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Development of Copper Precipitation-hardened 780 N/mm² High-Strength Steel with Lower Preheating Temperature Characteristics

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Abstract:

To improve the working environment associated with the preheating of conventional HT780 high-strength steel, a new HT780 steel with a preheating temperature that can be lowered by applying new hardening techniques has been developed. The essential points of the development are: (1) the hardness of the heat-affected zone (HAZ) is reduced by lowering the carbon content and without adding boron; (2) the base metal is hardened through the precipitation of copper, niobium and vanadium; and (3) effective precipitation-hardening and grain refinement are accomplished by the direct quenching and tempering (DQT) process. The new HT780 steel has a maximum HAZ hardness far lower than that of conventional HT780 steel. It does not crack when welded if preheated to 50°C, and excels in cold cracking resistance. The new HT780 steel also has superior linear heating properties and unlike conventional HT780 steel it can be water cooled. Futhermore, the new HT780 steel is comparable to conventional HT780 steel in weld joint toughness and fatigue properties.

1. Introduction

In recent years, high-strength steels have been applied in an increasing number of fields to meet the requirements for larger size, higher performance, lighter structural weight. In particular, high-strength steel with a minimum tensile strength of 780 N/mm² (hereinafter referred to as HT780 steel) has been gaining expanding usage in such applications as bridges and penstocks.

It is 30 years since HT780 steel was used for the first time in welded structures. After pursuit of better weldability and higher safety during this period, its carbon equivalent has been reduced from 0.6% to 0.5%, but HT780 steel must be still preheated to a temperature above 100°C to prevent cold weld cracking. Preheating causes deterioration in the working environment,

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induces deformation from local heating, and presents other serious obstacles to welding. There is strong demand for the development of a new steel that can be welded with a lower preheating temperature.

Because conventional HT780 has a high carbon equivalent steel it must be preheated to a high temperature. This steel's tempered martensite structure produced by quenching and tempering provids it with the desired strength and toughness. As a result, its ability to be hardened limits the reduction in the alloy content and prevents the hardness of the heat-affected zone (HAZ) to be reduced to a suitable level. Given the close correlation between cold weld cracking sensitivity and hardenability, it was considered that the preheat temperature of the HT780 steel should be high.

The spread of the thermomechanical control process (TMCP) in recent years has enabled direct quenching and tempering (DQT) and has made it possible to effectively utilize the precipitation-hardening phenomenon by combining quenching from the solution-treated condition with controlled rolling. The precipitation hardening method and the hardenability securing method are considered to have different effects on the hardness of the weld produced. The use of precipitation hardening is expected to reduce the cold cracking sensitivity of the weld.

A new HT780 steel was developed, based on the ideas of lowering the preheat temperature to 50℃ or less by increasing hardenability and reducing HAZ hardness influencing elements. The desired strength of the base metal was assured by adding precipitation-hardening elements and carrying out DQT. This article describes the development ideas, manufacturing technology, quality, and service performance of the new HT780 steel.

2. Performance Targets

The development targets of the new HT780 steel are given in **Table 1**. These targets were set for bridge applications. The strength and toughness properties followed the HBS-G-3103 specifications of the Honshu-Shikoku Bridge Authority, and the weld joint toughness complied with the specified toughness value[1) studied for the construction of the Nanko Bridge. The HAZ hardness of Hv ≦ 350 and the preheating temperature of ≦ 50°C were newly established according to the study results described later.

3. Basic Study of HT780 Steel of Lower Preheating Temperature Type

3.1 Causes of and corrective measures for cold weld cracking

Fig. 1 shows the HAZ hardness distribution of conventional HT780 steel in the maximum hardness test specified in JIS Z 3101. This is known as the Testing Method of Maximum Hardness in Weld Heat-Affected Zone. The HAZ has a hardness of about Hv 370 to 380 and a hardened martensite structure due to rapid cooling during the thermal cycle. The weld continuous cooling transformation (CCT) diagram of conventional HT780 steel is shown in **Fig. 2**. A cooling rate of 20℃/s or more produces a martensite structure with a hardness of Hv 360 or more. Cold weld cracking in this steel is delayed cracking caused by hydrogen that diffuses from the weld metal and welding environment into the HAZ. It has been traditionally said that the HAZ is highly sensitive to cold cracking when it has a martensite structure and is particularly likely to crack when its hardness is Hv 350 or more[2)]. In fact, conventional HT780 steel has a high maximum HAZ hardness of Hv 360 to 440 (as shown later in **Fig. 15**) and must be preheated to 70℃ or more to prevent cracking. For a preheating temperature of 50℃ or less to be sufficient, it is necessary to lower the HAZ hardness to Hv 350 or less.

3.2 HAZ hardness governing factors

Carbon and boron that are added to improve the hardenability of the base metal are regarded as important factors that raise the HAZ hardness of conventional HT780 steel as described above. **Table 2** gives the typical chemical composition of conventional HT780 steel. It should be noted that alloying elements like nickel, chromium and molybdenum are added in appropriate amounts to

Table 1 Development targets of new HT780 steel

Plate thickness (mm)	Strength		Toughness		Weld joint toughness	Weldability	
	YP	TS	$_vE_{-40°C}$	$_vT_{rs}$	$_vE_{0°C}$	Maximum HAZ hardness Hv	Critical preheating temperature to prevent cracking
	(N/mm²)		(J)	(℃)	(J)		
≦50	≧685	780/970	≧47	≦−40	≧47	≦350	≦50℃

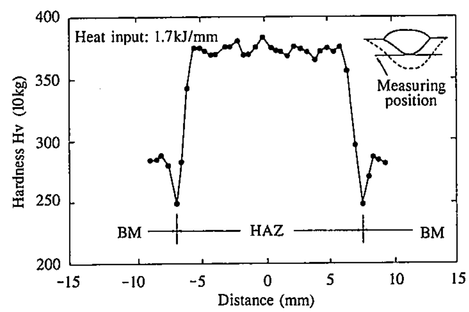


Fig. 1 Hardness distribution of conventional 780 steel in maximum HAZ hardness test

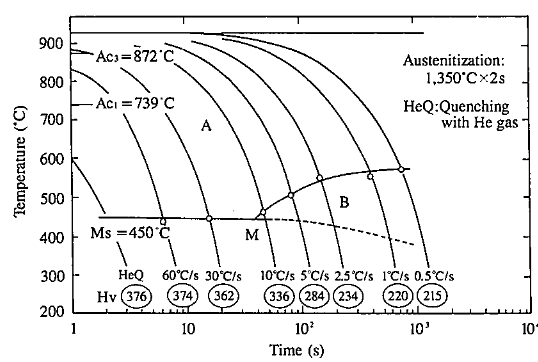


Fig. 2 Weld CCT diagram of conventional HT780 steel (chemical composition as shown in **Table 2**)

Table 2 Typical chemical composition of conventional HT780 steel (mass%)

C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B
0.12	0.24	0.88	0.004	0.001	0.17	0.98	0.48	0.40	0.04	0.0013

further improve hardenability and that carbon and boron are added in amounts of 0.12% and 0.0013%, respectively.

The hardness of martensite depends on the carbon content. **Fig. 3** shows the results of a study conducted on the effect of the carbon content on the maximum HAZ hardness of the current HT590 to HT780 steels with different carbon contents. The maximum HAZ hardness increases with increasing carbon content. In other words, the carbon content must be reduced to less than 0.07% to obtain a maximum HAZ hardness of Hv 350.

Boron was added in amounts of 0 to 12 ppm to the HT490 steel or 0.13%C silicon-manganese steel (Carbon equivalent (Ceq) = 0.42%, *P*cm = 0.23%), and the maximum HAZ hardness of the HT490 steel was investigated by the y-groove weld cracking test method specified in JIS Z 3158. The test results are shown in **Fig. 4**. It should be noted that both the maximum HAZ hardness and the preheating temperature to prevent weld cracking (hereinafter referred to as the critical preheating temperature) increase with increasing boron content and that the maximum HAZ hardness significantly rises when the boron content is only about 4 ppm. Yurioka et al.[3] and Yano et al.[4] reported the similar effect trace boron has in increasing the hardenability of the HAZ.

Trace boron was also investigated for its effect on the hardness of the HAZ in lower-carbon steels. Three 0.05%C steels

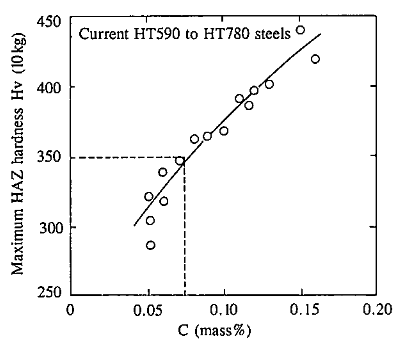


Fig. 3 Effect of carbon content on maximum HAZ hardness

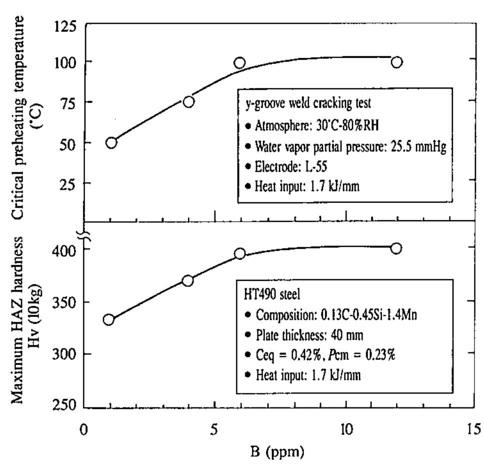


Fig. 4 Effect of boron content on maximum HAZ hardness and critical preheating temperature in y-groove weld cracking test

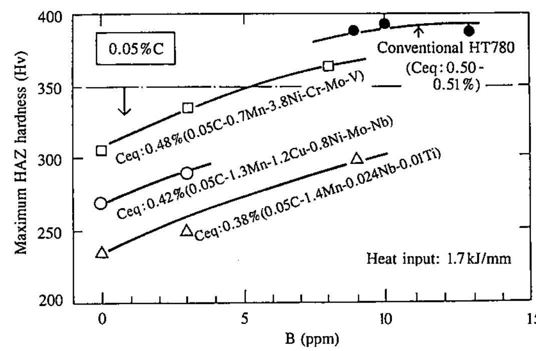


Fig. 5 Effects of boron content and carbon equivalent (Ceq) on maximum HAZ hardness of 0.05%C steels

with different carbon equivalents were produced by changing the boron content from 0 to 9 ppm and tested for the maximum HAZ hardness.

Fig. 5 shows the effects of the boron content and Ceq on the maximum HAZ hardness of 0.05%C steels. The maximum HAZ hardness increases with increasing carbon equivalent. The addition of boron increases the HAZ hardness in each steel, and boron is found to increase the HAZ hardness also when the carbon content is low. To improve the strength and HAZ toughness of the HT780 steel, it is necessary to add appropriate amounts of nickel, chromium, and molybdenum. The carbon equivalent is expected to amount to about 0.49% as a result. To lower the HAZ hardness to Hv 350 or less, it is indispensable that the boron content should be reduced to 3 ppm or less in the low-carbon steels as well.

3.3 Toughening of base metal

When the low-carbon boron-free composition is taken as the base composition to reduce the HAZ hardness as reporeted in the study results discussed above, there then arises the problem of how to secure the strength of 780 N/mm^2 steel. Attention was focused on the precipitation-hardening effect of copper. Copper easily enters in solid solution at the austenitizing temperature, finely precipitates in the subsequent tempering step, and effectively strengthens the steel. Copper precipitation-hardening steels have been studied extensively. A representative example is A710 steel developed by INCO of the United States[5,6]. It has a tensile strength of only about 590 N/mm^2, but features good weld cracking resistance. Tomita et al.[7] investigated the effects of various alloying elements on the strength and HAZ toughness of steels with a yield point of 490 N/mm^2 and clarified that copper is an effective strengthening element that does not reduce the HAZ toughness in the welding heat input range of 4.0 to 10.0 kJ/mm. Gordine[8] compared 1%Cu and copper-free linepipe steels in the CTS cold weld cracking test and reported that the 1%Cu steel has higher cold weld cracking resistance than the copper-free steel.

In this way, copper contributes to strengthening by precipitation hardening after tempering without increasing hardenability, and does not decrease the HAZ toughness and cold cracking resistance.

To obtain the tensile strength of 780 N/mm^2, copper was added in amounts of 0 to 1.5% to the 0.05%C, 1.0%Ni, boron-free steel. The effect of copper in increasing the strength of the steel after DQT, and the effect of copper added in combination with niobium and vanadium on the tempering temperature dependence of the copper precipitation-hardened steel were investigated. To establish the manufacturing technology to obtain the desired strength and toughness of the base metal, thermomechanical controlled process (TMCP) technology involving controlled rolling and direct quenching and tempering (DQT) was studied in comparison with the reheating, quenching and tempering (RQT) process for its effect on 0.05%C-1.0%Ni-boron-free steel.

Fig. 6 shows the effect of the copper content on the strength of 0.05%C-1.0%Ni-boron-free steel for 550℃ tempering after direct quenching. Copper raises the strength of the steel by about 100 N/mm² when added in an amount of 1%, but does not raise the strength as much when added in an amount of 1.5%. To obtain the toughness of conventional HT780 steel, it is desirable that the tempering temperature should be higher than 550℃. **Fig. 7** shows the effect of the tempering temperature on the strength of the copper precipitation-hardened steel. At a temperature above 550℃, the strength of the steel is markedly decreased by tempering when only copper is added. When copper is added together with niobium and vanadium, temper softening is alleviated, and the desired strength can be obtained despite tempering at 600℃. Niobium and vanadium are effective elements for strengthening without raising hardenability. A transmission electron micrograph of the copper precipitation-hardened steel tempered at 600℃ is shown in **Photo 1**. Extremely fine ε-Cu particles, measuring 100 Å or less in size, are observed.

Now, we shall consider the toughness of the copper precipitation-hardened steel. **Fig. 8** shows the effects of various process conditions on the strength and toughness of the copper precipitation-hardened steel. DQT in the TMCP process provides a better strength-toughness balance than RQT. In other words, DQT yields higher strength and toughness than RQT. Since upper bainite is formed in the hardened structure of the copper precipitation-hardened steel, the austenite grains will have to be refined to improve the toughness of the steel. As shown in **Fig. 9** and **Photo 2**, RQT results in limited refinement of the austenite grains, while DQT can accomplish the grain refinement of austenite by controlled rolling. The combination of controlled rolling and DQT can effectively achieve both the precipitation hardening and grain refinement of the copper precipitation-hardened steel and impart substained strength and toughness to the steel.

3.4 Effects of nickel content and carbon content reduction on weld toughness

The hardenability of the copper precipitation-hardened steel is

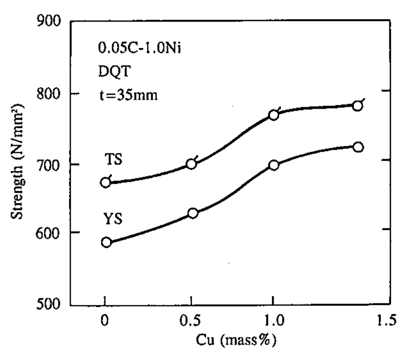


Fig. 6 Effect of copper content on strength of 0.05%C-1.0%Ni steel after tempering

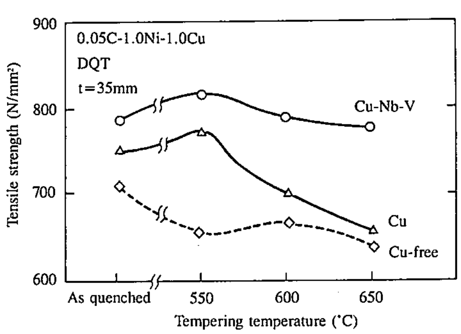


Fig. 7 Effect of tempering temperature on strength of 0.05%C-1.0%Ni-Cu steels

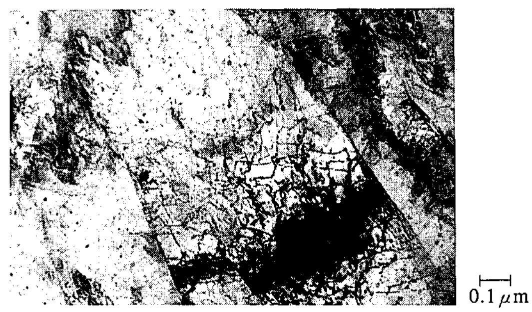


Photo 1 Transmission electron micrograph of 0.05%C-1.0%Ni-Cu-Nb-V steel tempered at 600℃

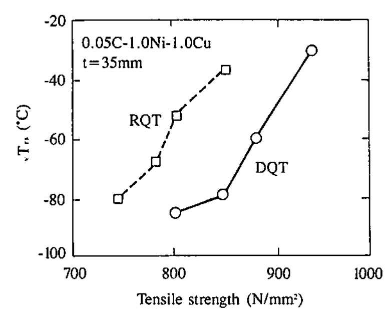


Fig. 8 Effects of process conditions on strength and toughness of 0.05%C-1.0%Ni-1.0%Cu steel

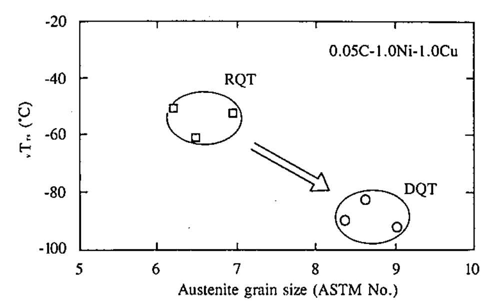
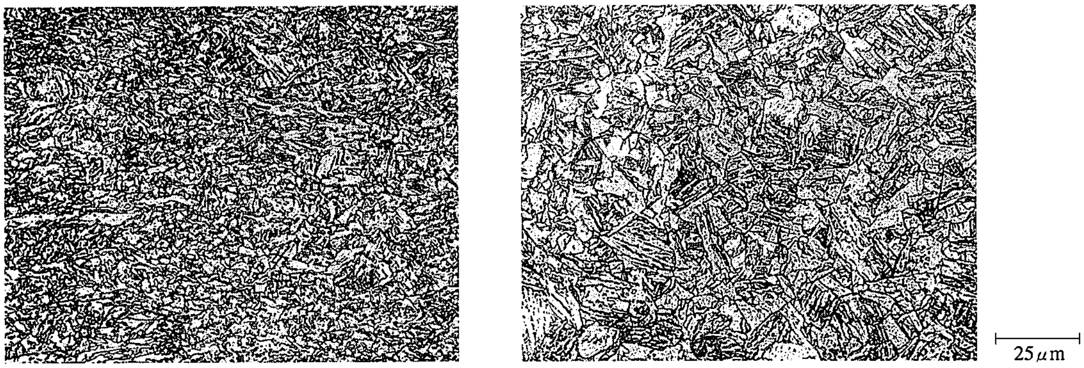


Fig. 9 Effects of process conditions on toughness and austenite grain size of 0.05%C-1.0%Ni-1.0%Cu steel



(a) DQ (b) RQ

Photo 2 Microstructures of direct-quenched (DQ) and reheat-quenched (RQ) 0.05%C-1.0%Ni-1.0%Cu steels

controlled at a low level as described in the previous section. This increases the likelihood of the HAZ structure becoming upper bainite. Nickel is known to raise the HAZ toughness of the steel. The effect of the nickel content on the HAZ toughness of low-carbon and boron-free copper precipitation-hardened steel was investigated by the weld thermal cycle simulation test. The results are shown in **Fig. 10**. The HAZ toughness improves with increasing nickel content. This is attributable to the increase in volume fraction of lower bainite. To obtain the desired HAZ toughness, it is necessary to add nickel in an amount of 0.7% or more.

The effects of single as well double thermal cycles were studied for multiple-layer welding. The results are given in **Fig. 11**. The double thermal cycle temperature of 800℃ lowers the HAZ toughness of both new and conventional HT780 steels compared with the single thermal cycle. The double thermal cycle temperature of 1000℃ raises the HAZ toughness of the new HT780 steel, but lowers the HAZ toughness of conventional HT780 steel. The 1000℃ structure results in upper bainite for both new and conventional HT780 steels. As shown in **Photo 3**, the martensite-austenite (M-A) constituent that forms in upper bainite and hampers the HAZ toughness exists as lumps in conventional HT780 steel. The volume fraction of the M-A constituent is smaller in the new HT780 steel. This means that the loss of HAZ toughness is alleviated by lowering the carbon content. Conventional HT780 steel declines in the HAZ toughness at 1000°C, because rapid heating to just above the Ac_3 transformation temperature reduces the amount of grain-boundary segregated boron, lowers the hardenability of the steel, and encourages

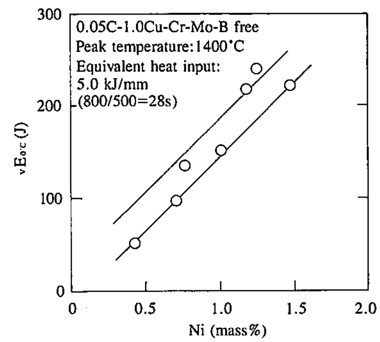


Fig. 10 Effect of nickel content on HAZ toughness

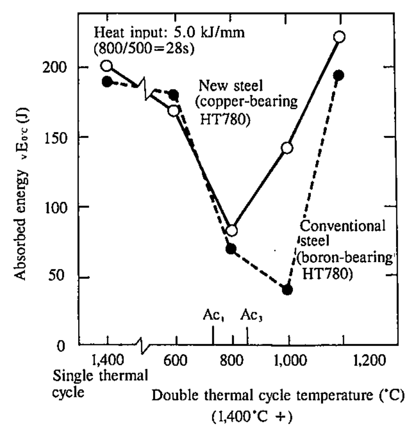
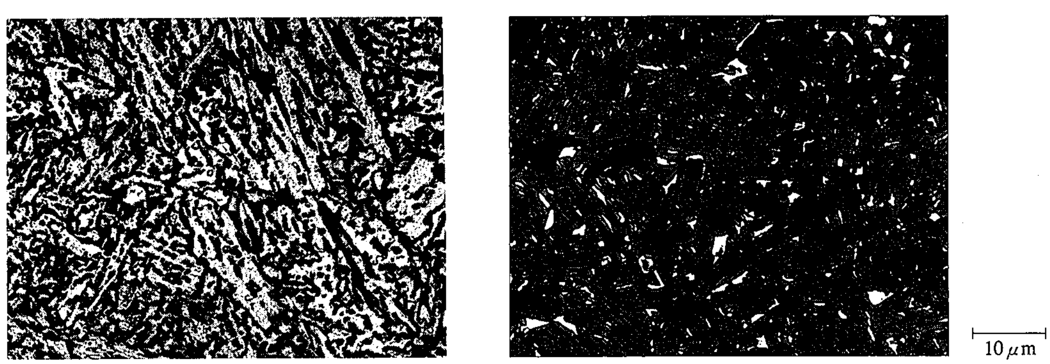


Fig. 11 Effect of double thermal cycle temperature on HAZ toughness



(a) New HT780 (b) Conventional HT780

Photo 3 M-A constituent structure of simulated HAZ of HT780 steel when exposed to double thermal cycles of 1400℃ and 1000℃ (etched in Lepera's reagent)

Table 3 Technical concepts of new HT780 steel

Target	Concept		Means
Improvement in weld cracking resistance	Reduction in HAZ hardenability Hv ≦ 350 Critical preheating temperature to prevent cracking ≦ 50℃		Reduction in C content (≦ 0.07%) B-free
Securement of strength	Precipitation hardening Maximum utilization of secondary hardening by tempering		Addition of Cu together with Nb and V TMCP technology (CR-DQT)
Securement of toughness	Base metal	Fine-grained bainite structure	Nb addition + TMCP
	Weld	Formation of lower bainite structure Heat input ≦ 5.0 kJ/mm Reduction in volume fraction of M-A constituent	Ni addition Reduction in C content

the formation of upper bainite[9].

Based on the basic study results discussed above, the technical concepts of the new HT780 steel may be summarized as shown in **Table 3**.

4. Properties of Copper Precipitation-Hardened HT780 Steel with Lower Preheating Temperature Characteristics

Based on the study results described in the preceding chapter, the optimum composition and manufacturing process for steel plates were determined, and new 38-mm thick HT780 steel plates were made on a commercial production line and their properties investigated.

4.1 Chemical composition and base-metal performance

The chemical compositions of two new HT780 steels are given in **Table 4**, and the tension and impact test results of the new HT780 steel plates produced by the process composed of controlled rolling and DQT are given in **Table 5**. The steels A and B are both low-carbon, boron-free, 1%Cu-1%Ni steels. Steel B is more adaptable for expansion of the available plate thickness range. The strength and toughness of the base metal are small in anisotropy and fully meet the specified property requirements. The microstructure of steel B is shown in **Photo 4**. It exhibits a fine bainite structure.

4.2 Weldability

The HAZ hardenability and cold cracking tendency of the new HT780 steels were investigated by the maximum HAZ hardness and y-groove weld cracking test methods.

Fig. 12 shows the maximum HAZ hardness test results of the new HT780 steels. The maximum HAZ hardness at a temperature of 20℃ is Hv 318 for steel A, Hv 322 for steel B, and much lower for conventional HT780 steel. The weld CCT diagram of steel B is shown in **Fig. 13**. Compared with the weld CCT

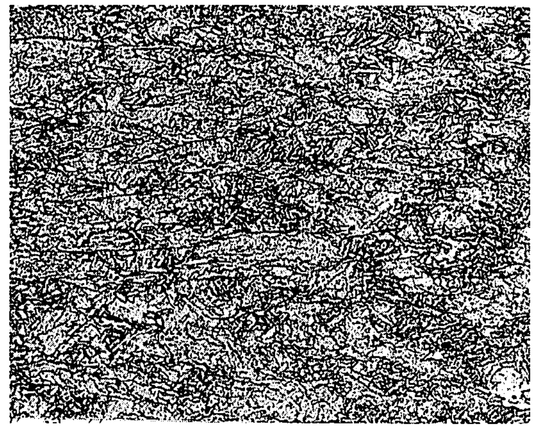


Photo 4 Microstructure of new HT780 steel B

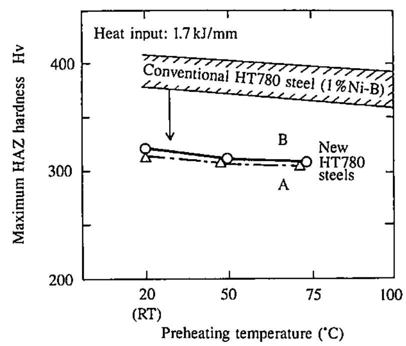


Fig. 12 Maximum HAZ hardness test results of new HT780 steels

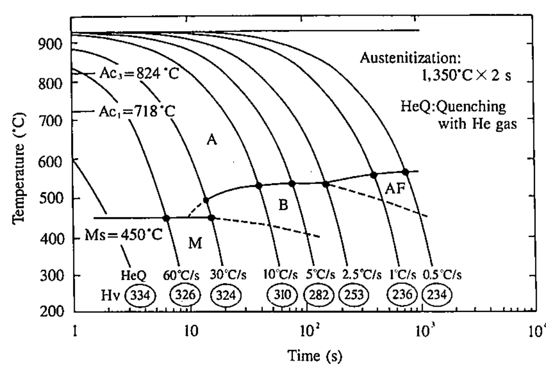


Fig. 13 Weld CCT diagram of new HT780 steel B

Table 5 Mechanical properties of new HT780 steels

Plate thickness (mm)	Steel	Direction*1	Tension test YS (N/mm²)	Tension test TS (N/mm²)	Tension test El (%)	Impact test $_vT_{rs}$ (℃)	Impact test $_vE_{-40}$ (J)
38	A	L	753	825	26	−68	204
		T	755	825	27	−66	191
	B	L	784	837	25	<−80	208
		T	804	856	25	<−80	187

*1 L:Longitudinal direction, T:Transverse direction
Tension test specimens: JIS Z 2201, No. 4
Impact test specimens: JIS Z 2202, No. 4

Table 4 Chemical compositions of new HT780 steels (mass%)

Steel	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	Ceq*1)	Pcm*2)
A	0.05	0.29	1.34	0.005	0.002	1.05	0.94	—	0.47	0.009	0.047	0.43	0.23
B	0.06	0.26	1.34	0.007	0.002	0.97	1.03	0.46	0.31	0.009	0.041	0.49	0.25

*1) Ceq=C+Mn/6+Si/24+Ni/40+Cr/5+Mo/4+V/14(%)
*2) Pcm=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B(%)

diagram of conventional HT780 steel shown in **Fig. 2**, the lower carbon content reduces the hardness of martensite, even at a cooling rate of 20℃/s or more, and the bainite structure appears at the low end of the time range.

Fig. 14 shows the y-groove weld cracking test results of the new HT780 steels A and B. Neither of steel A nor B cracked when preheated to 50℃ then welded with HT780 electrodes (E11016-G) in an atmosphere of 20℃ and 60%RH. Cracking in the weld metal occurred at 20℃. This suggests that the preheating temperature required to prevent the cracking of the HAZ is 20℃. In **Fig. 15**, the new and conventional HT780 steels are compared in terms of the relationship between the critical preheating temperature and maximum HAZ hardness. The maximum HAZ hardness of the new HT780 steels is Hv 350, and the critical preheating temperature is put at 50℃ accordingly. The cold cracking sensitivity of the new HT780 steels was experimentally studied further and evaluated by the traditional weld cracking-sensitive composition indexes of *P*cm and CEN. This will be described in Chapter 5.

4.3 HAZ softening

To investigate the HAZ softening of weld joints, bead-on-plate welds were made by the submerged arc welding (SAW) process, and the hardness distribution of the weld at 1 mm below the surface was measured. The results are shown in **Fig. 16**. Compared with conventional HT780 steel, the new HT780 steel B has lower maximum HAZ hardness, greater hardness of the HAZ softened zone, and less HAZ softening.

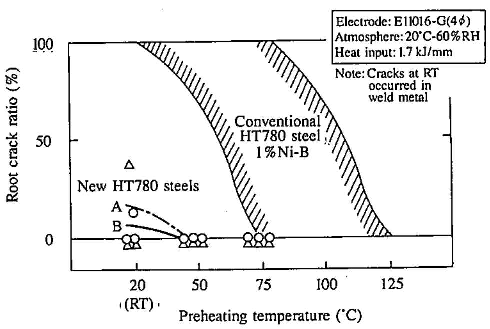


Fig. 14 y-groove cracking test results of new HT780 steels

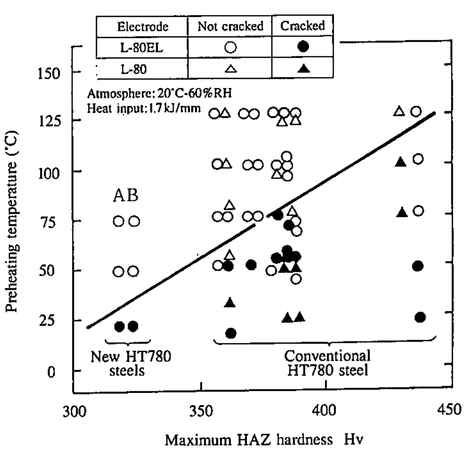


Fig. 15 Relationship between critical preheating temperature and maximum HAZ hardness of HT780 steels

4.4 Formability (Linear heating property)

Steel plates are linearly heated to correct their shape during fabrication. The resultant change in quality becomes a problem. The tension and impact test results of linear-heated specimens of the new HT780 steel B are shown in comparison with conventional HT780 steel in **Figs. 17** and **18**, respectively. The new HT780 steel B can be provided with substaintial strength and toughness when heated to a maximum of 880℃ and then cooled

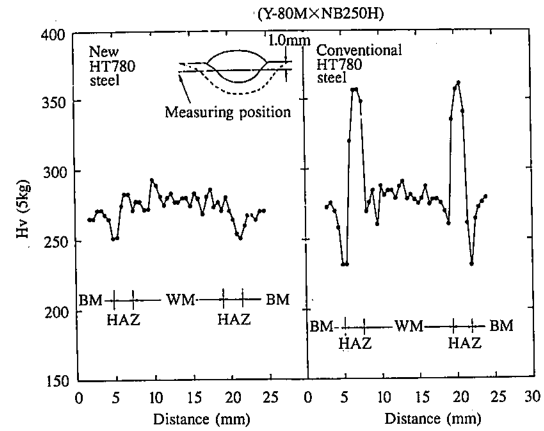


Fig. 16 Hardness distribution of SAW bead-on-plate welds at 1 mm below surface

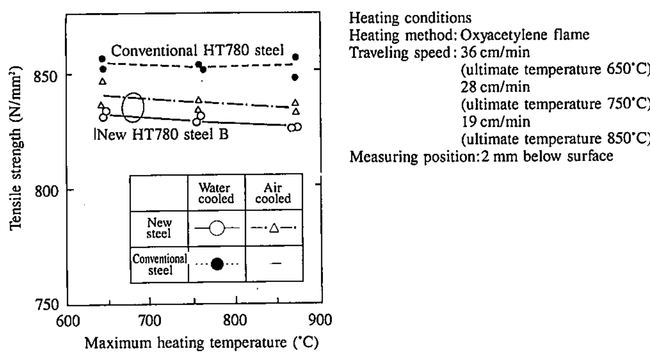


Fig. 17 Tension test results of linear-heated specimens of HT780 steels

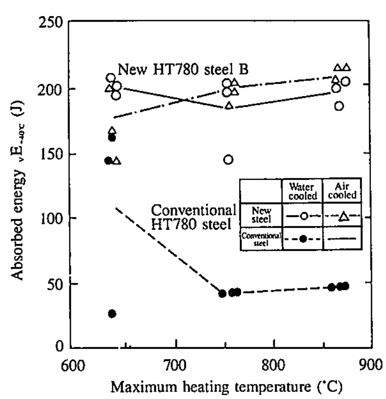


Fig. 18 Impact test results of linear-heated specimens

in water or air. Conventional HT780 steel declines in toughness when cooled in water. This is probably because as the maximum heating temperature approaches the Ac_3 transformation temperature, the heated part is hardened by water cooling and forms into martensite structure.

4.5 Hot weld cracking

Since the new HT780 steels have copper added, they were investigated for hot weld cracking. A hot cracking test specimen is illustrated in **Fig. 19**. It is cut with V-grooves[10]. The specimen was submerged arc welded in a single pass by changing the heat input from 1.94 to 5.28 kJ/mm. **Table 6** gives the V-groove hot cracking test results of the new HT780 steel B. The steel tested well with no cracks detected under any welding conditions.

4.6 Weld joint performance

The new HT780 steels were evaluated for weld joint performance. Submerged arc welded joint welding conditions are given in **Table 8**. Welding materials for the new HT780 steels are not especially adjusted for the different compositions and are the same as those used for conventional HT780 steel. Butt joints and corner joints were welded by using the welding materials for conventional HT780 steel (designated "equal quality" in **Table 7**). Some corner joints were welded by using welding materials for the HT590 steel (soft quality) to prevent cold cracking of the weld metal. The heat input was 4.55 kJ/mm for the butt joints and 4.8 kJ/mm for the corner joints. The SAW butt joint tension test results of the new HT780 steel B are given in **Table 8**. The long-gage tensile strength of the steel is much higher than the specified value of 780 N/mm². The impact test results of the butt joints and corner joints of the new HT780 steel B are shown in **Figs. 20** and **21**, respectively. The absorbed energy of the butt joints is higher than the target value of ${}_vE_{0^\circ C} \geqq 47$ J, and is equal to or better than that of conventional HT780 steel (of the chemical composition given in **Table 2**). The corner joints have a notch machined on the vertical side of the single-bevel groove and in the thickness direction (Z direction), but are quite tough.

4.7 Weld fracture performance

The new HT780 steels were investigated for fracture toughness to evaluate their safety when used to fabricate welded structures. **Fig. 22** shows the shape of a surface-notched and angular-distorted wide-plate tension test specimen used for studying the fracture toughness of actual welds. The specimen has a large angular distortion and a large notch, and each tip of the surface notch is located within the weld bond. The welding conditions are

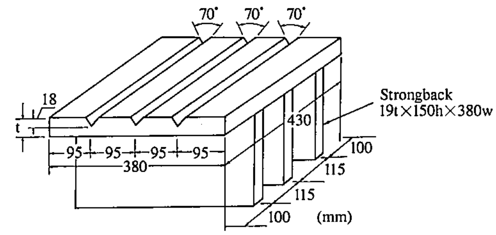


Fig. 19 Shape of hot cracking test specimen

Table 6 Hot cracking test results of new HT780 steel B

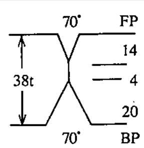
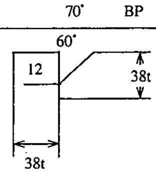
No.	Current (A)	Voltage (V)	Speed (m/min)	Heat input (kJ/mm)	Crack ratio (%)
1	600	27	30	3.24	0
2	700	30	30	4.20	0
3	800	33	30	5.28	0
4	600	27	40	2.43	0
5	700	30	40	3.15	0
6	800	33	40	3.96	0
7	600	27	50	1.94	0
8	700	30	50	2.52	0
9	800	33	50	3.17	0

Welding materials: F11A10-EG-M3 (Y-80M×NB-250H)
Preheating temperature: 100°C
Crack ratio was determined by radiography at 48 hours after end of welding.
Crack ratio =(Total crack length/Weld bead length)×100 (%)

Table 8 Tension test results of SAW butt joints

Test method	Yield strength (N/mm²)	Tensile strength (N/mm²)	Elongation (%)	Fracture location	Specimen shape
Long gage	750 755	823 825	19 16	HAZ HAZ	JIS Z 2201, No. 1A
Short gage	– –	827 829	– –	HAZ HAZ	JIS Z 3121, No. 1
Weld metal	706	886	22	–	JIS Z 3111, (12.5mm ϕ)

Table 7 Welding conditions for SAW butt and corner joints

Plate thickness (mm)	Welding process	Groove shape (mm)	Welding materials	Preheating and interpass temperatures (°C)	Welding conditions			
					Current (A)	Voltage (A)	Speed (cm/min)	Heat input (kJ/mm)
38	Butt joint SAW (Equal quality)		Y-80M × NB250H	Preheating:50°C Interpass: ≦150°C	650	35	30	4.55
38	Corner joint SAW (Equal quality)		Y-80M × NB250H	Preheating:50°C Interpass: ≦150°C	Tandem L:650 T:600	29 36	50 50	4.85

L:Leading electrode T:Travelling electrode the same as given for the butt joints in **Table 6**. **Fig. 23** shows the surface-notched and angular-distorted wide-plate tension test results of the new and conventional HT780 steels. The K_c value required of weld joints in bridges was calculated from the results of the study conducted by the Steel Product Group of the Superstructure Research Subcommittee for Honshu-Shikoku Bridges, Japan Society of Civil Engineers[1]. The calculated results are given in **Table 9**. The K_c value is 146 $MN/m^{1.5}$ (472 $kgf/mm^{1.5}$) for the lowest operating temperature of −10°C and 174 $MN/m^{1.5}$ (561 $kgf/mm^{1.5}$ when the seismic load is taken into account) for the operating temperature of 0°C. The K_c value of the new HT780 steel is high compared with the calculated values and is equal to or higher than that of conventional HT780 steel.

4.8 Fatigue life

The fatigue life of the base metal and weld metal was investigated. The shapes of fatigue test specimens for the base metal and weld metal are shown in **Figs. 24** and **25**, respectively. The base-metal fatigue test specimens were as rolled or machine finished, and the weld-metal fatigue test specimens were as welded (toes left intact). These two types of specimens were fatigue tested under pulsating tension. The welding condition are given in **Table 10**. The base-metal fatigue test results are shown in **Fig. 26**. The fatigue life of the new HT780 steel B is very long compared with the design curves of the Japan Society of Steel Construction (JSSC). The weld joint fatigue test results of the new HT780 steel B are shown in **Fig. 27**. The new HT780 steel B satisfies the JSSC design curves and has a fatigue life comparable to that of conventional HT780 steel[11].

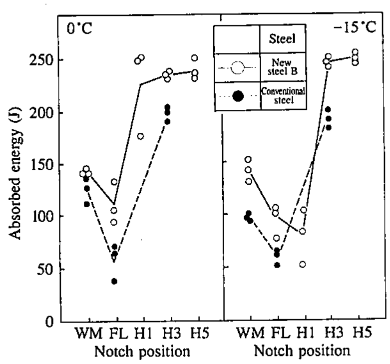


Fig. 20 Impact test results of SAW butt joints

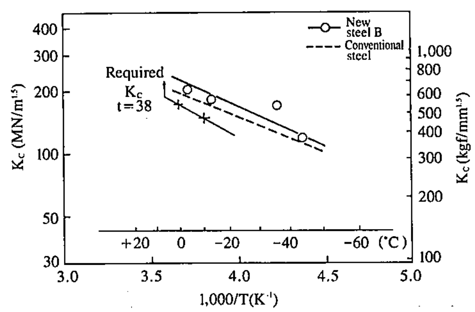


Fig. 23 Tension test results of surface-notched and angular-distorted wide-plate specimens

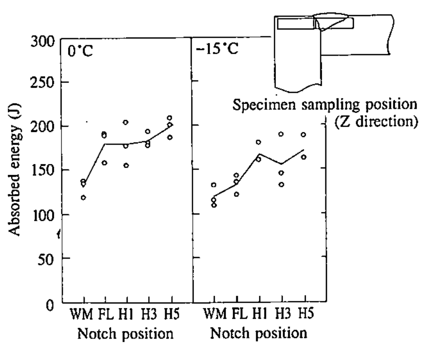


Fig. 21 Impact test results of SAW corner joints of new HT780 steel B

Table 9 K_c value required of HT780 steel weld joints

Temperature (°C)	Plate thickness (mm)	Yield stress (N/mm^2)	Applied stress (N/mm^2)	Notch depth (mm)	Notch half-length (mm)	Required K_c ($MN/m^{1.5}$)
0	38	686	676	8	40	174
−10	38	686	500	8	40	146

Required K_c value (total) is $K_c + K_{RS}$,
where K_{RS} is assumed to be a residual stress of 62 $MN/m^{1.5}$.

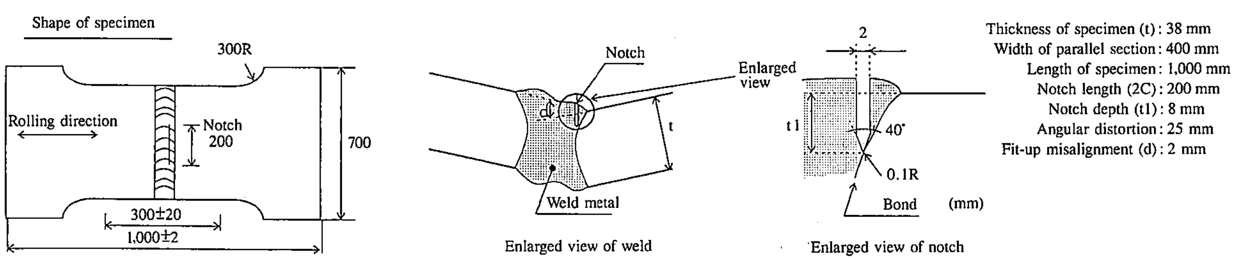


Fig. 22 Shape of surface-notched and angular-distorted wide-plate tension test specimen

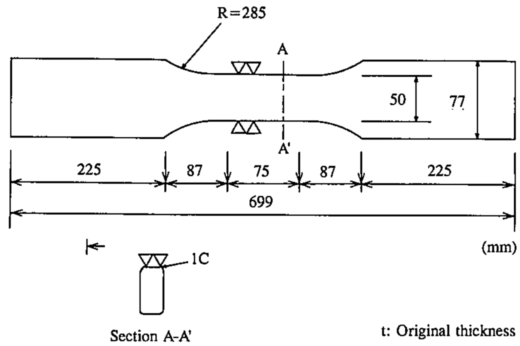


Fig. 24 Shape and dimensions of base-metal fatigue test specimen

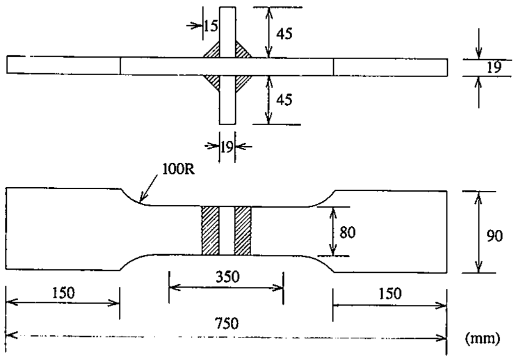


Fig. 25 Shape and dimensions of cruciform fillet weld joint

Table 10 Welding conditions for cruciform fillet weld joints

Welding process	Welding material	Preheating temperature (℃)	Welding conditions			
			Current (A)	Voltage (V)	Speed (cm/min)	Heat input (kJ/mm)
CO2	YM-80C	50	300	30	30	1.8

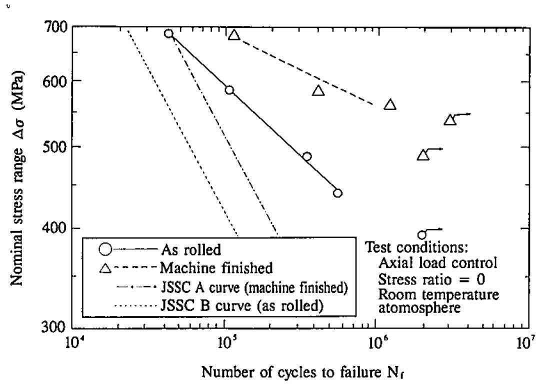


Fig. 26 Comparison of base-metal fatigue life of new HT780 steel B with JSSC design curves

5. Weld Cracking Sensitivity of Copper Precipitation-Hardened Steel

As discussed in the previous chapter, the newly developed copper precipitation-hardened steel has excellent cold cracking resistance. The cold cracking sensitivity of the steel was studied further and evaluated by the traditional weld cracking-sensitive composition indexes *P*cm and CEN. The chemical compositions of the test steels are given in **Table 11**. Steels A and B are the new HT780 steels discussed above and were trial made at the mill. Steel C is conventional HT780 steel to which boron was added, and steel D has 0.05% copper added to examine the cold cracking resistance of copper. All steels measured 38 mm in thickness. Electrodes of the same strength as the base metal (E11016-G) and electrodes of a higher hydrogen content than that of the base metal (E7016-G) were used. When the hydrogen content of these electrodes was determined by gas chromatography, it was 5 ml/100 g for E7016-G and 2.2 ml/100 g for Ell016-G. The presence or absence of cracks and the critical preheating temperature are given in **Table 12**. The new HT780 steels A and B can be protected against cold cracking when preheated to 50℃ and welded with either electrode E11016-G or E7016-G. Cold

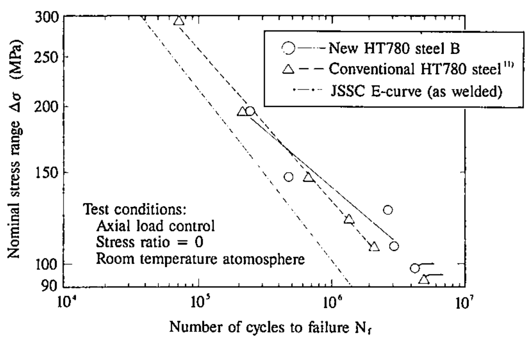


Fig. 27 Comparison of weld joint fatigue life of new HT780 steel with weld joint fatigue life of conventional HT780 steel and with JSSC design curve

Table 12 y-groove weld cracking test results (crack ratio in %)

Steel	Electrode	Preheating temperature (℃)						Critical Preheating temperature (℃)
		20	50	75	100	125	150	
A	E11016-G	0	0	0				20
	E7016-G	0.1*1	0	0				50
B	E11016-G	0.2*1	0	0				50
	E7016-G	0.7*2	0	0				50
C	E7016-G			0.8	0.1	0	0	125
D	E11016-G	0	0	0				20
	E7016-G	0.7*1	0.5	0				75

*1 Crack in weld metal
*2 Crack in weld metal and HAZ

Table 11 Chemical compositions of test steels (mass%)

Steel	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	B	*P*cm	CEN
A	0.045	0.29	1.34	0.005	0.002	1.05	0.94	—	0.47	0.009	0.047	0.0001	0.226	0.285
B	0.06	0.26	1.34	0.007	0.002	0.97	1.03	0.46	0.31	0.009	0.041	0.0001	0.249	0.339
C	0.128	0.26	0.80	0.007	0.004	0.21	0.86	0.52	0.49	—	0.039	0.0018	0.264	0.453
D	0.06	0.25	1.36	0.008	0.001	0.52	1.01	0.46	0.31	0.011	0.040	0.0004	0.229	0.325

cracking occured in Conventional HT780 steel when welded after preheating to 50℃. When steels B and D are compared, the cold cracking of steel D could not be prevented when welded with the electrode E7016-G, unless preheated to 75℃. Steel D with a copper content half that of steel C had a higher critical preheating temperature. Posible reasons are that the effect of trace boron is manifested as described above and that the effect of copper on cracking sensitivity is reduced when copper is added in an amount exceeding 0.5%. The latter effect of copper can be replaced by the problem of whether or not the coefficient of copper in the carbon equivalent used for the evaluation of cracking sensitivity is appropriate. In other words, the problem is that of whether or not the copper term in the carbon equivalent can be considered linear within the range of 1% Cu.

The test data were arranged by the two typical weld cracking-sensitive composition indexes *P*cm[12] and CEN[13]. *P*cm and CEN can be expressed as shown below by using the chemical composition of each steel. The *P*cm formula emphasizes the influence of carbon, while the CEN formula has the influence of alloying elements changed according to the carbon content.

$$Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B \quad \cdots\cdots(1)$$

$$CEN = C + A(C)\{Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr + Mo + Nb + V)/5 + 5B\} \quad \cdots\cdots(2)$$

where,

$$A(C) = 0.75 + 0.25\tanh\{20(C-0.12)\}$$

The test data of the new and conventional HT780 steels welded with the high-hydrogen E7016-G electrodes are arranged in terms of *P*cm. Some of conventional HT780 steel's test data at the high end of the *P*cm range[14] are also shown in order to clarify the relationship between the critical preheating temperature and *P*cm of conventional HT780 steel (non-copper precipitation-hardened steel). The correlation between the critical preheating temperature and *P*cm of conventional HT780 steel is close and almost linear. This verifies the validity of *P*cm as a cracking-sensitive composition index. The new HT780 steel (copper precipitation-hardened steel) is not located on the straight line and is shifted toward the low end of the critical preheating temperature range. Since the weld metal of steel A cracked when welded without preheating, its critical preheating temperature is set at 50℃. Given its essential cracking sensitivity, however, steel A may not suffer cold cracking after it is welded without preheating. From **Fig. 28**, it can be said that the new HT780 steel does not lie on the *P*cm line for conventional HT780 steel. **Fig. 29** similarly shows the relationship between the CEN and critical preheating temperature of the new and conventional HT780 steels. The CEN difference between the new and conventional HT780 steels is smaller, but similar to that observed with respect to *P*cm.

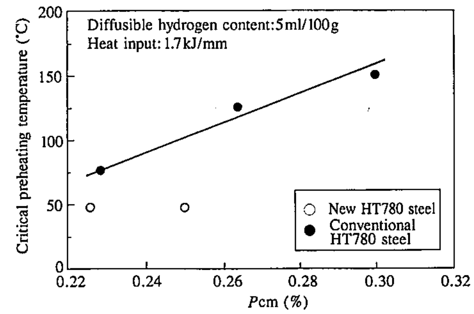


Fig. 28 Relationship between critical Preheating temperature in y-groove weld cracking test and *P*cm

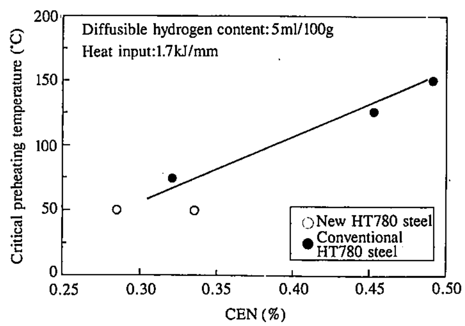


Fig. 29 Relationship between critical preheating temperature in y-groove weld cracking test and CEN

6. Conclusions

To improve the HT780 steel preheating environment, a new HT780 steel that can be successfully welded after preheating to a lower temperature than required for conventional HT780 steel was developed according to hardening techniques entirely different from the hardenability improving methods for conventional HT780 steel. The features of the new HT780 steel may be summarized as follows:

(1) Based on the low-carbon, boron-free compostion required to reduce HAZ hardness, the chemical composition of the new HT780 steel was selected to obtain high strength in a wide tempering temperature range through hardening by the precipitation of copper with niobium and vanadium to secure the desired strength of the base metal. The DQT process is applied to the selected chemical composition to achieve substaintial strength and toughness through efficient precipitation hardening and grain refinement.

(2) The maximum HAZ hardness of the new HT780 steel is much lower than that of conventional HT780 steel. The new HT780 steel does not crack when welded after preheating to 50℃, and excels in cold cracking resistance. The new HT780 steel is located below the lines relating the critical preheating temperature to the weld cracking-sensitive composition indexes *P*cm and CEN for conventional HT780 steel.

(3) The new HT780 steel also has excellent linear heating properties and unlike conventional HT780 steel can be successfully water cooled.

(4) The strength and toughness of weld joints of the new HT780 steel are much higher than the target values. The fracture toughness of weld joints of the new HT780 steel as determined by notched and angular-distorted wide-plate tension test specimens are equal to or higher than those of conventional HT780 steel.

(5) The fatigue life of the base metal and weld joints of the new HT780 steel meet the JSSC design curves, and are comparable to that of conventional HT780 steel.

Since the new HT780 steel has excellent weldability as noted above, it is expected to be extensively used in bridges, penstocks, buildings, pressure vessels, and similar applications.

Acknowledgments

The new HT780 steel was used in the stiffeners of the Akashi Kaikyo Bridge. The authors are indebted to those concerned at the Honshu-Shikoku Bridge Authority, Mitsubishi Heavy Industries, Yokogawa Bridge Works, Kawada Industries, and Miyaji Iron Works for their advice and guidance in the commercialization of the new HT780 steel.

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