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780-N/mm^2 Class High Tensile Strength Steel Plates with Large-Heat-Input-Weldability and Low-Weld-Cracking-Susceptibility for Architectural Construction

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Abstract:

Two steels were developed for use as new 780-N/mm^2 high-tensile strength heavy-gage steel plates (HT780) for super highrise buildings. One (steel A) is a 1.4Ni-B steel mainly designed to ensure the desired toughness of the heat-affected zone (HAZ) of large heat input welds. The other (steel B) is a low C-1.2Cu-1.4Ni-B free steel mainly designed to lower the preheating temperature. The two new steels were produced as heavy-gage plates by the combination of controlled rolling, controlled cooling, and off-line heat treatment. They were confirmed to have the following properties: (1) The tensile properties of both steels A and B satisfy the development target values and are sufficient for HT780 steels of the low-yield ratio type, and their Charpy impact test results are also good; (2) The maximum preheating temperature at which cracking is prevented in the y-groove weld cracking test is an extremely good 75°C for steel A and 50°C for steel B. The cracking resistance of steel B, which makes use of copper precipitation strengthening in assuring the base-metal strength and reducing the maximum hardness, is especially high; (3) Both steels A and B yielded the same impact values as those of conventional 490-N/mm^2 steels when a 100-mm thick HT780 skin plate was electroslag welded to a 50-mm thick SM490 diaphragm and was Charpy impact tested at 0°C; (4) Steel B was examined by conducting the fracture and fatigue tests of cruciform weld joints of an HT780 box column with SM490 H-shape beams. It was confirmed that the weld joints have fracture performance equal or superior to that of weld joints of conventional 490-N/mm^2 steels and that steel B can be fatigue designed like the conventional 490-N/mm^2 steels.

1. Introduction

Many of the super highrise buildings constructed in recent years have large-span interior spaces. Demand for high-strength steels as principal materials of construction for these buildings is increasing. The SM570Q steel is already used in many super highrise building construction projects. These super highrise buildings are tending to continue increasing in height and span, and are a source of mounting demand for heavy-gage, high-strength steels with a tensile strength of 780 N/mm^2 (hereinafter referred to as the HT780 steels).

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The HT780 steels for super highrise buildings must have the usual mechanical properties, of course. They must also provide good weldability for cutting construction costs, excellent strength and toughness of weld joints made with large heat input by such processes as electroslag welding and submerged arc welding, and superior earthquake-resistance as represented by a low yield ratio.

Nippon Steel established an SHB (super highrise building) committee jointly with Tomoe Corporation and Nippon Steel Welding Products & Engineering. The SHB committee, chaired by Professor Morihisa Fujimori of Kanagawa University, is aimed at the development and applied research of the HT780 steels for super highrise buildings. Centering on the results achieved by the SHB committee[1-16], this paper describes the ideas behind the new HT780 steels developed by Nippon Steel for super highrise buildings and the basic service performance properties of the new HT780 steels.

2. Development Targets of New HT780 Steels

The development targets of the new HT780 steels for super highrise buildings in this research and development work are presented below. The development target values are listed in **Table 1**.

(1) The preheating temperature required to prevent low temperature cracking at welding should be made as low as possible for building construction. (The minimum preheating temperature for the conventional HT780 steels is 125°C.)

(2) The toughness of weld joints made with a very large heat input of 1,000 kJ/cm should be high (${}_vE_0 \geq 20$ J).

(3) From an earthquake-resistance point of view, the load-deformation relationship in the large-deformation region should be stabilized by reducing the yield ratio and assuring uniform elongation.

(4) Fracture strength and fatigue strength should be high for welded structural steels.

3. Development Ideas of New HT780 Steels

To accomplish the above-mentioned development targets, preliminary studies were conducted that gave consideration to the following issues.

3.1 Chemical compositions

3.1.1 Improvement in toughness of large heat input weld joints

A weld joint made with a large heat input of 1,000 kJ/cm cools slowly and does not readily develop a quenched microstructure. Since the microstructure mainly composed of upper bainite and formed from coarse prior austenite grains is extremely disadvantageous in terms of toughness, it is necessary to ensure a minimum necessary alloy content and to increase the volume fraction of the upper bainite structure.

The relationship between the hardenability index DI $\{= 0.367\sqrt{C}(1 + 0.7Si)(1 + 3.33Mn)(1 + 0.35Cu)(1 + 0.36Ni)(1 + 2.16Cr)(1 + 3.0Mo)(1 + 1.75V)(1 + 1.77Al)\}$ and the results (${}_vE_0$) of the Charpy impact test using specimens simulating the HAZ of welds made at the heat input of 1,000 kJ/cm was arranged beforehand. The results are shown in **Fig. 1**. To meet the target value of ${}_vE_0 \geq 20$ J, the DI must be at least 7 inches when its variability is taken into account.

A high nickel addition may be considered as a method for improving the toughness of the HAZ. Given the resultant cost increase, however, there is a limit to the amount of nickel that can be added.

3.1.2 Reduction in preheating temperature

Preheating for preventing low temperature cracking at welding is performed to prevent the HAZ from hardening and to reduce the diffusible hydrogen concentration. Prevention of the HAZ hardening phenomenon is especially indispensable in terms of base-metal development.

Fig. 2 shows the effect of the boron content on the hardness of the HAZ as studied by fixing the carbon equivalent C_{eq} (= C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14) of the steel at 0.48%. The effect of boron is to raise the hardness of the HAZ when its content is a mere 3 ppm. This strong hardening effect of

Table 1 Development target values of new HT780 steels for super highrise buildings

Mechanical properties						Carbon equivalent Ceq (%)
Yield strength σ_y (N/mm²)	Tensile strength σ_B (N/mm²)	Yield ratio YR (%)	Elongation EL (%)	Uniform elongation (%)	${}_vE_0$ (J)	
630≦	780-930	85≧	16≦	[8≦]	47≦	0.60≧

Note: The value enclosed in brackets is shown merely for an information.

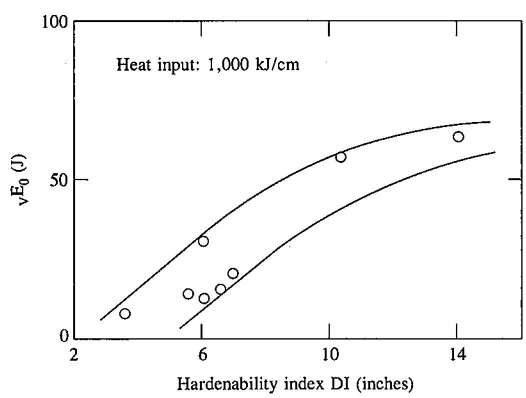

Fig. 1 Effect of hardenability index (DI) on toughness of welds at very large heat input

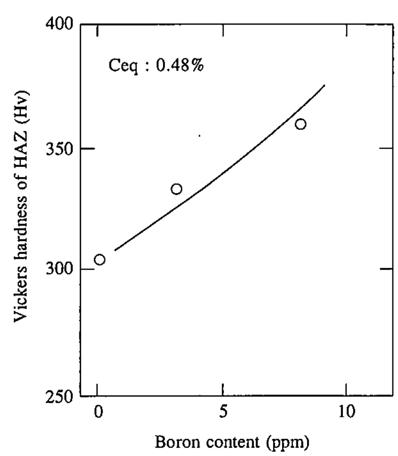

Fig. 2 Effect of boron content on weld HAZ hardness

boron favors the toughness of large heat input weld joints, but raises their low temperature cracking susceptibility. Great care must be thus exercised when adding boron.

Nippon Steel has already developed an HT780 steel of the copper precipitation strengthening type to prevent the hardening of the HAZ for use in applications other than buildings[17]. This idea is basically adopted for the new HT780 steels for super highrise buildings as well. Copper does not appreciably increase the hardenability of a steel, but greatly strengthens the steel by forming fine body-centered cubic (bcc) precipitates of high coherency with the matrix when the steel is properly heat treated.

3.2 Manufacturing process considerations

For the development of the new HT780 steels for super highrise buildings, a manufacturing process study is as indispensable as the chemical composition study discussed above. As the amount of alloying element additions is limited to emphasize weldability, it is imperative to ensure the desired strength and toughness of the new HT780 steels with a maximum thickness of about 100 mm and to make the yield ratio of the steel plates sufficiently low.

As expected, it is difficult to obtain a fully quenched microstructure to the center of steel plates with a maximum thickness of about 100 mm. This development work adopted a direct quenching method[17] that can quench the steel after thorough solution heat treatment.

Lowering the yield ratio of a steel is equivalent to lowering its yield strength while minimizing the loss of its tensile strength. The simplest method of lowering the yield strength is to introduce a soft phase (such as ferrite) that is easy to yield and work harden. To this end, the steel plate is quenched, heated to an appropriate temperature between the Ac_1 temperature and the Ac_3 temperature, and quenched to develop a dual-phase microstructure. This heat treatment is called lamellarizing and is already applied to reduce the yield ratio of Nippon Steel's existing building structural steels[18,19].

4. Basic Performance of New HT780 Steels

4.1 Chemical compositions

Based on the results discussed in Section 3, Nippon Steel developed two new 100-mm thick HT780 steels: steel A of the large heat input type and steel B of the low-preheating temperature type. Their chemical compositions are shown in **Table 2**.

4.2 Characteristics of steel A of large heat input type

The chemical composition of steel A is mainly designed to ensure the HAZ toughness of weld joints made at a large heat input. The carbon content 0.11% is the same as that of the conventional HT780 steels. Boron is added to minimize the additions of other alloying elements, such as chromium and molybdenum. The nickel content is raised to 1.4%. **Photo 1** shows the base-metal microstructure of steel A.

4.3 Characteristics of steel B of low-preheating temperature type

The chemical composition of steel B is designed to reduce the low temperature cracking susceptibility during welding. The carbon content is limited to 0.07%, and no boron is added. The nickel content is raised to 1.4%, and the precipitation-strengthening element carbon is added in a maximum amount of 1.2% to assure a sufficient strength despite low hardenability. Steel B appears to be high in carbon equivalent (C_{eq}), but is less sensitive in low temperature cracking because the HAZ hardness is low[17]. **Photo 2** shows the base-metal microstructure of steel B. A plate of steel B was controlled rolled, direct quenched, lamellarized, tempered, and overaged at 600°C for 1 h to coarsen copper precipitates. Thin-film specimens were prepared from the plate and observed under a 200-kV field-emission transmission electron microscope to examine the copper precipitates. An example is shown in **Photo 3**. The lattice image of a copper precipitate about 20 nm in diameter and nearly spherical in shape is observed as indicated by the arrows at the center of the micrograph. The size and distribution interval of the copper precipitates are approximately the same as those of copper precipitates observed in a copper precipitation-strengthened HT780 steel (1%Cu) similarly overaged at 600°C[1]. The fine copper precipitates observed here are the bcc structure that are coalesced and coarsened to ε-copper precipitates of the face-centered cubic (fcc) structure by aging, and they actually contribute to the strengthening of the steel.

Table 2 Chemical compositions of new HT780 steels

Steel	Chemical composition (wt%)										Ceq	Pcm
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B		
A	0.11	0.30	1.03	0.006	0.003	0.28	1.41	0.54	0.48	0.04	0.0015	0.56	0.28
B	0.07	0.29	1.34	0.005	0.002	1.18	1.46	0.62	0.44	0.04	-	0.58	0.29

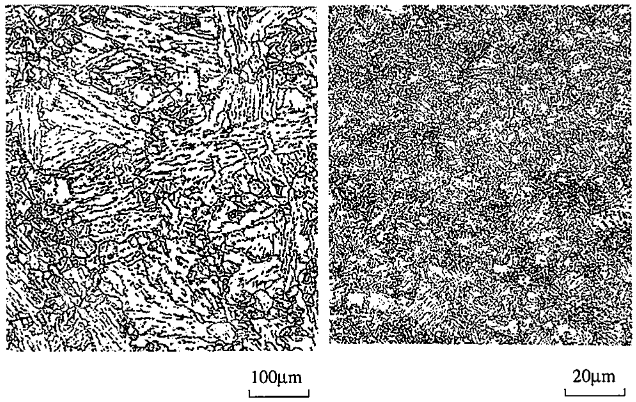

Photo 1 Microstructures of new HT780 steel (steel A)

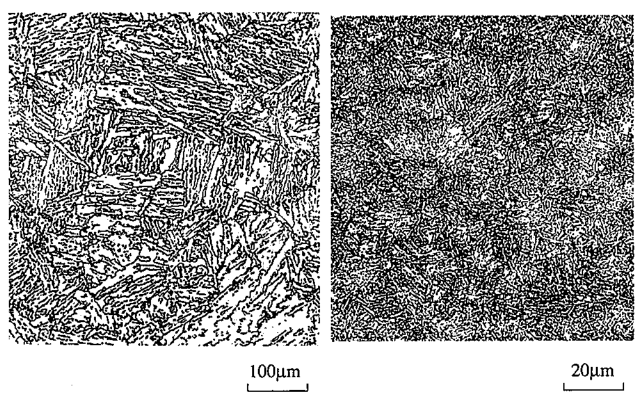

Photo 2 Microstructures of new HT780 steel (steel B)

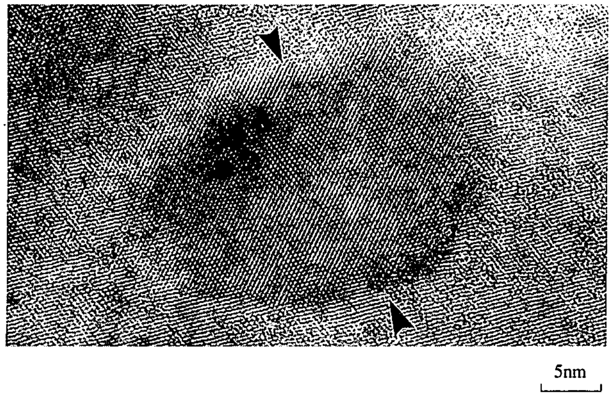

Photo 3 Field-emission transmission electron microstructure of thin-film specimen of new HT780 steel (steel B)

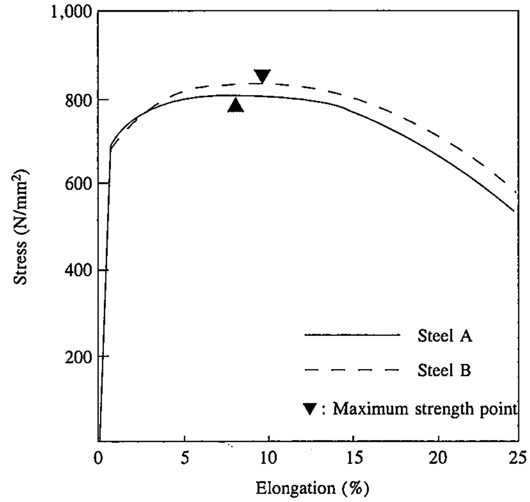

Fig. 3 Stress-elongation curves of new HT780 steels (steels A and B)

4.4 Base-metal performance of steels A and B

Table 3 lists the base-metal mechanical properties of steels A and B, and **Fig. 3** shows the tensile test stress-elongation curves of steels A and B. Both steels A and B meet the tensile properties required of HT780, and their yield ratio ranges from 78 to 82% and are satisfactory for low-yield ratio steels. The ductile-to-brittle transition temperature of steels A and B in the Charpy impact test is -60°C or lower.

4.5 Welding performance of steels A and B

Fig. 4 shows the maximum hardness test results of steels A and B. The maximum hardness is 360 to 370 Hv for steel A and 330 to 340 Hv for steel B. Steel B, designed to lower the preheating temperature, is lower in hardness.

Fig. 5 shows the weld cracking susceptibility of steels A and B as evaluated by the y-groove weld cracking test. The maximum preheating temperature required to prevent weld cracking is 75°C for steel A and 50°C for steel B. The cracking resistance of steel B designed to reduce the maximum hardness is particularly excellent.

4.6 Weld joint performance of steels A and B

Steels A and B were test welded to simulate the electroslag welding of 100-mm thick HT780 skin plates of super highrise building box columns and diaphragms of 50-mm thick SM490 steel plates. Specimens taken from the weld joints and notched in various skin plate weld locations were Charpy impact tested at 0°C. The results are shown in **Fig. 6**. The Charpy impact values are less than 20 J for the conventional HT780 steel when the notch is located at 3 or 5 mm in the HAZ, but are higher for both steels A and B. Steel A exhibits lower impact values than steel B, probably because its heat input is far larger.

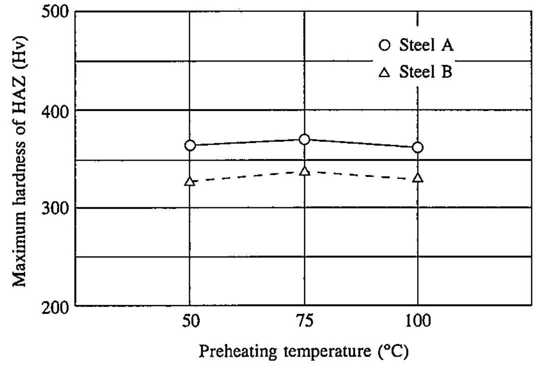

Fig. 4 Weld HAZ maximum hardness test results

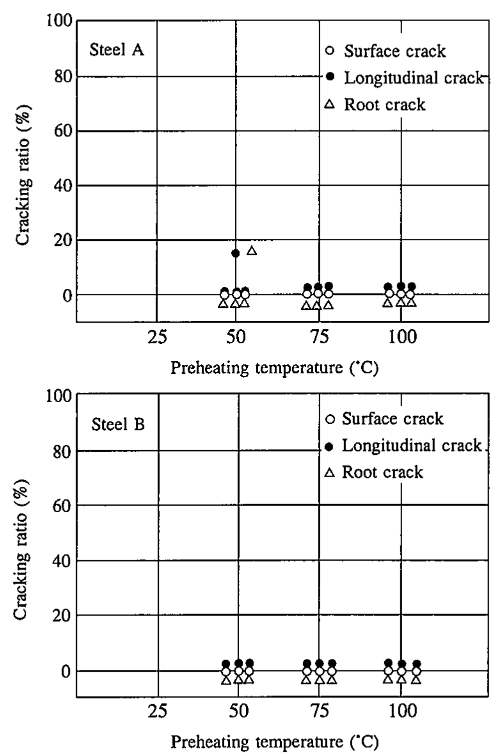

Fig. 5 Results of y-groove weld cracking test

Table 3 Base-metal mechanical properties of new HT780 steels

Steel	Tensile properties				Charpy impact properties		
	σ_y (N/mm²)	σ_B (N/mm²)	YR (%)	EL (%)	50%FATT (°C)	$_vE_0$ (J)	$_vE_{-20}$ (J)
						Average/minimum	
A	659 659	806 810	82 82	26 25	<-60	192/188	190/188
B	665 673	844 860	79 78	27 26	-77	209/208	193/190

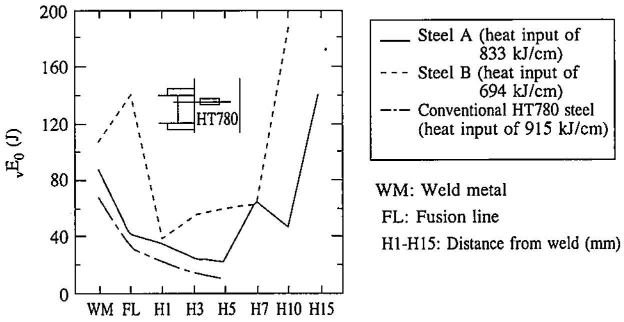

Fig. 6 Charpy impact test results of electroslag weld joints

5. Application Test as Building Structural Steel

5.1 Purpose

Cruciform weld joints of HT780 box columns and SM490H beams were fracture and fatigue tested to study the basic performance as building structural material of steel B developed mainly for lowering the preheating temperature.

5.2 Fracture strength of weld joints

Fifteen full-thickness wide specimens from weld joints in five types used in the fabrication of box columns and illustrated in **Fig. 7** were subjected to monotonic tensile test.

Specimens A and C were each prepared by carbon dioxide-shielded (MAG) welding and electroslag (ES) welding of an HT780 column flange to an SM490 beam flange and diaphragm in cruciform. Specimens A and C were used for the strength evaluation of column flange and diagram ES welds, respectively. Specimens B were prepared by the MAG welding of an HT780 column flange and an SM490 beam flange in cruciform and were used for the strength evaluation of the beam flange MAG welds. For the purpose of investigating the effect of undercuts on fracture behavior, specimens A, D-H, and D-S had a 0.15-mm wide, 2.0- or 5.0-mm deep, and 200 mm long surface notch cut at the toe of each MAG weld. The parallel section of the wide specimens was dimensioned as shown in **Fig. 8**, and their elongation was measured by taking the length of the parallel section as the gage length.

Table 4 gives the test results, and **Fig. 9** shows the stress-elongation curves of typical specimens. In the unnotched specimens A1 and A2, a brittle crack initiated at the ES weld, propagated to the ES weld bond, changed to a ductile crack in the HT780 base metal, and ended in a brittle fracture. Similar to the unnotched specimens A1 and A2, the notched specimen A3 had a brittle crack initiated at the ES weld, and the notch did not serve as fracture ori-

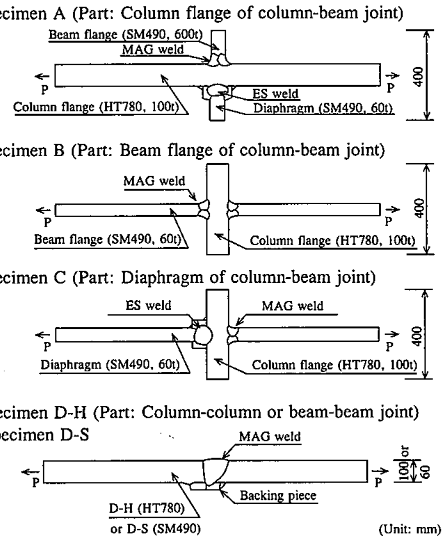

Fig. 7 Weld joints used in fracture strength test

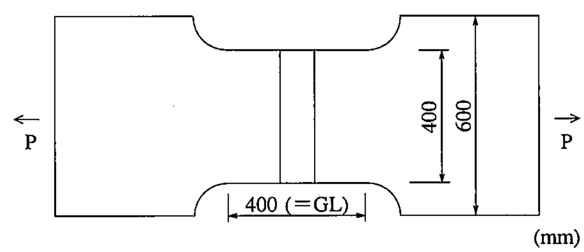

Fig. 8 Specimen used for determining fracture strength of weld joint

Table 4 Fracture strength test results of weld joints

Specimen symbol	Notch depth (mm)	σ_y (N/mm²)	σ_{max} (N/mm²)	ε_{max} (%)	Fracture mode	
A1	0	666	819	4.0	At σ_{max}	Brittle crack initiates at ES weld, propagates in weld bond, turns ductile in HT780 base metal, and ends in brittle fracture
A2	0	665	828	5.3		
A3	2.0	672	856	6.3	After σ_{max}	Ductile crack initiates at ES weld and propagates
B1	0	421	614	9.0		Ductile fracture occurs in base metal
B2	0	424	613	8.7		
B3	0	436	617	7.9		
C1	0	428	613	8.0		Crack initiates at ES weld backing piece and ends in fracture in base metal
C2	0	442	613	8.6		Brittle fracture occurs in ES weld
C3	0	436	610	8.7		Ductile fracture occurs in base metal
D-H1	2.0	687	838	6.1		Crack initiates at notch, obliquely propagates in weld metal, and ends in ductile fracture
D-H2	5.0	701	828	4.8		
D-H3	0	710	847	7.8		Crack initiates at weld toe and results in ductile fracture in base metal
D-S1	2.0	408	579	12.0		Crack initiates normal to notch and propagates in bond zone
D-S2	5.0	402	574	8.6	At σ_{max}	Large ductile crack occurs in D-S1
D-S3	0	407	585	12.3	After σ_{max}	Ductile fracture occurs in base metal

Notes: σ_y = 0.2% offset yield strength, σ_{max} = maximum stress, and ε_{max} = elongation at σ_{max}.

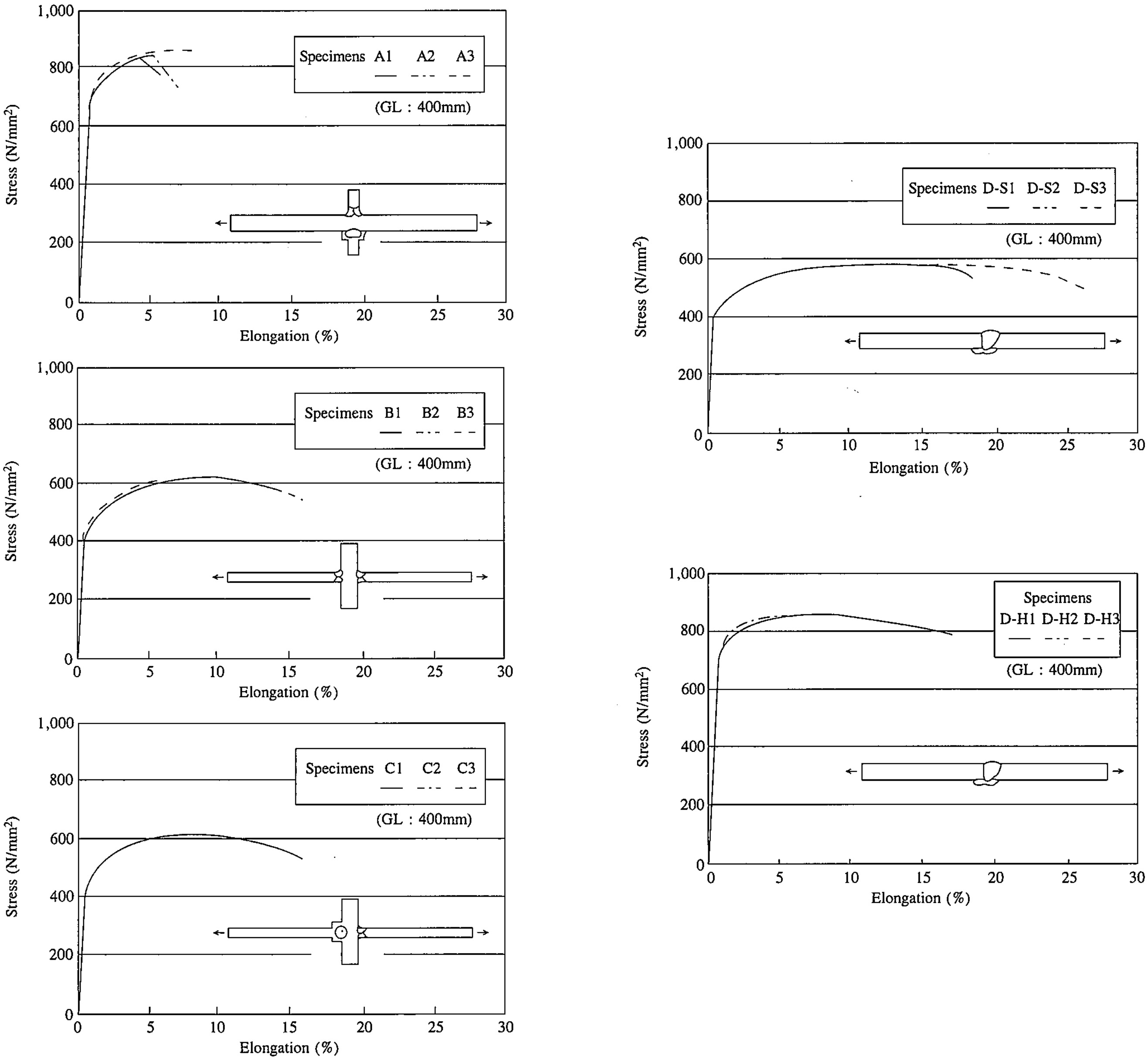

Fig. 9 Stress-elongation curves of weld joints

gin. The specimens B each ductilely failed in the SM490 base metal. The specimens C exhibited an SM490 base metal fracture, an SM490 base metal fracture in the ES weld backing piece area, and an ES weld metal fracture. With the notched specimens D-H1 and D-H2, a brittle crack initiated at the notch, obliquely propagated through the weld metal, and resulted in a ductile fracture. The unnotched specimen D-H3 suffered a ductile fracture propagating from the weld toe into the HT780 base metal. Of the specimens D-S, the notched specimens D-S1 and D-S2 had a ductile crack propagating normal to the plate surface and ending in a brittle fracture along the weld bond. The unnotched specimen D-S3 ductilely failed in the SM490 base metal.

Fig. 10 compares the fracture and yield stresses of the base metal determined in the tensile test with those of various weld joints tested using wide specimens. The fracture and yield stresses

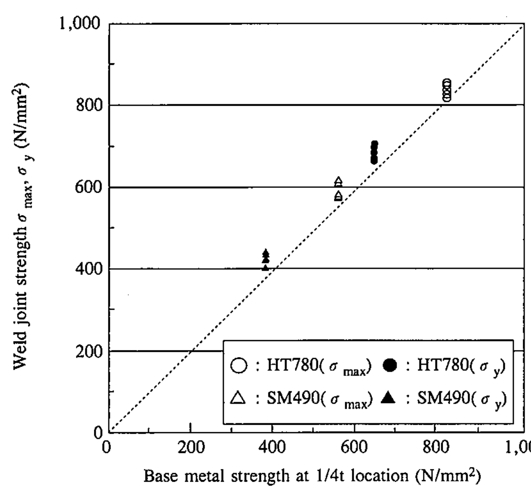

Fig. 10 Strength comparison of base metal and various weld joints

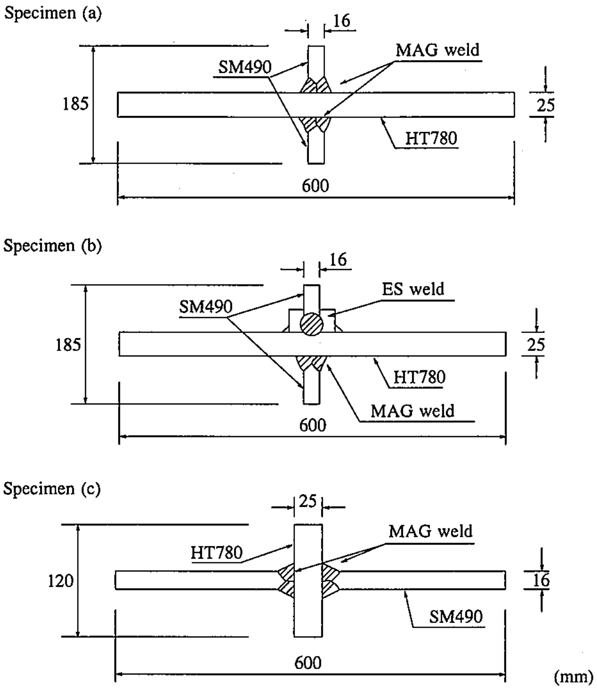

Fig. 11 Weld joint specimens used in fatigue strength test

of the weld metal are equal or superior to those of the base metal, and are high to secure the plastic deformation of the parallel section of the specimens.

5.3 Fatigue strength of welds

The three types of weld joints shown in **Fig. 11** and used in the fabrication of box columns were used as fatigue strength test specimens.

The specimen (a) is a non-load-transmitting cruciform joint made by the MAG welding of SM490 rib plates to the HT780 main plate. The specimen (b) is a joint made by the ES welding of one SM490 rib plate to the HT780 main plate, and has the ES weld backing piece connected by MAG welding. The specimen (c) is a load-transmitting cruciform joint composed of HT780 sandwiched between the SM490 main plates, with all welds being made by the MAG process. The specimens (a) and (b) were also prepared in another form with ground weld toes. The fatigue test of the specimens was conducted at the stress ratio (minimum load/maximum load) of R = 0.1 by controlling the axial force and load. The ground-joint versions of the specimens (a) were also fatigue tested at R = 0.5.

The relationship between the nominal stress range and the fatigue life of each specimen is shown in **Fig. 12**. In **Fig. 12**, the fatigue design curves D and E of the Japanese Society of Steel Construction (JSSC)[5] and the value of $\Delta\sigma$ at which the maximum stress becomes the yield stress (the dotted line and the alternate long and short dash line) are indicated.

The specimens (a) satisfy the JSSC curves E and D in the as-welded and ground joint conditions, respectively. The specimens (b) are larger in the slope of the S-N curves and positioned at the shorter end of the fatigue life range than the specimens (a), but satisfy the JSSC curve D in the ground joint condition. All of the specimens (b) initiated a crack at the weld toe between the ES weld backing piece and the main plate, and failed. The specimens (c) do not exhibit the effect of grinding as clearly as the specimens (a), but satisfy the curves E and D in the as-welded and ground joint conditions, respectively. These results confirm that the new HT780 steels in both the as-welded condition and the toe-ground condition can be fatigue designed in the same way as the conventional HT780 steels up to the yield stress level of the stress range.

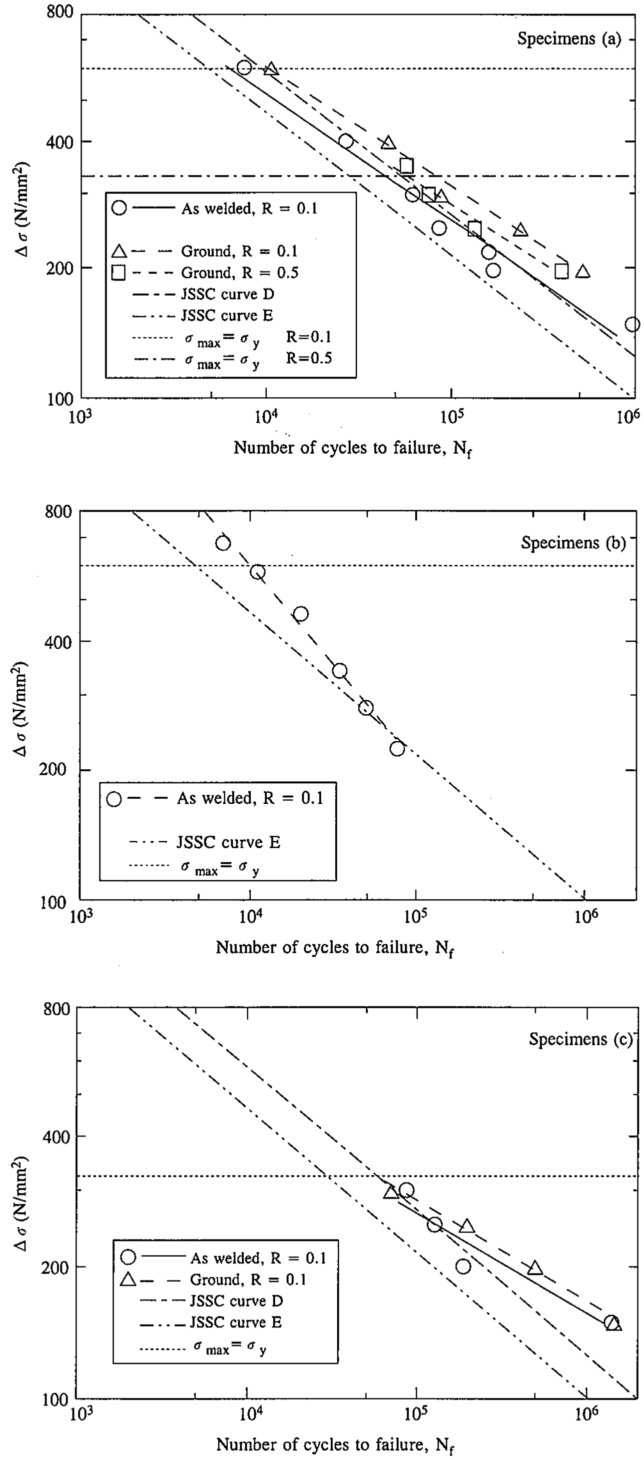

Fig. 12 S-N curves of weld joints

6. Conclusions

Two types of steels, or 1.4Ni-B type steel (steel A) and low-C-1.2Cu-1.4Ni-B free type steel (steel B), were developed as new heavy-gage HT780 steels for super highrise buildings. The two steels were produced in the form of 100-mm thick plates by the combination of controlled rolling, controlled cooling, and off-line heat treatment. They were confirmed to have the following properties.

(1) The tensile properties of both steels A and B meet the development target values. Their yield ratio of less than 85% is satisfactory for low-yield ratio steels. Their Charpy impact test properties are also good.

(2) The maximum preheating temperature required to prevent cracking in the y-groove weld cracking test is a very good 75°C and 50°C for steels A and B, respectively. The cracking resistance of steel B with copper precipitation strengthening assuring the base-metal strength and reducing the maximum hardness is especially good.

(3) In the Charpy impact test at 0°C of weld joints made to simulate the electroslag welding of 100-mm thick HT780 skin plates and 50-mm thick plate diaphragms, both steels A and B yielded impact values equivalent to those of conventional 490 N/mm^2 steels.

(4) When weld joints made in steel B and used in HT780 box column-SM490 H-shape beam cruciform joints were fracture and fatigue tested, it was confirmed that they have fracture performance equal or superior to that of the base metal and that steel B can be designed for fatigue in the same way as the conventional 490 N/mm^2 steels.

Acknowledgments

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