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# A Chart Method to Determine Necessary Preheat Temperature in Steel Welding*

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**Abstract**

*Preheating is carried out to avoid cold cracking in steel welding. The occurrence of cold cracking is considered to be governed by accumulating diffusible hydrogen, welding residual stresses and hardness at the crack initiation site. The hydrogen accumulating at the crack site depends on the initial diffusible hydrogen content in weld metal, the weld heat input and the wall thickness. The local residual stress is governed by the weld metal yield strength, the joint restraint and the notch stress concentration factor. The HAZ hardness is influenced by the steel chemical composition, the weld heat input and the plate (wall) thickness.*

*These influential factors affect cold cracking independenly or in an interacted manner. It must be, thus, difficult to predict the necessary preheat temperature by a theoretical method or simple formulae. The method presently proposed is completely based on the empirical results by y-groove weld cracking tests. The present method determines the necessary preheat temperature through the charts describing the following respective effects : 1) steel composition ; 2) diffusible hydrogen content of weld metal ; 3) weld heat input ; 4) wall thickness ; 5) weld metal yield strength ; 6) joint restraint. As to the steel composition, this method uses CEN carbon equivalent that preferably assesses weldability of a wide variety of steels. Also, this method considers a logarithmic dependence of the weld metal hydrogen and the analysis of hydrogen diffusion in a weld has proved that the hydrogen effect on cold cracking must be logarithmic.*

**Key Words :** *Preheating, Hydrogen, Weld metal, Carbon equivalent, Heat input, Cold cracking, Hardness, Heat-affected-zone, Steel*

## 1. Introduction

There have been many methods[1-12] proposed to determine the necessary preheat temperature in the steel welding. These methods consider some or all of the important influential factors to cold cracking, that are the steel chemical composition, the weld metal diffusible hydrogen, the welding heat input, the weld thickness, the welding residual stresses, and the joint restraint. However, there are considerable differences among the methods in assessing the significance of these factors. For instance, the linear effect of weld metal hydrogen is considered in some methods but its logarithmic effect is considered in other methods. Also, the effect of steel chemical composition differs from method to method in evaluating the importance of each alloy element.

This study reconsiders a chart method[13] proposed by one of the authors, mainly focussing on the influences of hydrogen and steel chemical composition. The validity of some of the preheat determining methods is compared with that of the chart method, based on the cold cracking experimental results.

## 2. Chart Method

Since Dearden and O'Neil[14] published a concept of carbon equivalency in 1940, many indices evaluating the cold cracking susceptibility of a steel have been reported. Some of the important ones are listed in Table 1[14-19,6]. They are roughly divided into three groups ; the first is of a $CE_{IIW}$ type which originated from the Deardens' carbon equivalent, the second is of a Pcm type which regards carbon as more important than the first group, and the third is of a CEN type in which the significance of an alloy element varies depending on a carbon content.

Fig. 1 shows the critical preheat temperature, that is the minimum preheat temperature necessary to avoid cold cracking in the y-groove weld

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**Table 1** Various Types of Carbon Equivalency for Steel Welding.

| Group | Formula | Ref. |
|---|---|---|
| A | $CE\ (IIW) = C + \frac{Mn}{6} + \frac{Cu+Ni}{15} + \frac{Cr+Mo+V}{5}$ | 14 |
| | $CE\ (WES) = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14}$ | 15 |
| | $CE\ (Stout\ II) = C + \frac{Mn}{6} + \frac{Cu}{40} + \frac{Ni}{20} + \frac{Cr}{10} + \frac{Mo}{10}$ | 16 |
| B | $P_{CM} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B$ | 17 |
| | $CE\ (Graville) = C + \frac{Mn}{16} - \frac{Ni}{50} + \frac{Cr}{23} + \frac{Mo}{7} + \frac{Nb}{8} + \frac{V}{9}$ | 18 |
| | $CE\ (Düren) = C + \frac{Si}{25} + \frac{Mn}{16} + \frac{Cu}{16} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{40} + \frac{V}{15}$ | 19 |
| C | $CE\ (Stout\ I) = 1000 \cdot C \cdot (\frac{Mn}{6} + \frac{Cr+Mo}{10} + \frac{Ni}{20} + \frac{Cu}{40})$ | 16 |
| | $CEN = C + A(C) \cdot \{\frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr+Mo+Nb+V}{5} + 5B\}$ | 6 |
| | Where $A(C) = 0.75 + 0.25 \tanh\{20(C-0.12)\}$ | |

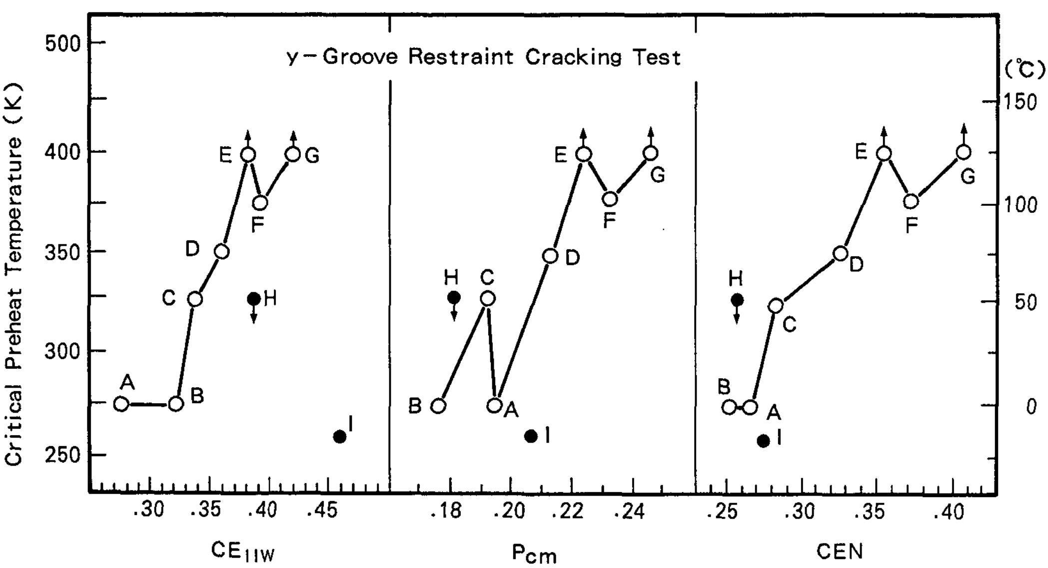



**Fig. 1** *Relation between Critical Preheat Temperatures and Carbon Equivalents.*

cracking tests[20], plotted against three groups of carbon equivalent. The cracking tests include those conducted in the Shipbuilding Research Group[21] and the independently conducted tests for a low-carbon low-alloy steel and a copper precipitation steel[22]. Table 2 shows the chemical composition of the tested steels. In Fig. 1, the critical preheat temperature for steel H is not higher than 50°C. This means that no HAZ cracks but weld metal cracks were observed in the non-preheat condition while they were stopped at 50°C preheating.

As shown in Fig. 1, $CE_{IIW}$ is a preferable index for carbon steels and carbon manganess steels but absolutely unacceptable for low-carbon low-alloy steels. Pcm is suitable for the steels except steel

**Table 2** Chemical Composition of Steels for y-Groove Weld Cracking Tests.

| Steel | Process | C | Si | Mn | Cu | Ni | Cr | Mo | Nb | V | B | $CE_{IIW}$ | Pcm | CEN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | CR·AcC | .15 | .18 | .73 | | | | | | | | .278 | .195 | .269 |
| B | CR·AcC | .10 | .24 | 1.28 | | | | | | | | .320 | .176 | .252 |
| C | CR | .11 | .31 | 1.31 | | | | | .02 | | | .338 | .192 | .286 |
| D | CR·AcC | .14 | .27 | 1.20 | | | | | | | | .354 | .213 | .326 |
| E | AR | .14 | .37 | 1.43 | | | | | | | | .384 | .225 | .356 |
| F | CR | .15 | .29 | 1.42 | | | | | | | | .391 | .231 | .373 |
| G | AR | .15 | .43 | 1.59 | | | | | | | | .421 | .247 | .405 |
| H | QT | .07 | .28 | 1.38 | | | .21 | .21 | | .04 | .0015 | .389 | .181 | .254 |
| I | DQT | .05 | .28 | .56 | 1.09 | .84 | .38 | .19 | | .04 | | .460 | .207 | .277 |

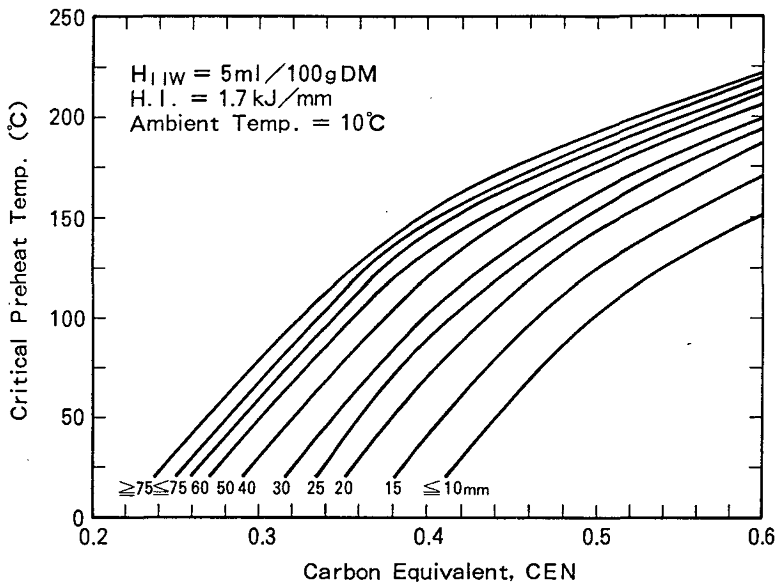



**Fig. 2** Master Curves for Cetermining Necessary Preheat Temperature.

A, a carbon (lean alloy) steel and steel I, a copper precipitation steel. In the welding of structural steels with a heat input of around 1.7 kJ/mm, roughly speaking, a martensite (hard phase) volume is rather high at HAZ (weld heat affected zone) of low alloy steels with fairly high hardenability and, on the contrary, it is rather low in lean alloy steels with low hardenability. Hardness of a martensite phase is determined by a carbon content alone and that of HAZ with a low fraction of martensite is determined by a $CE_{IIW}$ type of carbon equivalent[23]. Since HAZ hardness strongly affects the cold cracking susceptibility, $CE_{IIW}$ is a preferable index for carbon steels. On the other hand, the effect of carbon becomes more significant to HAZs with a high volume fraction of martensite. Pcm regards carbon as more important than $CE_{IIW}$, and thus Pcm is suitable for low-carbon low-alloy steels except such a special steel as a copper precipitation steel.

CEN carbon equivalent is considered suitable for all the types of steels from Fig. 1, since CEN was proposed to evaluate the cold cracking susceptibility of a wide variety of steels[6]. In fact, CEN approaches to $CE_{IIW}$ as carbon increases and it approaches to Pcm as carbon decreases. It follows that CEN was adopted as a yardstick of the steel susceptibility to cold cracking in the chart method.

Fig. 2 shows the master curves indicating the relationship between the critical preheat temperatures in y-groove weld cracking tests, the CEN carbon equivalent, and the plate thickness. This relationship is valid under the condition that the diffusible weld metal hydrogen (by gaschromatograph method or mercury method) is 5 ml/100 g, the welding heat input is 1.7 kJ/mm, and the ambient temperature is 10°C. Japanese steel manufactures have carried out y-groove weld cracking tests as one of the steel performance testing whenever a new steel has been developed and they have, therefore, had the sufficient data concerning y-groove weld cracking testing. A chart of Fig. 2 is thus derived from the empirical data.

Fig. 3 shows the effect of weld metal diffusible

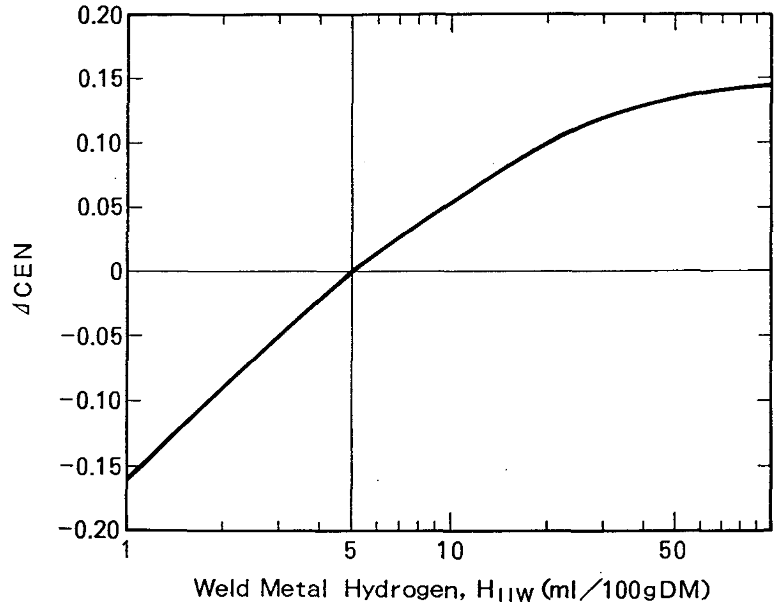



**Fig. 3** CEN Correction Depending on Weld Metal Hydrogen.

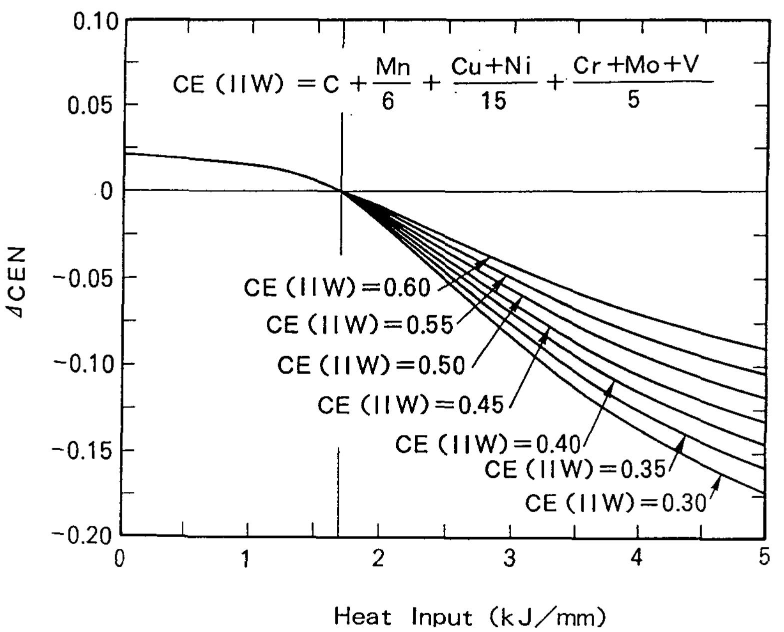



**Fig. 4** CEN Correction Depending on Weld Heat Input and $CE_{IIW}$.

hydrogen on the critical preheat temperature in y-groove weld cracking tests in terms of a CEN increment. As shown in Fig. 3, the effect of weld metal hydrogen is nearly logarithmic. The logarithmic dependence in the chart method is based on a number of experimental facts[2,3,6,8,24]. Fig. 4 shows the effect of a weld heat input on the critical preheat temperature also in terms of a CEN increment. With increasing weld heat input, the CEN increment becomes negative because of the reduction in HAZ hardness arisen from slow cooling due to high heat input welding. When a volume fraction of martensite at a HAZ becomes low in such a case of high heat input welding, a HAZ hardness is determined by the carbon equivalent similar to $CE_{IIW}$ as mentioned before. It follows that the decrement of CEN lowers in a steel with higher $CE_{IIW}$ in a higher heat input region as shown in Fig. 4.

When diffusible weld metal hydrogen and a weld heat input differ from 5 ml/100 r and 1.7 kJ/mm of the standard condition respectively, an increment or a decrement in CEN is given corresponding to the bias from the standard as shown in Fig. 3 and Fig. 4. The total bias from the standard can thus be converted into the sum of the CEN increments. Then, the critical preheat temperature for a y-groove weld cracking test with a given thickness is found by substituting the total of the CEN increments (Figs. 3 and 4) and the original CEN calculated from the steel composition into CEN in the mater curves of Fig. 2.

In y-groove weld cracking testing, a one-pass short bead is deposited on a 2 mm wide slit under a very severe constraint. This testing is considered very stringent because of no post heat effect by subsequent weld passes, the existence of an acute notch at the weld root and the effect of high tensile residual stresses. This situation considerably differs from that met with the normal welding practice. From this reason, fabricators in Japan usually employ the preheat temperature 75°C lower than the critical one in y-groove weld cracking testing of the same welding conditions as those in practice. This is the case for the fabrication of a TS (tensile strength) 490 MPa grade of steel. As the steel strength and thereby the weld metal strength increases over TS590 MPa, a decrement from the critical preheat temperature in y-groove weld cracking testing should be reduced, i.e., the preheat temperature in practice must be closer to the critical. This is because toe cracking, under-bead HAZ cracking and weld metal cracking other than root cracking are more likely to occur in multi-pass welds with an increase in the steel strength and the weld metal strength.

Fig. 5 gives the permissible decrement from the critical preheat temperature in the master curve of Fig. 2, depending on the weld metal strength and the restraints. Fig. 5 uses the weld metal yield strength instead of the steel strength. The

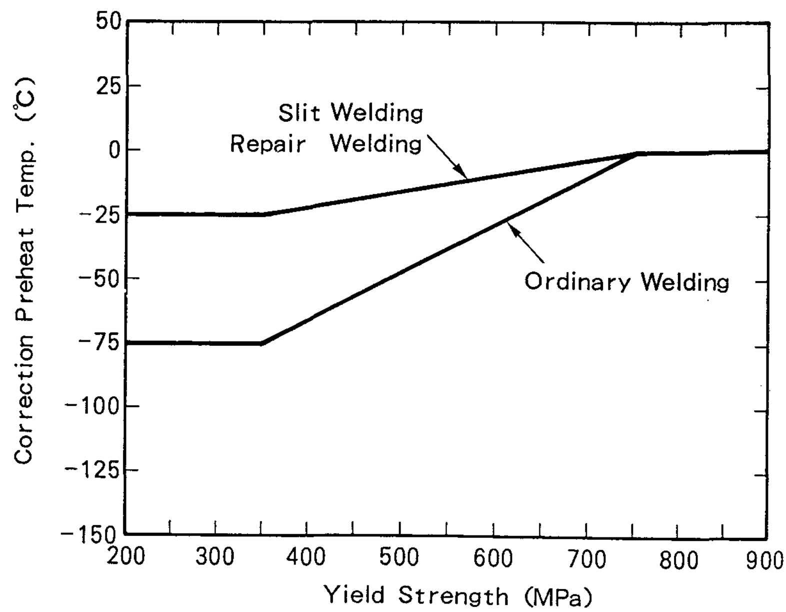



**Fig. 5** Correction of Necessary Preheat Temperature for Welding Practice.

reason for this is that the weld metal strength of the finally deposited weld determines the maximum level of tensile residual stresses[25]. Fig. 5 also suggests that the use of a soft weld metal or an under-matching joint is beneficial for the avoidance of cold cracking.

As a result, the necessary preheat temperature in the practical fabrication is determined in the chart method in the following manner: (1) to calculate CEN and $CE_{IIW}$ from the steel chemical composition; (2) to find a CEN increment through the deviation of the weld metal hydrogen from the standard in Fig. 3; (3) to find a CEN increment through the deviation of the heat input from the standard and $CE_{IIW}$ in Fig. 4; (4) to correct CEN by adding the sum of the CEN increments to the original CEN; (5) to determine the critical preheat temperature in y-groove weld cracking testing from the corrected CEN and the plate thickness in the master curve of Fig. 2; (6) to determine the necessary preheat temperature in practice through the correction in Fig. 5 depending on the weld metal strength and the joint restraint.

Let us show a example of the prediction. Suppose CEN and $CE_{IIW}$ be 0.38% and 0.45%, respectively. A plate to be welded is 20 mm thick. A welding heat input, a weld metal diffusible hydrogen content and a weld metal yield strength are supposed to be 2.5 kJ/mm, 10 ml/100 g, and 450 MPa, respectively. The CEN correction due to the hydrogen content is 0.05% from Fig. 3, and that due to the heat input and $CE_{IIW}$ is $-0.03$%. Hence, the total of the CEN increments is 0.02% (0.05−0.03) and the corrected CEN is 0.40% (0.38+0.02). Then, the necessary preheat temperature for y-groove weld cracking tests is given as 70°C from CEN of 0.40% and a thickness of 20 mm from Fig. 2. The acceptable reduction of preheat temperature is 20°C for repair welding and 60°C for normal welding practice. Finally, the chart method predicts that the necessary preheat temperature is 50°C (70°C−20°C) for repair welding and no preheat (70°C−60°C) is required in normal welding for this example. It is of quite inconvenience to look into several charts of Fig. 2 to Fig. 5 in this method. An application software that programmed this procedure is thus prepared[26].

## 3. Comparison of Experiments and Predictions

The y-groove weld cracking tests were additionally conducted to examine the validity of the chart method. The tested steels ranged from the mild steel of a TS400 MPa grade to the high strength steel of a TS780 MPa grade. Their chemical compositions are shown in Table 3. The weld metal hydrogen in the tests were varied between 1 ml/100 g and 40 ml/100 g by the use of a gas metal arc welding (GMAW), low hydrogen electrodes, laboratory-made electrodes, and cellulose electrodes. The weld heat inputs employed were 1.7 kJ/mm and 3.2 kJ/mm. Table 4 shows the carbon equivalents of the tested steels and the welding conditions.

After the completion of test welding, y-groove weld cracking test pieces were kept for three days in a chamber where the temperature was constantly held at 20°C. The occurrence of root cracking was macro-photographically examined on five transversely sectioned pieces from a y-groove weld cracking test piece, and then the critical preheat temperature at which root cracks are stopped was determined. Thus obtained critical preheat temperatures are shown as $T_{cr}$ in Table 4.

Necessary preheat temperatures for the test cases in Table 4 were predicted by the preheat determining methods of the BS-5135[10], the AWS-D1.1-91[11], the AWS-D1.1-Appendix-XI-91[12], and the chart method. The assumption made in the prediction is that the restraint level is high for the AWS Appendix-XI, the welding condition is normal for the BS-5135, and the weld metal yield strength is 90% of the steel tensile strength in the chart method. The predicted results are listed in Table 5. The chart method can predict two preheat temperatures; one is the critical preheat temperature for y-groove weld cracking tests and the other is the necessary one for actual welding practices ($T_a$ in Table 5).

A satisfactory agreement is recognized between the y-groove weld cracking test results ($T_{cr}$) and the prediction by the chart method, while a fairly good agreement is recognized

**Table 3** Chemical Composition of Steels for Additional y-Groove Weld Cracking Tests.

| Steel | C | Si | Mn | P | S | Cu | Ni | Cr | Mo | V | B | CE(IIW) | Pcm | CEN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TS400MPa | .116 | .22 | 1.18 | .022 | .0028 | .009 | .02 | .019 | - | - | - | .318 | .184 | .270 |
| TS490MPa | .174 | .40 | 1.38 | .017 | .0045 | .009 | .02 | .023 | - | - | - | .411 | .258 | .414 |
| TS590MPa | .173 | .29 | 1.30 | .018 | .0057 | .007 | - | .018 | - | .054 | .0001 | .404 | .255 | .405 |
| TS780MPa | .131 | .24 | 0.80 | .006 | .0035 | .21 | .80 | .51 | .466 | .032 | .0009 | .534 | .267 | .455 |

Table 4　Experimental Conditions and results for y-Groove Weld Cracking Tests.

| Test No. | Steel | Thickness (mm) | Carbon Equivalent CE(IIW) (%) | Pcm (%) | CEN (%) | Heat Input (kJ/mm) | Electrode | Hydrogen (ml/100gr) | Tcr[1] (℃) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | E7016-G | 5 | 20 |
| 2 | TS400MPa | 25 | 0.318 | 0.184 | 0.270 | 1.7 | E7016-X[2] | 13 | 20 |
| 3 | | | | | | | E7010-G | 40 | 75 |
| 4 | | | | | | | ER70S-G[3] | 1 | 20 |
| 5 | TS490MPa | 20 | 0.411 | 0.258 | 0.414 | 1.7 | E7016-G | 5 | 100 |
| 6 | | | | | | | E7016-X[2] | 13 | 125 |
| 7 | | | | | | | E7010-G | 40 | 150 |
| 8 | TS590MPa | 25 | 0.405 | 0.255 | 0.404 | 1.7 | E7016-X[2] | 13 | 100 |
| 9 | | | | | | | E7010-G | 40 | 125 |
| 10 | | | | | | | ER70S-G[3] | 1 | 20 |
| 11 | TS780MPa | 40 | 0.534 | 0.267 | 0.455 | 1.7 | E11016-G | 3 | 100 |
| 12 | | | | | | | E7016-G | 5 | 150 |
| 13 | | | | | | | E7016-X[2] | 13 | 175 |
| 14 | TS790MPa | 40 | 0.534 | 0.267 | 0.455 | 3.2 | E7016-G | 5 | 100 |

1):Necessary preheat temperature to avoid cold cracking at HAZ
2):E7016-X is E7016-G with middle hydrogen, made on an experimental basis
3):ER70S-G is for GMAW process. Others are for SMAW process

Table 5　Predicted Necessary Preheat Temperatures.

| Test No. | Steel | Tcr (℃) | Predictions: BS-5135 | AWS-D1.1 | AWS-D1.1 Appendix XI | Present Method y-groove | Present Method Ta[1] |
|---|---|---|---|---|---|---|---|
| 1 | | 20 | 20 | - | 20 | 20 | 20 |
| 2 | TS400MPa | 20 | 20 | 66 | 85 | 20 | 20 |
| 3 | | 75 | 20 | 66 | 116 | 61 | 20 |
| 4 | | 20 | 20 | 20 | 20 | 20 | 20 |
| 5 | TS490MPa | 100 | 20 | 20 | 116 | 80 | 22 |
| 6 | | 125 | 20 | 66 | 138 | 132 | 74 |
| 7 | | 150 | 20 | 66 | 149 | 153 | 95 |
| 8 | TS590MPa | 100 | 20 | - | 138 | 137 | 87 |
| 9 | | 125 | 20 | - | 149 | 155 | 105 |
| 10 | | 20 | 125 | 80 | 129 | 20 | 20 |
| 11 | | 100 | 125 | 80 | 149 | 125 | 114 |
| 12 | TS780MPa | 150 | 125 | 80 | 149 | 156 | 145 |
| 13 | | 175 | 175 | - | 149 | 184 | 173 |
| 14 | | 100 | 20 | 80 | 149 | 121 | 110 |

1):Necessary preheat temperature for ordinary conditions predicted by using the Present Method between the AWS Appendix-XI and $T_{cr}$. However, the necessary preheat temperature given by the AWS Appendix-XI (a high restraint case) is fairly higher than $T_a$, that should be employed in practice by the chart method, for the lower tensile strength steels. Instead, AWS D1.1 gives the necessary preheat temperatures close to $T_a$.

The AWS Appendix-XI and the BS-5135 give the same preheat temperatures irrespective of the steel grade or the steel strength level if the relevant steel carbon equivalent does not differ. For instance, the AWS Appendix-XI gives the almost same preheat temperature for the TS490 MPa steels and the TS780 MPa steels because of their similar Pcm values, and the BS-5135 also give the same temperatures for the TS490 MPa and TS590 MPa steels because of their similar $CE_{IIW}$ values. On the contrary, the chart method considers the effect of residual tensile stresses or the weld metal strength and gives $T_a$ different from $T_{cr}$ as shown in Table 5.

The AWS Appendix-XI successfully predicts the effect of weld metal hydrogen on the y-groove weld cracking tests ($T_{cr}$) for TS490 MPa grade steels (Test No. 4, 5, 6 and 7). There seems to be no effects of weld metal hydrogen for the TS400 MPa, TS490 MPa and TS590 MPa steels according to the BS-5135. This stems from the fact that the plate thicknesses of those steels are 20 mm and 25 mm which are too thin for the BS-5135 to recognize the hydrogen effect.

The AWS D1.1 and the AWS Appendix-XI do not consider the effect of a welding heat input, and thus the same preheat temperatures are predicted for the test cases of No. 12 and No. 14. The BS-5135 takes this effect into account. However, a considerable difference is seen between the 1.7 kJ/mm heat input of Test No. 12 and the 3.2 kJ/mm heat input of Test No. 14 ; the preheat temperature for the former case is 125°C and that for the latter is 20°C. The heat-input effect of that extent would be expected in the steels with lower hardenability or lower $CE_{IIW}$ as shown in Fig. 4 but it is not so for such a steel as a TS780 MPa grade with high hardenability.

## 4. Effect of Weld Metal Hydrogen

The BS-5135 classifies the weld metal hydrogen, $H_D$ into four groups : A ($15<H_D$), B ($10<H_D \leq 15$ ml/100 g), C ($5<H_D\leq 10$ ml/100 g), and D ($H_D\leq 5$ ml/100 g). In the BS-5135, the necessary preheat temperature is determined by a graph corresponding to the given $CE_{IIW}$ which depends on the hydrogen level (scale A to D). These four different levels of a linear scale can be converted into the difference in $CE_{IIW}$. It may be stated that each graph in the BS-5135 is given for the $CE_{IIW}$ corrected by a hydrogen level. The chart method follows the BS-5135 in the concept of the conversion of the hydrogen effect into carbon equivalency. In the BS-5135, furthermore, the conversion from the hydrogen group A to B is equal to 0.02 in $CE_{IIW}$, A to C is 0.04 and A to D is 0.09, respectively. This conversion is somewhat logarithmic. Nevertheless, the BS-5135 seems to be unable to reflect the effect of weld metal hydrogen correctly on the preheat temperature determination, especially in the lower hydrogen welding, because it is based on the linear grouping of weld metal hydrogen of a 5, 10, and 15 scale. In fact, the AWS A5 Committee[27] has concluded that "a logarithmic scale of benchmarks for defining better low hydrogen electrodes was more logical than the IIW linear system" which is equivalent to the BS -5135.

A JSSC (Japan Steel Structure Construction) procedure[4] adopts a linear effect of hydrogen. The cold cracking susceptibility index, $P_c$ in this procedure is as follows :

$$P_c = Pcm + H_D/60 + K/4000 \qquad (1)$$

where, $H_D$ : diffusible weld metal hydrogen by a glycerine method (ml/100 g), K : restraint intensity of a joint (Kgf/mm/mm).

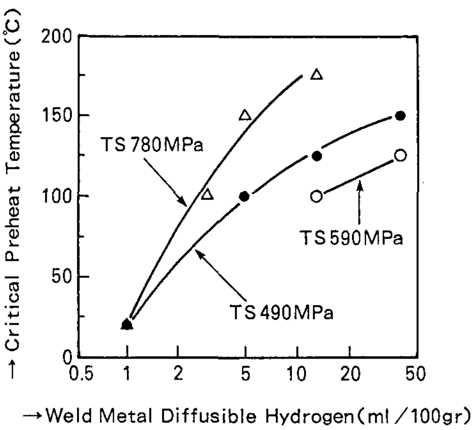
Itoh et al.[3] later suggested that the term of $H_D$ should be replaced by 0.093 $\log(H_D)$, taking the logarithmic effect of hydrogen into account. Many methods regard a weld metal effect as logarithmic while the coefficient of $\log(H_D)$ being slightly different[2,6,8,9,12,24].

The experimental results concerning the hydrogen effect are plotted in Fig. 6, where the critical preheat temperatures in y-groove weld cracking tests are indicated against a logarithm of hydrogen in Fig. 6a and in a linear scale in Fig. 6b. It is absolutely obvious that the logarithmic description of the hydrogen effect is more logical than the linear description.

Let us now attempt to verify the logarithmic dependence of hydrogen. Cold cracking is generally initiated when a weld cools below 100°C[28]. The hydrogen effusion from a weld is limited below 100°C or thereabouts because of the low hydrogen diffusion rates in lower temperatures. In other words, the remaining hydrogen at 100°C, ($H_R$), that is effective to the cold cracking initiation and propagation, is determined as a function of thermal history till 100°C[9] :

$$H_R = H_o \cdot f(t_{100}) \qquad (2)$$

where, $H_o$ : initial hydrogen content that is the weld metal diffusible hydrogen (ml/100 g), $t_{100}$ :



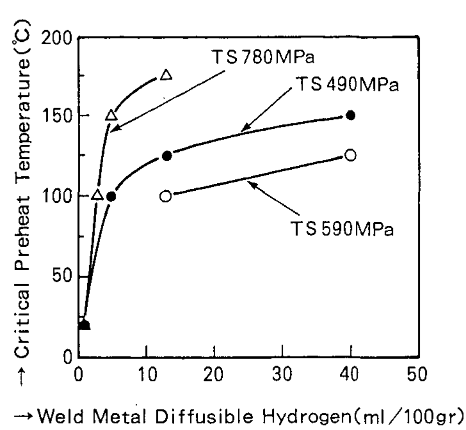




**Fig. 6** Relation between y-Groove Weld Cracking Test Results and Weld Metal Hydrogen.

**Table 6** Welding Conditions for a Case Study.

| Steel | Carbon Equivalent | Critical Preheat Tcr (℃) | Weld Metal Hydrogen Ho (ml/100g) | Cooling Time $t_{100}$ (s) |
|---|---|---|---|---|
| Steel-1 | CE1 | 50 | 2 | ta |
| | | 100 | 4 | tb |
| Steel-2 | CE2 | 50 | 5 | ta |
| | | ? | 10 | ? |

cooling time to 100°C after the completion of welding (s).

The primary objective of preheating is to extend $t_{100}$ and to reduce $H_R$.

A case study is attempted to verify the logarithmic relation. Let us suppose in this case study that the critical preheat temperatures are 50°C under the welding of weld metal hydrogen of 2 ml/100 g and 100°C under 4 ml/100 g for the Steel-1 with carbon equivalency of CE1. Suppose the critical preheat temperature is 50°C under the weld metal hydrogen of 5 ml/100 g for the Steel-2 with CE2, then what is the critical preheat temperature for Steel-2 in the welding with weld metal hydrogen of 10 ml/100 g? This situation is depicted in Table 6.

From Eq. 2, the residual hydrogen is given as:

$$H_R(\text{Steel-1}) = 2\cdot f(t_a) = 4\cdot f(t_b) \quad (3)$$

$$H_R(\text{Steel-2}) = 5\cdot f(t_a) \quad (4)$$

Then, the following relation results from Eq. 3 and Eq. 4:

$$H_R(\text{Steel-2}) = 10\cdot f(t_b) \quad (5)$$

Since $t_b$ is the cooling time for the 100°C preheating, Eq. 5 implies that 100°C is the answer for the critical preheat temperature for Steel-2 welded with weld metal hydrogen of 10 ml/100 g.

Almost all the methods determining necessary preheat temperature use a parameter which includes the carbon equivalency and the hydrogen effect. This parameter may be called a cold cracking susceptibility index, CI which is expressed like Pc in Eq. 1 as:

$$CI = CE + g(H_o) \quad (6)$$

Assuming that $g(H_o)$ is of a logarithmic function, i.e., $g(H_o) = A\log(H_o)$ where A is constant, then CI is given for the case of Table 6 as follows:

$$CE1 + A\log(2) = CE2 + A\log(5)$$
$$\text{for 50°C preheat} \quad (7)$$

$$CE1 + A\log(4) = CE2 + A\log(10)$$
$$\text{for 100°C preheat} \quad (8)$$

An identical answer is derived from both Eq. 7 and Eq. 8:

$$CE1 - CE2 = A\log(5/2) \quad \text{from Eq. 7}$$
$$= A\log(10/4) \quad \text{from Eq. 8} \quad (9)$$

As indicated in Eq. 9, there is no inconsistency in the logarithmic assumption for the hydrogen effect. However, if the linear function is assumed for $g(H_o)$, then $g(H_o) = B\,H_o$ where B is constant and it follows:

CE1+B×2=CE2+B×5
for 50°C preheat (10)
CE1+B×4=CE2+B×10
for 100°C preheat (11)
From Eq. 10, CE1−CE2=B×3 (12)
From Eq. 11, CE1−CE2=B×6 (13)

Eq. 12 and Eq. 13 do not meet each other. It can, therefore, be concluded that the effect of weld metal diffusible hydrogen on the cold cracking susceptibility must be logarithmic.

## 5. Other Considerations in Preheating

The occurrence of cold cracking is greatly influenced by a notch concentration factor at the vicinity of a cracking initiation site, and a notch concentration factor is notably high in root welds in partial penetration welding[6]. However, in normal welding practice, root cracks are inspected after the completion of V-groove welding or at the back gouging of root welds of a first pass side in double-V (X) and double single bevel (K) welding. The chart method is on the premise of these cases. Therefore, preheat temperatures should be somewhat higher than that given by the chart method for the partial penetration welding in which a difficulty inherently arises in the inspection of root cracking. The preheat for the repair welding case in Fig. 5 may be recommended for the partial penetration welding.

The cooling time to 100°C, $t_{100}$ is governed not only by a preheating temperature but also by a preheating method. Localized preheating or preheating with a rapid heating rate considerably shortens $t_{100}$. The master curves of Fig. 2 is for homogeneous preheating, and uniform preheating with a slow heating rate is thus recommended in welding practices. Otherwise, preheating temperatures must be raised higher than that given by the chart method.

The master curves assumes that y-groove weld cracking tests are conducted at the ambient temperature of around 10°C. The authors proposed a method of the conversion of an ambient temperature effect to the CEN increment so that the chart method can be used for the case of a different ambient temperature[29]. At any rate, the necessity of preheating is relaxed in a hot climate but higher preheating temperatures than that given by the chart method should be employed in a cold climate.

Furthermore, the most recommended measures to avoid cold cracking especially in stringent conditions is postheating immediately after the completion of welding or the sustenance of a weld at temperatures higher than the necessary preheat temperature during multi-pass welding. This measures is very effective from a viewpoint of the extension of $t_{100}$ which results in the enhancement of hydrogen effusion from a weld. Although there is no rule stipulating the condition of the immediate postheating, the temperature and the duration for this heat treatment may be 150° or thereabouts and around 10 mins per 25 mm thickness, respectively.

## 6. Conclusion

A chart method determining preheat temperatures was reviewed focussing on the effect of carbon equivalency and weld metal diffusible hydrogen. The validity of the BS-5135, the AWS D1.1, and the chart method was compared based on the cold cracking test results.

1) A number of carbon equivalents have been proposed. However, there is no perfect carbon equivalency which can evaluate HAZ hardness and a microstructure change both affected by a welding cooling rate. Among them, CEN carbon equivalent is considered a preferable index in assessing the cold cracking susceptibility of a wide variety of steels.

2) The effect of weld metal diffusible hydrogen on the cold cracking susceptibility must be not linear but logarithmic, from both the experimental facts and the analysis of hydrogen diffusion.

3) It seems difficult for a simple formula of the susceptibility index to determine necessary preheat temperatures in steel welding. This is because cold cracking is influenced independently or in an interacted manner by many factors including the steel chemical composition, the weld heat input, the weld thickness, the weld metal diffusible hydrogen, the weld metal strength, the joint constraint and others. A chart method, which takes all the above effects into account and is based on CEN and logarithm of hydrogen, is considered preferably reliable for a wide variety of welding conditions.

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