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Methods for Predicting Maximum Hardness of Heat-Affected Zone and Selecting Necessary Preheat Temperature for Steel Welding

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Abstract:

Weldability of steel refers to the maximum hardness of the heat-affected zone (HAZ) and the cold cracking susceptibility of welds. These properties must be fully understood because they may have a serious impact on the overall reliability of welded structures. Steel users should examine these problems first of all when they weld steel. Development of highly accurate prediction formulae for the maximum hardness of the HAZ and cold cracking susceptibility is important in properly understanding the properties of steel. Nippon Steel has worked long on the development of prediction formulae for the maximum hardness of the HAZ and the preheat temperature required to prevent cold cracking in welds. The basic ideas and application examples of these methods are described.

1. Introduction

Welding is used in ships, bridges, storage tanks, pressure vessels, industrial machinery, automobiles, rolling stock, and many other fields. Problems associated with welding are common issues in these fields. Nippon Steel produces various types of steels. These steels are mostly assembled into final structures by welding. An easy-to-weld steel is an easy-to-use steel from the standpoint of steel users.

Whether or not the properties of a final structure are as originally designed largely depends on whether or not the properties of welds are as specified. The properties of welds often cause more problems than the base metal properties, and in many cases they govern the overall performance of the structure.

Welding is a key technology in that it determines the service properties of the fabricated structure.

The term "weldability" is used to mean the ease with which steel can be welded. This concept refers to all weld properties, including strength and toughness, in a broad sense and to heat-affected zone (HAZ) hardness and cold cracking susceptibility in a narrower sense. This report describes the methods of evaluating the weldability or maximum HAZ hardness and cold cracking susceptibility of various steel types.

2. Weldability of Steel

When steel is welded, it is heated. The heated portion has a microstructure that is different from that of the base metal and is called the heat-affected zone (HAZ). Usually, rapid heating and cooling, characteristic of welding, produce a hard microstructure in the HAZ. The hard microstructure of the HAZ is one factor

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responsible for the property deterioration of welds. To prevent the stress corrosion cracking of welds in sour service, for example, the maximum hardness of the HAZ should be held under the Vickers hardness Hv of 248. Cold cracking susceptibility, another indicator of weldability, increases with increasing hardness. Steels that tend to produce hard welding HAZ are hard-to-fabricate and therefore hard-to-use steels.

Cold cracking in the HAZ is the so-called hydrogen-induced cracking. In the process of welding, the welding arc decomposes the water vapor in the atmosphere and the moisture in the welding consumable, and introduces hydrogen into the weld being made. The workpiece may be preheated to prevent cold cracking. Preheating, however, increases the welding work load and is therefore uneconomical. Therefore, the lower the minimum preheat temperature for preventing cold cracking, the higher is the weldability of the steel. The HAZ thus involves some problems that are alien to the base metal. The overall reliability of many structures practically depends on the quality of welds.

The weldability of steel has been traditionally evaluated by the concept "carbon equivalent", which was first proposed by Dearden and O'Neill[1]. This concept represents the weldability of steel by a linear expression of steel constituents. Since the coefficient of carbon is put at unity, it is named the carbon equivalent. The carbon equivalent formula of Dearden and O'Neill was partly modified later, and adopted as the carbon equivalent formula CE(IIW) of the International Institute of Welding (IIW).

$$CE(IIW) = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5 \quad \cdots\cdots(1)$$

The CE(IIW) is adopted also by Lloyd's. Since Dearden and O'Neill, many carbon equivalents have been reported. These carbon equivalents have been developed to expand the applicable compositional ranges, for particular types of steels, or for the maximum hardness and cold cracking susceptibility separately. They have been utilized by many researchers and in that course have undergone a process of elimination. Besides the CE(IIW), the following carbon equivalents are cited as typical ones[2,3]:

$$Pcm = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B \quad \cdots\cdots(2)$$

$$CEN = C + A(C)\{Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr + Mo + Nb + V)/5 + 5B\} \quad \cdots\cdots(3)$$

where,

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

The coefficients of alloying elements like manganese in Eq. (1) are relatively large and are smaller in Eq. (2). Eq. (3) is characteristic in that the coefficient of each alloying element is a function of carbon, and is used in the method of evaluating the cold cracking susceptibility of steels as described later.

The carbon equivalent is convenient for comparing two or more different types of steels, but is not definitive enough to know weldability, or HAZ hardness and minimum preheat temperature necessary to prevent cold cracking. The methods for predicting the maximum hardness of the HAZ and the minimum preheat temperature required to prevent cold cracking (hereinafter referred to as the critical preheat temperature) are described below.

3. Prediction Formula for Maximum Hardness of HAZ

The carbon equivalent is available as an index for evaluating the weldability of steels, as noted above. This concept is also used in a prediction formula for the maximum hardness of the HAZ. Here is discussed the basic idea behind the HAZ maximum hardness prediction formula developed by Nippon Steel[4].

Fig. 1 shows a maximum hardness curve in the upper part and continuous cooling transformation (CCT) curves in the lower part. The cooling time from 800 to 500°C ($\Delta t8/5$) that depends on the welding conditions is logarithmically plotted along the X-axis, and the measured maximum hardness of the HAZ is plotted along the Y-axis. It is empirically known that the HAZ maximum hardness constitutes a curve sloping downward to right. The reason why the weld thermal history is represented by the $\Delta t8/5$ is that the transformation start and finish temperatures of steels are about 800 and 500°C, respectively. Development of a maximum hardness prediction formula is to make a mathematical expression of the maximum hardness curve. The authors adopted the following way of thinking.

We first focused on two points, M and Z, on the maximum hardness curve in the upper part of **Fig. 1**. The point M is the critical point at which the martensite volume fraction reaches 100%. A longer cooling time introduces microstructures such as bainite, into the HAZ. The point Z is the critical point at which the martensite volume fraction becomes almost 0% in the HAZ. A shorter cooling time raises the martensite volume fraction above 0%. The maximum hardness curve must smoothly pass through the two points M and Z. At the left side of the point M, the HAZ microstructure becomes wholly martensitic, and therefore does not appreciably change in hardness. At the right side of the point Z, the HAZ microstructure is predominantly bainitic. As the $\Delta t8/5$ increases further, ferrite and pearlite increase in volume fraction. The HAZ is hardest in the portion that is heated to a peak temperature of 1,400°C or more, or is adjacent to the weld metal. Since this portion has high hardenability owing to coarsened austenite grains, ferrite and pearlite need not be so

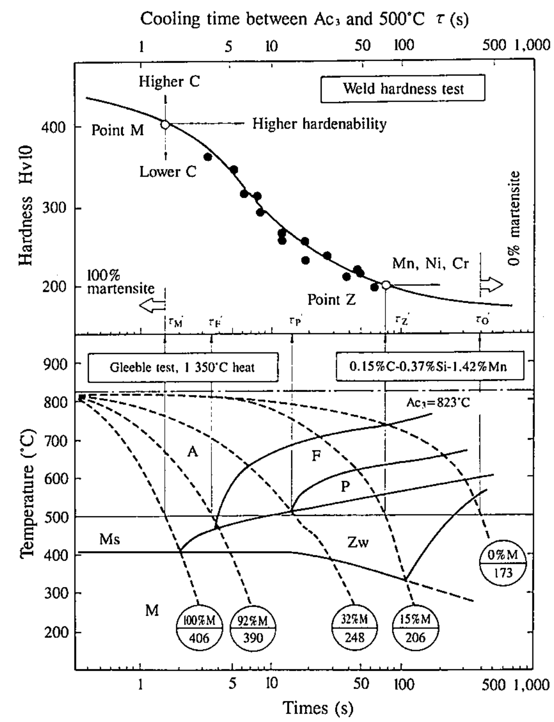

Fig. 1 HAZ maximum hardness curve and CCT diagram

strictly considered in the actual cooling time range. Hence, the maximum hardness of the HAZ at the right side of the point Z is that of bainite and is considered to be almost constant. The curve used to predict the maximum hardness of the HAZ should run almost parallel with the X-axis at the left of the point M and at right of the point Z.

The authors decided to use an inverse trigonometric function (arctangent function) to describe a curve with such characteristics. If the coordinate of the point M is (τ_M, H_M) and that of the point Z is (τ_B, H_B), the maximum hardness curve is given by

$$Hv = (H_M + H_B)/2 - (H_M - H_B)\arctan(X)/2.2 \quad \cdots\cdots(4)$$

where $X = 4 \cdot \log(\tau / \tau_M)/\log(\tau_B / \tau_M) - 2$.

This makes use of the characteristic arctan(X) function that it is almost constant where $X > 2$ and $X < -2$. X is set so that $X = -2$ when $\Delta t8/5 = \tau_M$ and $X = +2$ when $\Delta t8/5 = \tau_B$. Eq. (4) is determined to make $Hv = H_M$ when $X = -2$ and $Hv = H_B$ when $X = +2$. This method is found to be capable of accurately predicting the maximum hardness of the HAZ.

Next, it is necessary to define τ_M and H_M as the coordinate of the point M and τ_B and H_B as the coordinate of the point Z. These four coordinate values depend on the chemical composition of steel and must be obtained each as a function of the steel chemistry. They are defined from the experimental data of various steels as follows:

$$\tau_M = \exp(10.6CE1 - 4.8) \quad \cdots\cdots(5)$$

where,

$$CE1 = Cp + Si/24 + Mn/6 + Cu/15 + Ni/12 + Cr(1 - 0.16\sqrt{Cr})/8 + Mo/4 + \Delta H$$

$$Cp = C\ (C \leq 0.3),\ C/6 + 0.25\ (C > 0.3)$$

$$\Delta H = 0\ (B \leq 1\ ppm),\ 0.03f_N\ (B = 2\ ppm),\ 0.06f_N\ (B = 3\ ppm),\ 0.09f_N\ (B \geq 4\ ppm)$$

$$f_N = (0.02 - N)/0.02$$

$$H_M = 884C(1 - 0.3C^2) + 297 \quad \cdots\cdots(6)$$

$$\tau_B = \exp(6.2CE3 + 0.74) \quad \cdots\cdots(7)$$

where,

$$CE3 = Cp + Mn/3.6 + Cu/20 + Ni/9 + Cr/5 + Mo/4$$

$$H_B = 145 + 130\tanh\{2.65CE2 - 0.69\} \quad \cdots\cdots(8)$$

where,

$$CE2 = C + Si/24 + Mn/5 + Cu/10 + Ni/18 + Cr/5 + Mo/2.5 + V/5 + Nb/3$$

Applicable range of the maximum hardness prediction formula depends on that of Eqs. (5) to (8) and on the number of steel types used in experiments. Eqs. (5) to (8) include data on many types of steels from 0.8%C eutectoid steel through 9%Cr steel to 9%Ni steel. Eq. (4) is thus considered to have the widest applicable range among the HAZ maximum hardness prediction formula available now. **Fig. 2** compares the predicted and measured values of HAZ maximum hardness. As seen, the predicted values agree well with the measured values.

Of particular note in Eqs. (5) through (8) is the ΔH in Eq. (5). The ΔH generally represents the effect of boron and indicates that trace additions of boron have a strong effect and that a boron addition of 4ppm is comparable to a maximum carbon increase of 0.09%, for example. When added in larger amounts, boron does not correspondingly increase its effectiveness. This is probably because trace boron segregates throughout the grain boundaries owing to coarsened prior austenite grains.

Eqs. (4) to (8) can be utilized to predict the maximum hardness of the HAZ when a given steel is welded under a given set of conditions. The same series of equations, conversely, can be utilized to predict the steel chemistry range that holds the maximum HAZ hardness below a certain level under the given welding conditions. This provides the steelworks with the freedom of steel chemistry design in satisfying various other steel property requirements while conforming to the client's specification of maximum HAZ hardness.

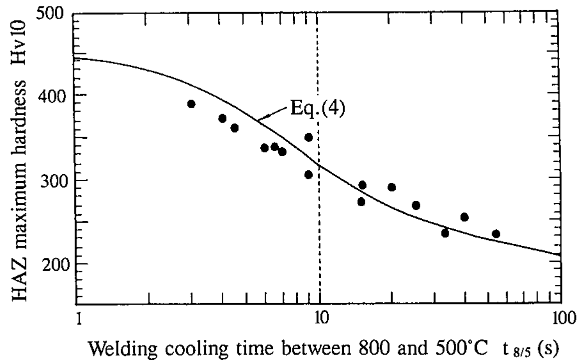

Fig. 2 Comparison of measured and predicted values of HAZ maximum hardness

The τ_M in Eq. (5) is an index of the ease with which the HAZ can transform to a martensitic structure, or the CE1 in the τ_M can be taken as an index of hardenability (carbon equivalent indicating hardenability). As hardenability indexes, the ideal critical diameter (D_I) and multiplying factor have been discussed in the field of steel heat treatment. The CE1 and the multiplying factor express the same metallurgical concept and should be essentially the same. The correlation between these two indexes remained unclear until recent heat conduction analysis clarified that they are essentially the same[5].

D_I is given by the following equation, using the multiplying factor:

$$D_I = D_{I0} \cdot f_C \cdot f_{Si} \cdot f_{Mn} \cdots \quad \cdots\cdots(9)$$

where,

$$f_C = \sqrt{C},$$

$$f_{Si} = 1 + A_{Si} \cdot Si$$

$$f_{Mn} = 1 + A_{Mn} \cdot Mn$$

In Eq. (9), f_C, f_{Si}, f_{Mn},···· are multiplying factors for the alloying elements. Only f_C is a root square of carbon, and the others are linear expressions of the respective elements (A_{Si}, A_{Mn}, ···· are constants).

Using the theory of heat conduction, the carbon equivalent as an index of hardenability can be calculated from f_X in Eq. (9) (X is an alloying element other than carbon). This is no other than the calculation of the coefficient of each element in the carbon equivalent. The equation involved was found to be simple in form as given below. The coefficient C_X of the element X is given by

$$C_X = A_X/4.2(1 + A_X \cdot X_0) \quad \cdots\cdots(10)$$

The X_0 is the mean value of element X for steels used to determine the CE1 values. The A_X is introduced in various pieces of literature. In **Table 1**, the A_X reported in some of the references are compared with the experimentally measured values of the corresponding coefficients. From **Table 1**, it is evident that the validity of the CE1 is endorsed also by multiplying factors.

4. Selection of Critical Preheat Temperature

When steel is welded, the welding arc introduces hydrogen

Table 1 Comparison of coefficients of alloying elements in carbon equivalent

	Experiment		Calculation				
Element	CE1	Maynier[6]	Hollomon[7]	Craft[8]	Kramer[9]	Hodge[10]	Grossmann[11]
Si	1/24	—	1/9.2	1/8.8	1/10.2	1/5.9	1/7.5
Mn	1/6	1/4.1	1/5.2	1/5.1	1/7.7	—	1/5.5
Cr	1/8	1/8.5	1/3.9	1/4.0	1/4.5	—	1/3.9
Ni	1/12	1/7.9	1/18.6	1/16.2	1/20.5	1/24.5	1/22.2
Mo	1/4	1/6.5	1/3.4	1/3.8	1/4.51	1/2.9	1/3.4
Cu	1/15	—	1/17.2	—	1/11.0	—	—

Each coefficient was experimentally determined by hardness test and calculated from multiplying factors reported in literature.

into the weld metal. When the hydrogen diffuses into portions of a hardened microstructure such as the HAZ, there arises a risk of crack occurrence. The hydrogen-induced cracking susceptibility depends on such factors as the HAZ microstructure, hydrogen content, weld residual stress, restraint intensity, and stress concentration factor. These factors are interwoven in such a complex manner that they cannot be simply evaluated for the effect they may have on the hydrogen-induced cracking susceptibility. Presence of cracks in welds is fatal to the reliability of welded structures, and, therefore, the cold cracking susceptibility of steels has continued to be an important subject of research to date.

Past research results indicate that crack occurrence in steels depends on the following factors:

1) Steel composition
2) Amount of hydrogen introduced by welding
3) Residual stress in weld (restraint intensity and stress concentration factor)
4) Welding thermal hysteresis

Factor 1) is often represented by the carbon equivalent calculated from the chemical composition. There are three typical carbon equivalents as calculated by Eqs. (1) to (3). Factor 2) depends on the welding consumable, welding method, and humidity in the atmosphere. The hydrogen content is usually expressed by the volume at one atmosphere and 0°C of hydrogen present in 100g of welding deposited metal. The hydrogen content is 1 ml/100g or less when the weld area is gas shielded as in TIG welding, but increases to as much as 40ml/100g when a cellulosic electrode is used. Factor 3) or residual stress refers to the stress that remains in the weld after localized thermal expansion and contraction and resultant plastic strain in the rapid heating and cooling process. The level of residual stress in a welded joint depends on the restraint intensity and stress concentration factor of the welded joint. For this reason, the cold cracking susceptibility is sometimes discussed in terms of the restraint intensity and stress concentration factor in place of the residual stress. Factor 4) or weld thermal hysteresis depends on the welding conditions and preheat temperature, but refers here to the welding heat input that strongly influences the hardness and microstructure of the HAZ.

Cold cracking can be prevented through such measures as selection of a low-carbon equivalent steel (considering factor 1)), selection of low-hydrogen welding consumables and methods (considering factor 2)), joint design for low restraint intensity and stress concentration (considering factor 3)), and increase of welding heat input (considering factor 4)). There may be cases, however, where the particular property requirement of the planned welded joint places a limitation on the adoption of the above measures (for example, selection of a low carbon equivalent steel is restricted from the consideration of base metal strength).

Preheating is an alternative in such cases. Preheating facilitates the escape of hydrogen from the weld thanks to the fact that the diffusion coefficient of hydrogen in steel becomes relatively high at temperatures of 100°C and above. When the temperature of the weld falls below 100°C, the diffusion coefficient of hydrogen steeply diminishes, and hydrogen remains in the weld to induce cold cracking. Over a long term, hydrogen diffuses even at temperatures below 100°C, and the residual hydrogen content decreases. Cold cracking, however, is likely to occur within a few hours after welding. Therefore, hydrogen that remains in the weld at temperatures below 100°C can be regarded as residual hydrogen. Selection of preheat temperature is in other words the question of how long time the welded joint temperature should be kept above 100°C so that residual hydrogen is prevented from inducing low-temperature cracking.

The chart method[12] developed by Nippon Steel for selecting the critical preheat temperature for specific steels and called the master curve method by the authors is described below.

The first issue is what to select as carbon equivalent. The CEN expressed by Eq. (3) was adopted. The CEN is characteristic in that the coefficients of elements other than carbon are each given as a function of carbon. For example, AWS (American Welding Society) D1.1[13] recommends the CE(IIW) of Eq. (1) for $C \geq 0.11\%$ and the *P*cm of Eq. (2) for $C < 0.11\%$. The CE(IIW) and Pcm are different in the coefficients of alloying elements. This suggests that the magnitude of their effect varies with the carbon content or that each coefficient is a function of carbon.

The A(C) in the CEN is set so that the CEN approaches the CE(IIW) in a high-carbon region (Zone I) and approaches the *P*cm in a low-carbon region (Zone II), so that the applicable range of the CEN becomes wider than that of the CE(IIW) and *P*cm. In **Fig. 3**, the critical preheat temperature determined for various steels in the y-groove weld cracking test are compared with the carbon equivalents calculated by Eqs. (1) to (3). Among the three carbon equivalents, the CEN is shown to have the best correlation with the critical preheat temperature. This is the reason for adopting the CEN.

The second issue is what preheat temperature to select. The authors made it possible to predict the critical preheat temperature by the y-groove weld cracking test specified in JIS Z 3158. The reason is that steel manufacturers and many steel users often refer to the results of the y-groove weld cracking test when determining the critical preheat temperature in their actual welding operations. Of course, the critical preheat temperature determined by the y-groove weld cracking test depends on the welding heat input and hydrogen content. The experimental procedure first predicted the critical preheat temperature under the standard conditions of 1.7 kJ/mm heat input and 5ml/100g hydrogen content. **Fig. 4** shows the relationship between the CEN calculated from the experimental data of various steels and the critical preheat temperature determined by the y-groove weld cracking test. The critical preheat temperature varies with the plate thickness, because the restraint intensity of the specimen varies with the plate thickness. **Fig. 4** shows curves that constitute the base of this selection procedure. In that sense, these curves are named the master curves.

The effect of the heat input and hydrogen content is

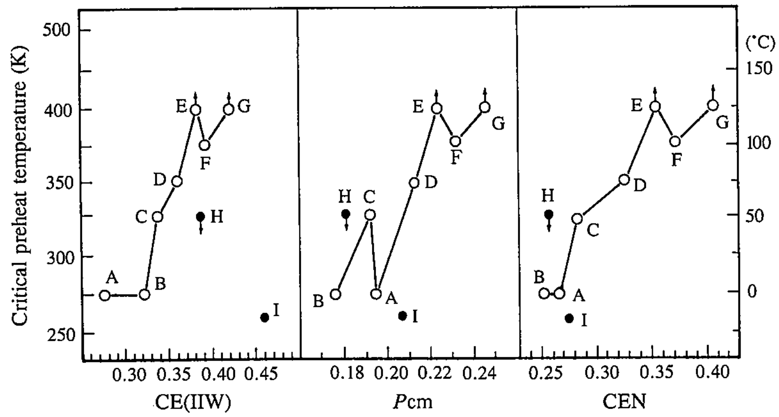

Fig. 3 Relationship between carbon equivalents and critical preheat temperature (y-groove weld cracking test)

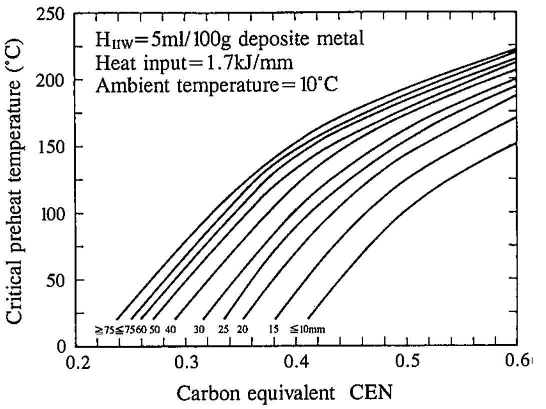

Fig. 4 Master curves in preheat temperature prediction method

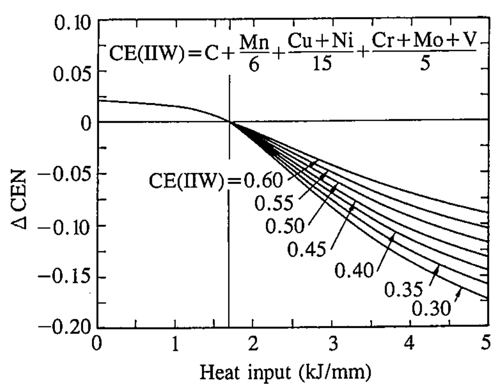

Fig. 5 Relationship between heat input and ΔCEN

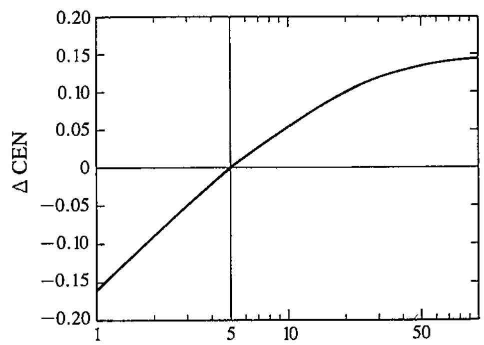

Fig. 6 Relationship between weld metal hydrogen content and ΔCEN

expressed as a change in the CEN (ΔCEN). This method is similar to BS 5135. When the actual heat input and hydrogen content are different from the standard conditions, this method determines which standard conditions they correspond to. **Figs. 5** and **6** show the curves to determine the ΔCEN when the heat input and hydrogen content are different from the standard conditions.

In **Fig. 5**, the effect of the heat input differs with the CE(IIW), as is evident from the maximum hardness prediction formula of Eq. (1). The cold cracking susceptibility of the HAZ is strongly influenced by its hardness and hardenability. When a high-hardenability steel is welded, the HAZ microstructure becomes predominantly martensitic even if the heat input changes to some extent. The hardness of the HAZ does not significantly change in this case. The effect of heat input is thus small. When a lower-hardenability steel is welded, the heat input has important bearings as it changes the bainite volume fraction. The carbon equivalents expressing hardenability and bainite hardness are those in Eqs. (5) and (7). These two carbon equivalents are of the CE(IIW) type. For this reason, the effect of the heat input must be distinguished by the value of CE(IIW), as shown in **Fig. 5**.

In **Fig. 6**, the X-axis is a logarithmic plot. This is because the effect of hydrogen on the cold cracking susceptibility is logarithmic. When **Fig. 6** was prepared, this fact was confirmed from experimental results. Lately, the logarithmic plot was proved adequate for the diffusion of hydrogen[14].

Figs. 4 to **6** can be used to predict the critical preheat temperature in the y-groove weld cracking test. An example is given here.

First, assume that the CEN and CE(IIW) are calculated to be 0.38% and 0.45%, respectively, from the chemical composition of the steel concerned. The plate thickness is 20mm, the heat input is 2.5kJ/mm, and the hydrogen content is 10ml/min. The ΔCEN under the influence of the heat input is —0.03% from **Fig. 5**, and the ΔCEN under the influence of the hydrogen content is 0.05% from **Fig. 6**. The cold cracking susceptibility of the steel under these conditions can be calculated to be the same as the CEN of 0.40 (0.38 — 0.03 + 0.05) under the standard conditions. The critical preheat temperature for the plate thickness of 20mm and the CEN of 0.40% is predicted to be 70°C from **Fig. 4**.

The critical preheat temperature predicted in this way is actually on the safe side. A lower preheat temperature can be adopted in an actual welding procedure. This is because the restraint intensity and stress concentration in the y-groove weld cracking test are much severer than in the actual welding operations. **Fig. 7** must also be used to predict the preheat temperature in the actual welding operations. In **Fig. 7**, the actual preheat temperature is given as a reduction from the preheat temperature predicted in the y-groove weld cracking test. Repair welding, for example, involves a relatively high restraint intensity and small preheat temperature reduction compared with ordinary welding. When a 450-MPa steel is welded, the preheat temperature reduction is 10°C for repair welding and 60°C for ordinary welding according to **Fig. 7**. This means that the steel must be preheated by 60°C for repair welding and by 10°C for ordinary welding, or practically without preheating in the latter case.

Table 2 compares the critical preheat temperature calculated by the chart method with that measured by the y-groove weld cracking test. The values calculated by the methods described in BS 5135 and AWS D1.1 are given for reference. The values by

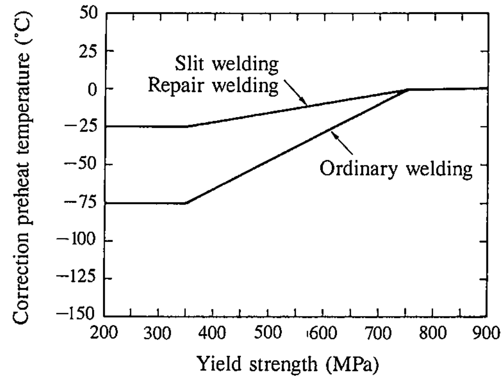

Fig. 7 Relationship between preheat temperature of y-groove weld cracking test and preheat temperature adopted in actual welding procedure

Table 2 Comparison of critical preheat temperature determined by y-groove weld cracking test with critical preheat temperature predicted by three different methods

Steel	Hydrogen (ml/100g)	Heat input (kJ/mm)	Tcr (°C)	BS5135*1 (°C)	AWS D1.1 (°C)	Present model (°C)	
						y-gr.*2	Ta*3
TS400MPa	5	1.7	20	20	20	20	20
	13		20	20	85	20	20
	40		75	20	116	61	20
TS490MPa	1	1.7	20	20	20	20	20
	5		100	20	116	80	22
	13		125	20	138	132	74
	40		150	20	149	153	95
TS590MPa	13	1.7	100	20	138	137	87
	40		125	20	149	155	105
TS780MPa	1	1.7	20	125	129	20	20
	3		100	125	149	125	114
	5		150	125	149	156	145
	13		175	175	149	184	173
TS780MPa	5	3.2	100	20	149	121	110

*1 BS 5135 estimates preheat temperature for actual welding (compare with Ta).
*2 y-groove weld cracking test
*3 Preheat temperature predicted by chart method

the BS 5135 method are estimates for actual welding procedures and therefore cannot be compared with the experimental results (Tcr). The chart method clearly ensures higher accuracy than the method of AWS D1.1. The excellent accuracy of the chart method is confirmed also through comparison with the method of BS 5135, which fails to fully take into account the effect of the hydrogen content (as observed for TS490MPa).

5. Examples of Application

5.1 Maximum hardness of HAZ

An example of HAZ maximum hardness regulation is Hv ≤ 248 established to prevent sulfide stress cracking in sour environments. In girth welding of line pipe, the first bead is deposited at increased speed to shorten the pipeline laying period. Severe weldability is demanded of the line pipe steel to limit the maximum hardness of the HAZ. The line pipe steel must satisfy strength, toughness, and other property requirements as well as weldability.

According to the HAZ maximum hardness prediction formula, the maximum hardness of the HAZ is the H_M of Eq. (6). First of all, it is important to hold the H_M low. Since the H_M is a function of carbon alone, lowering the carbon content is effective in holding the H_M low. It is practically impossible to keep the H_M under 248, however. Care must be exercised in selecting the contents of other elements. It is necessary to minimize the volume fraction of a hard microstructure, or to lower the hardenability expressed by Eq. (4) and to reduce the volume fraction of the martensitic structure. To this end, the CE1 in Eq. (5) must be decreased. Among the items comprising the CE1, B (boron) in ΔH has a relatively large effect. Hardenability can be significantly reduced by lowering the boron content. Hardenability can be reduced further by reducing the contents of such other elements as manganese and molybdenum, but the contents of these elements should be judiciously selected to ensure strength, toughness, and other properties.

The maximum hardness of the HAZ in actual welds depends not only on the heat input but also on the plate thickness. These two factors govern the Δt8/5. The heat input being equal, permissible compositional ranges expand with decreasing plate thickness. All these factors are duly considered in determining the final chemical composition and manufacturing conditions of specific steels.

The final chemical composition of a given steel does not depend on HAZ hardness alone. It must be determined considering other factors as well. For simplicity's sake, here are presented HAZ maximum hardness curves for actual line pipe steels.

Table 3 gives the chemical compositions of two steels used for predicting the critical preheat temperature. The plate thicknesses are 12.3 and 28mm. Girth welding heat inputs are 1.0 and 2.0kJ/mm, and corresponding values of the Δt8/5 are 8 to 20 for the plate thickness of 12.3mm and 5 to 10s for the plate thickness of 28mm. **Fig. 8** shows HAZ maximum hardness curves for the two steels and HAZ maximum hardness ranges for their girth welding. The curve for the plate thickness of 12.3mm lies above that for the plate thickness of 28mm. Being of light gage, the two steels meet the HAZ hardness requirement of Hv ≤ 248, that is, have sufficiently high weldability for their intended application.

5.2 Cold cracking susceptibility

The cold cracking susceptibility of the Grade X65 and X70 steels introduced in Section 5.1 above is examined here. These

Table 3 Chemical compositions of line pipe steels (wt%, * : wt ppm)

Steel	Thickness(mm)	C	Si	Mn	P	S*	Ni	Mo	Al	Ti	Nb	Ca*	N*	O*	CE(IIW)	*P*cm	CEN
X65	28.0	0.051	0.25	1.14	0.005	5	0.32	0.21	0.05	0.015	0.048	37	17	12	0.304	0.137	0.193
X70	12.3	0.088	0.263	1.03	0.005	5	0.35	0.256	0.013	0.016	0.051	43	39	18	0.334	0.171	0.242

Table 4 Chemical composition of copper precipitation-hardened HT780 steel with low cold cracking susceptibility (wt%)

C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	CE(IIW)	*P*cm	CEN
0.06	0.26	1.34	0.007	0.002	1.05	0.94	0.46	0.31	0.009	0.041	0.572	0.249	0.339

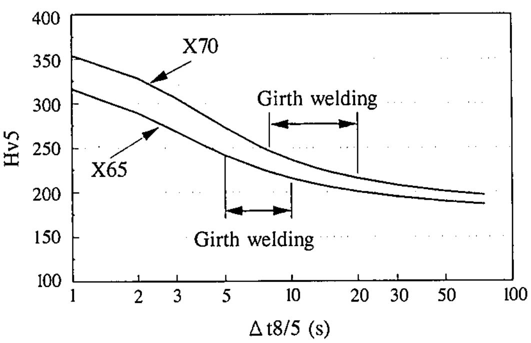

Fig. 8 HAZ maximum hardness of girth welds in line pipe steels

line pipe steels are often girth welded using cellulosic electrodes. Study must be made into whether or not cold cracking will occur under this condition. The CEN and CE(IIW) are calculated for the two steels as follows:

X65: CEN = 0.193%, CE(IIW) = 0.304%

X70: CEN = 0.242%, CE(IIW) = 0.334%

The hydrogen content is about 40ml/100g for cellulosic electrodes. From **Fig. 6**, ΔCEN = 0.13%. For the most rigorous heat input of 1.0kJ/mm, ΔCEN = 0.02% from **Fig. 5**. Under the standard conditions, the following CEN values are considered applicable to X65 and X70:

X65: CEN = 0.193 + 0.13 + 0.02 = 0.343

X70: CEN = 0.242 + 0.13 + 0.02 = 0.392

The master curves of **Fig. 4** show that the critical preheat temperature as measured in the y-groove weld cracking test is 60°C for X65 and 40°C for X70. Each is lower than 100°C. Since actual preheat temperatures can be much lower than these values according to **Fig. 7**, X65 and X70 are thus found to have good weldability.

5.3 HT780 steel with low cold cracking susceptibility

Since preheating decreases the welding efficiency and increases the welding cost, it should preferably be alleviated as far as possible. Preheating can be minimized by considering factors 1) to 4) in Chapter 4. Here is introduced the development of a steel with low cold cracking susceptibility, a steel that can be welded at a lower preheat temperature with other conditions being equal. The preheat temperature can be lowered by reducing the carbon equivalent, but the reduction of the carbon equivalent is objectionable from the point of view of ensuring the desired strength of steel. An example of steel that has solved these contradictory problems is the copper precipitation-hardening HT780 steel with low cold cracking susceptibility[15] developed by Nippon Steel.

Table 4 gives the chemical composition of the copper precipitation-hardening HT780 steel with low cold cracking susceptibility. The method whereby the conventional HT780 steel is provided with desired strength is reviewed first. The conventional HT780 steel (such as WT780) is given the desired strength by adding 0.13% carbon and 15 to 20 ppm boron and by quenching and tempering. In other words, the desired strength is obtained by increasing hardenability. Hardenability, an important factor in steel manufacture, has been traditionally evaluated by the ideal critical diameter D_I or multiplying factor. As discussed previously, the multiplying factor has been found to be essentially the same as the carbon equivalent. This means that the traditional method of ensuring the desired strength of the conventional HT780 steel by enhancing its hardenability cannot reduce the carbon equivalent and hence the preheat temperature. To lower the preheat temperature, conversely, the carbon equivalent must be lowered. The resultant lack of hardenability makes it difficult to achieve the desired strength.

To satisfy these contradictory requirements at the same time, the desired strength may be obtained by making use of another metallurgical phenomenon such as precipitation. Nippon Steel hit upon the idea of keeping the carbon content less than 0.07%, adding no boron, and making up for the loss of strength due to the lack of hardenability by the precipitation of copper. The A710 has been long available as a steel that makes use of this copper precipitation. It was pointed out that the cold cracking susceptibility of the A710 steel is superior to that evaluated by the CE(IIW) and *P*cm. Hence, Nippon Steel focused on copper as the precipitating element. The HT780 steel with low cold cracking susceptibility is the HT780 steel to which copper precipitation hardening is applied, and weldability comparable to that of the A710 steel is expected in it.

Fig. 9 shows the y-groove weld cracking test results of conventional steels and the copper precipitation-hardened HT780 steel with low cold cracking susceptibility. It is evident that the copper precipitation-hardening HT780 steel (indicated by the open circle) is located on the lower preheat temperature side of

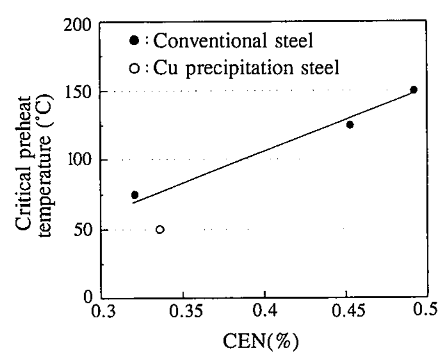

Fig. 9 Relationship between CEN and critical preheat temperature

the conventional steels (indicated by the solid circles), that is, has a lower critical preheat temperature. The open circle deviates from the straight line in **Fig. 9**, because 1% Cu is outside the applicable range of the carbon equivalent CEN. It will be necessary to develop a new carbon equivalent that takes this point into account.

5.4 Others

Weldability is evaluated not only when developing new steels but also when determining appropriate welding conditions for conventional steels. The chart method for determining the critical preheat temperature uses multiple diagrams and involves a complicated procedure. Computer software[16] is available for summarily determining the critical preheat temperature free from the errors that tend to incur on the complicated chart method.

6. Conclusions

The methods developed by Nippon Steel for predicting the weldability (HAZ hardness and cold cracking susceptibility) of steels have been discussed above.

Weldability is an index of the ease of steel use. The reliability of welds cannot be ensured without proper understanding of weldability. The authors trust that these methods will be helpful in deepening the understanding of steel weldability and prove useful in actual steel welding operations.

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