracking, and it can be welded without preheating in actual field construction work.

4.2 Properties of welded joints

For the purpose of evaluating the properties of welded joints of the developed steels, the authors prepared welded joint specimens under the conditions specified in **Table 6** simulating the following welding methods commonly employed for welded rectangular-hollow-section columns: electroslag (SESNET) welding for skin plate-to-diaphragm joints, submerged arc welding (SAW) for column corners, and CO_2 gas metal arc welding (GMAW) in a flat position for a column-to-beam joint.

Table 5 Results of Y-groove weld cracking test

Steel	Plate thickness (mm)	Welding method	Welding consumable	Welding condition				Preheat temperature (°C)	Cracking ratio (%)		
				Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/mm)		Surface	Root	Section
A	50	SMAW	L-62 4mm ϕ	170	25	15	1.7	0	96*	100*	98*
								25	0	0	0
								50	0	0	0
E	45	GMAW	YM-60C 1.4mm ϕ	320	35	36	1.9	0	0	0	0
								25	0	0	0
								50	0	0	0
F	50	SMAW	L-62 4mm ϕ	170	25	15	1.7	0	100*	100*	100*
								25	0	0	0
								50	0	0	0

* : Cracking in weld metal

Note) Welding was conducted under atmosphere of 20 - 22°C and 45 - 63% RH.
In the case of preheating temperature of 0°C of steel E, welding was done in a chamber the atmosphere of which was controlled to 0°C.

Table 6 Welding conditions

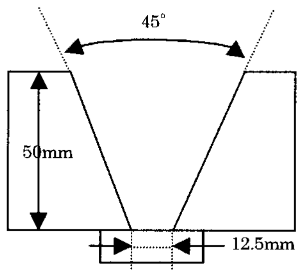
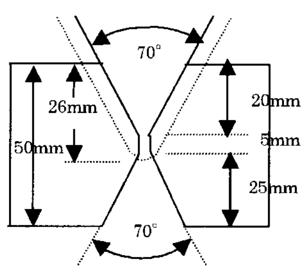
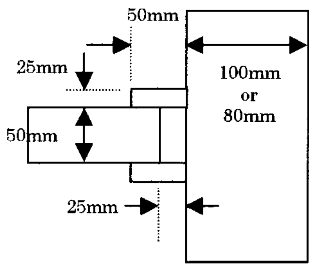
	Steel	A	A or F	A/B	F/G
	Plate thickness (mm)	50	50	50/100	50/80
	Welding position	Flat	Flat	Vertical	
	Welding method	GMAW	SAW	SESNET	
	Welding consumables	YM-60C (1.6mm ϕ)	Y-DM (4.8mm ϕ) × YF-15	YM-60A (1.6mm ϕ) × YF-15	
Welding condition	Welding current (A)	400	700	380	
	Welding voltage (V)	37	32	52	
	Welding speed (cm/min)	35	30	1.65	1.60
	Heat input (kJ/mm)	2.5	4.5	71.9	71.3
	Preheat and interpass temperature (°C)	Preheat temp. : none Interpass temp. : ≤ 150°C	Preheat temp. : none Interpass temp. : ≤ 150°C		
	Groove shape				

Table 7 shows the results of the tensile test and **Fig. 4** those of the Charpy impact test of the welded joints. No exceptional softening was observed even with the joints welded at large heat input such as SESNET welding, evidencing good joint strength. The joints welded by GMAW and SAW exhibited good toughness from weld metal to all the portions of HAZs. The toughness of the specimen joints welded by SESNET welding was substantially the same as that of conventional steels. However, there are sometimes cases in which extremely high toughness values (for example, $_vE_0 \geqq 70$ J) are required for welded joints recently, and the toughness of the SESNET joints at a fusion line (FL) and HAZ portions near an FL is rather low against such a standard. As a response to such a requirement, Nippon Steel has separately developed a high-HAZ-toughness steel applying the HTUFF technology[8]. Combination of the developed highly weldable steel with technologies such as HTUFF in consideration of specific requirement can realize high HAZ toughness even under a welding condition of large heat input.

Table 7 Tensile properties of welded joints

Steel	Welding method	Heat input (kJ/mm)	Tensil strength (N/mm^2)	Fracture position
A	GMAW	2.5	643	Base material
			644	Base material
A	SAW	4.5	647	Base material
			648	Base material
A / B	SESNET	71.9	609	Base material
			611	Base material
F	SAW	4.5	673	Base material
			675	Base material
F / G	SESNET	71.3	638	Base material
			635	Base material

Test piece : JIS Z 3121 No.1

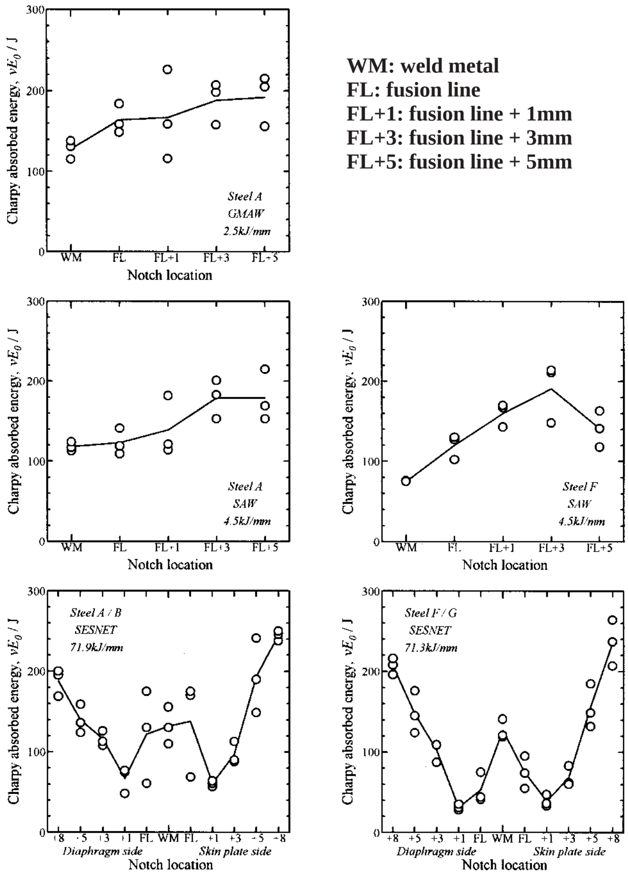


Fig. 4 Charpy impact properties of welded joints

5. Summary

A low-P_{cm}-type BT-HT440 (SA440) steel that allows welding at a low preheating temperature or without preheating has been developed on the basis of B-free low-C chemical composition in combination with precipitation hardening with alloying elements such as Cu. While the developed steel is characterized by greatly enhanced weldability over that of conventional SA440 steels, it conforms to the specification of the 590N/mm^2-class high-performance steels accredited by the then Minister of Construction for building structure applications (SA440B and C). For this reason, its properties other than weldability are no different from those of conventional SA440B and C steels, and it can be used in the same manner as these steels. In recognition of these advantages, the developed steel has been used for various buildings such as the new Traffic Bureau Building of Osaka City.

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