Determination of Necessary Preheating Temperature in Steel Welding

Findings include a new carbon equivalent to assess the susceptibility of steel to cold cracking more satisfactorily

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ABSTRACT. Various tests used when determining critical preheating temperatures to avoid cold cracking were examined. These included the Stout slot, H-slit type, V-groove restraint, and y-groove restraint tests. Both conventional and newly developed types of steel having carbon contents ranging between 0.02 and 0.26% were used.

Examination of the cracking tests resulted in the proposing of a new carbon equivalent that more satisfactorily assesses the susceptibility of steel to cold cracking than do CE(IIW) and P<sub>cm</sub>. It is expressed as:

\[ CE = C + \frac{A(C)}{24 \times \frac{Si}{6} + \frac{Mn}{15} + \frac{Cu}{20} + \frac{Cr + Mo + Nb + V}{5} + 58} \]

where \( A(C) = 0.75 + 0.25 \tan h \left( \frac{C - 0.12}{20} \right) \).

As a parameter describing the probability of the occurrence of cold cracking in steel welding, a cracking index (CI) was proposed. It is expressed as:

\[ CI = CE + 0.15 \log H_{ig} + 0.30 \log (0.017 K_{owe}) \]

According to the procedure proposed in this study, the necessary preheating temperatures to avoid cold cracking are determined by satisfying the following criterion:

\[ t_{100} \geq (t_{100})_{cr} \]

where \( t_{100} \) is the cooling time to 100°C (212°F); this is influenced, not only by the preheating temperature employed, but also by welding heat input, plate thickness and preheating method. Critical time \( (t_{100})_{cr} \) is given as:

\[ (t_{100})_{cr} = e^{67.6 Cl + 163.8 Cl^2 - 41.0} \]

Introduction

Methods to determine the necessary preheating temperature for the prevention of cold cracking in steel welding include the 1974 British Standard 5135 (Ref. 1) and a procedure described in Japan Steel Structure Construction (JSSC – Ref. 2). However, there is a considerable difference between the necessary preheating temperatures determined by the two procedures.

British Standard 5135 uses the IIW carbon equivalent as a parameter for determining the preheating temperature, while the JSSC procedure uses Ito’s carbon equivalent, P<sub>cm</sub> (Ref. 3). The IIW carbon equivalent satisfactorily evaluates the cold cracking susceptibility of ordinary carbon or carbon-manganese steels; however, the low-carbon low-alloy steels, such as the recently developed pipeline steels, are more accurately assessed by P<sub>cm</sub>. This has been a problem, especially in deciding the allowable value for the chemical composition of pearlite-reduced pipeline steels or low-carbon-low-alloy structural steels.

Experimental Procedure

Weld Cracking Tests

Stout, et al. (Ref. 4) proposed a slot-weld cracking test in which the weldability of pipeline steel, in the case of welding with high-hydrogen types of cellulose electrodes, can easily be evaluated. Figure 1 shows the dimensions of the standard test piece used.

It was noticed that fluctuations in width of the root opening of this test piece greatly influenced experimental results (Ref. 5). Therefore, slots with a 2.4 mm (0.09 in.) opening were machined on the flat plates. The accuracy of the machined openings was within 0.1 mm (0.004 in.). The weld metal was deposited on the slot using flat position welding with a 4 mm (0.16 in.) diameter electrode cellulose type AWS E7010 in a cold chamber where the ambient temperature was held at 10°C (50°F). The welding voltage, current and torch speed were approximately 28V, 160A, and 5 mm/s (11.8 ipm), respectively.

In order to investigate cold cracking in the case of low-hydrogen welding, the present study used the results of H-slit tests (Ref. 6, 7), V-groove tests and y-groove tests (Ref. 8). Figure 2 shows the shape of the H-slit test piece in which the restraint intensity is varied with a change in the slit length B<sub>s</sub>. The restraint intensity R<sub>f</sub> (kgf/mm · mm) is a force per unit weld length necessary to reduce a root opening by unit length. Table 1 shows R<sub>f</sub> for each test piece used in the present study. The meaning of r<sub>f</sub> and R<sub>f</sub> is explained in the Appendix under the heading, “Restraint Stress Acting on Weld.”

In each type of cracking test, test pieces were preheated to the various temperatures up to 200°C (392°F) until crack initiation was completely stopped. The Stout test pieces were preheated in the furnace, while other test pieces were locally preheated by electrical strip heaters in the manner shown in Fig. 2. In the case of multipass welding, the interpass temperatures were kept almost the same.

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as the preheating temperatures.

Each test piece was transversely cut into five sections after more than 72 hours (h) had passed since completion of the welding. Macrographic observation of nitric etched weld sections led to the determination of the critical preheating temperatures $T_m$ at which the occurrence of cold cracks was prevented. Figure 3 shows an example of a weld with a root crack in the Stout test.

Materials

The Stout slot weld tests were carried out with various types of steels employed for ordinary structures, pressure vessels, boilers, and pipelines. Their tensile strengths ranged between 40 and 85 kgf/mm$^2$ (57 and 121 ksi), and their chemical compositions are shown in Table 2. In the Stout test, one type of electrode, i.e., AWS E7010, was used irrespective of the strength level of the tested steel. The hydrogen content in the deposited weld metal using this electrode was 35 ml/100g by JIS glycerin displacement method. This value, $H_w$, can be converted to $H_{sw}$ by the mercury displacement method (Ref. 9):

$$H_{sw} = 1.30 H_w + 0.61 \quad (1)$$

Table 3 shows the chemical compositions of steels used in the H-slit cracking tests, the V-groove tests and the Y-groove restraint tests. These steels were for structural or pressure vessel usage with greater thicknesses up to 100 mm (3.9 in.). Tests, other than the Stout test, employed electrodes whose strength corresponded to those of the steels tested. Table 4 shows nominal yield strengths and hydrogen contents of the welding materials used; welding conditions for the cracking tests are also described in Table 4.

Results and Discussion

Critical Preheating Temperature Measured in Tests

Critical preheating temperature $T_m$ in the Stout tests is shown in Table 2. The results of the H-slit, V-groove and Y-groove restraint tests are summarized in Table 5. $K_y$ in Table 5 is the stress concentration factor at the notch where a crack is initiated, and its value is given in the Appendix under the heading, "Restraint Stress Acting on Weld." The mean stress acting on the weld metal is given as a function of $\sigma_y$ and $R_F$ as (Ref. 10):

$$\sigma_w = \frac{0.050 R_F}{(R_F \leq 20 \sigma_y)}$$

$$\sigma_w = \sigma_y + 0.0025 (R_F - 20 \sigma_y), \quad (R_F > 20 \sigma_y) \quad (2)$$

The critical preheating temperatures were obtained separately for single-pass root cracking (Fig. 4), multipass root cracking (Fig. 5) and multipass toe cracking (Fig. 6) for each steel tested. Toe cracks were not observed in the specimens of SM41B, SM53B, HW45, and HW70 steel. $T_m$ for multi-pass root cracking was found to be less than that for single-pass root cracking by over 50°C (122°F). Table 5 also lists $t_{100}$, which is the duration of the cooling time to 100°C (212°F) after welding and corresponds to $T_m$ measured in the tests.

The weldment eventually cools to the ambient temperature whether it is preheated or not. Some hydrogen escapes from the weld metal surface during the cooling period after welding. However, hydrogen escape becomes more and more inactive with a decrease in the temperature of the weld metal and it becomes negligibly small at temperatures less than 100°C (212°F).

The residual hydrogen in welds contributes to the initiation of cold cracking when it cools below 100°C (212°F) in an
ordinary structural steel weld. It follows that the $t_{900}$ is significant in selecting preheating temperatures.

Preheating increases the cooling time to $100^\circ$C ($212^\circ$F) and thus is effective in preventing the initiation of cold cracking. However, the duration of the cooling time to $100^\circ$C ($212^\circ$F) is determined, not only by the preheating temperature, but also by the plate thickness, the particular preheating method used and other factors. These relations are shown in Figs. 11 and 12 in the Appendix. Consequently, it is advisable to consider the critical cooling time to $100^\circ$C ($212^\circ$F) rather than rely solely on the preheating temperature when desiring to avoid cold cracking in steel welding (Ref. 2).

### Carbon Equivalent to Assess Cold Cracking

Many carbon equivalents have been proposed as parameters indicating a steel's susceptibility to cold cracking at the heat-affected zone. They can be divided into two groups wherein CE(IW)

$$CE(IW) = C + \frac{Mn}{6} + \frac{Cu + Ni}{15} + \frac{Cr + Mo + V}{5}$$

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

$P_{cm}$ has been shown to be reliable for evaluating the cold cracking tendency in low-carbon low-alloy steel (Ref. 11). On the other hand, CE(IW) is reported to be a more appropriate parameter than $P_{cm}$ for evaluating the cold cracking susceptibility of steels whose carbon content is more than 0.16% (Ref. 7). Therefore, it is not possible for one simple carbon equivalent formula to describe, overall, the cold cracking tendency of steels if their
carbon contents range widely.

It is with this point of view in mind that the authors propose the following carbon equivalent, which has an accommodation factor $A(C)$ as a function of the carbon content:

$$CE = C + A(C) \cdot \left\{ \frac{\text{Si}}{24} + \frac{\text{Mn}}{6} + \frac{\text{Cu}}{15} + \frac{\text{Ni}}{20} + \frac{\text{Cr} + \text{Mo} + \text{Nb} + V}{5} + 3B \right\}$$

(5)

where $A(C) = 0.75 + 0.25 \tanh \left( \frac{20(C - 0.12)}{2} \right)$.

$A(C)$ increases with an increase in carbon content. It approaches 0.5 as the carbon content decreases below 0.08% and 1.0 as it increases above 0.18%. The relationship between this carbon equivalent and CE(IW) is shown in the Appendix under "New Carbon Equivalent."

Experimental results from the Stout cracking tests were used to compare the three types of carbon equivalents for validity in assessing the cold cracking tendency of steels. The relation of $T_{a}$ to the three carbon equivalents was plotted in Fig. 7. It is seen that the carbon equivalent expressed in equation (5) had the highest linear correlation coefficient ($r = 0.911$%); therefore, it is the most reliable of the three carbon equivalents, provided that the carbon content of the steels to be compared ranges widely.

Index to Describe Cracking Probability

Ito, et al. proposed $P_{cr}$ (Ref. 3) and Suzuki recently proposed $P_{a}$ (Ref. 11) as parameters to describe the likelihood of cold cracking. The parameters involve chemical composition, hydrogen content and acting stress, which are three major causes of cold cracking in welds.
In this study, a cracking index, based on the same concept as $P_w$ or $P_H$, was introduced using the new carbon equivalent (CE) from equation (5) as:

$$CI = CE + 0.15 \log H_{JS} + 0.30 \log(0.017 K_w a_w)$$  

(7)

A CI was computed for each of the weld cracking tests and is also listed in Table 5. The CI thus obtained were plotted against ($t_{100}$) corresponding to $T_0^*$ in Fig. 8 by making use of $t_{100} - T_0$ relations shown in Figs. 11 and 12 in the Appendix. Then, a curve representing the relationship between ($t_{100}$) and CI was obtained by best fitting it to the plotted experimental results in Fig. 8. It was expressed as:

$$(t_{100})_r = \exp(67.6 CI^3 - 182.0 CI^2 + 163.8 CI - 41.0)$$  

(6)

The ($t_{100}$) is the critical value, in that cracking can be prevented under the welding condition described by the cracking index, CI, if the duration of the cooling to 100°C (212°F) in actual welding exceeds the ($t_{100}$).

**Determination of Necessary Preheating Temperature**

The following procedure may be used to determine the necessary preheating temperature in steel welding. It is the same in its basic concept as the procedure proposed by JSSC (Ref. 2).

1. Obtain the carbon equivalent of the steel to be welded using equation (5).
2. Obtain the hydrogen content of the welding material.
3. Determine $K_w$ using the chart in Fig. 9, and $a_w$ using Fig. 10 and equation (2).
4. Calculate CI using the values of CE from equation (5), $H_{JS}$, $K_w$ and $a_w$ using equation (7).
5. Calculate ($t_{100}$) from CI using equation (8).
6. Finally, select the preheating temperature, taking into account $h$, $2b$, and $E$ in Figs. 11 and 12 so that the following condition is satisfied:

$$(t_{100})_r > (t_{100})_c$$  

(9)

The necessary preheating temperatures were estimated according to the procedure for H-slit tests and others. They are shown as the estimated $T_0^*$ in Table 5. Since the procedure above was conducted by the authors, it may have some limitations. Moreover, the following precautions are required:

1. Unnecessary high preheating temperatures are given for the welding of mild steels and for the welding with high-hydrogen welding materials. Both cases did not fit equation (8) as seen in Fig. 8.
2. Weld metal cracking is more likely to occur than heat-affected zone cracking when welding steels with a lower CE or when using high-hydrogen materials.
3. The critical preheating temperature for multipass root cracking is less than that for single-pass root cracking by approximately 50°C (90°F), provided that interpass temperatures are kept...
higher than the preheating temperatures.
4. If root cracks are to be removed by backgouging, the preheating temperature for toe cracking ($K_t = 1.5$) may be employed.

Conclusions

1. The CE from equation (5) is a more appropriate parameter than CE(IIW) or $P_{cm}$ for assessing the susceptibility of steel to cold cracking.

2. The cracking index, $C_l$, given by equation (7) satisfactorily describes the likelihood of cold cracking of steel under varying chemical compositions, welding material hydrogen content, and joint restraint intensity.

3. The necessary preheating temperature can be determined by satisfying the condition that $t_{100} > (t_{100})_{cr}$. The critical cooling time $(t_{100})_{cr}$ is given as a function of $C_l$ by equation (8).

Appendix

Restraint Stress Acting on Weld

The occurrence of cracking is greatly influenced by the severity of the notch where a crack is initiated. Figure 9 shows the stress concentration factors at weld roots and toes with various types of weld grooves (Ref. 11).

Watanabe, et al. (Ref. 12) calculated the two-dimensional restraint coefficient, $r_f$, for an H-slit test specimen as:

$$r_f = \frac{E}{B_s + (L_c/2L_s)B_s + B_s'}$$  \hfill (A1)

where $E$ is Young's modulus; $B_s$, $L_c$, and $L_s$ are...
are shown in Fig. 2; and $B'_s$ is an imaginal increment of the slit length due to the elastic reaction of a steel specimen. $B'_s$ is 304 mm (12 in.) for type I specimens and 446 mm (17.6 in.) for type II.

Generally speaking, $r_f$ is 70 kgf/mm$^2$ (26.3 kpsi) for the severest restraint and about 40 kgf/mm$^2$ (15,000 lbf/in.$^2$) for ordinary restraint (Ref. 10). The restraint intensity, $R_p$, is given by the product of $r_f$ and the plate thickness, $h$, in the case of thin plate and pipe. However, an FEM analysis of three-dimensional elastic test pieces revealed that $R_p$ did not increase in proportion to $h$ in a greater thickness region (Ref. 13). The approximate relationship between $R_p$, $r_f$, and $h$ is given as:

$$R_p = 71 r_f \left( \arctan \left( \frac{0.017 h}{h/400} \right) \right)$$ (A2)

This relation is graphically shown in Fig. 10.

Cooling Time to 100°C

The cooling time to 100°C (212°F) after the completion of welding under various conditions is available in the literature (Ref. 14). For the limited case of local preheating by electric heaters, times are given in Fig. 11 for 1,700 J/mm (76,200 J/in.) of heat input and in Fig. 12 for 3,000 J/mm (122,600 J/in.).

New Carbon Equivalent

The carbon equivalent proposed—CE as calculated from equation (5)—has an accommodation factor, $A(C)$, which is a function of the carbon content of the steel as:

$$A(C) = 0.75 + 0.25 \tanh \left( \frac{20(C - 0.12)}{C} \right)$$ (6)

The graphic relation of $A(C)$ to carbon content, $C$, is given in Fig. 13. The CE as calculated from equation (5) can be rewritten as:

$$CE_{eq}(s) = C + A(C) \cdot (CE\text{ (IIW)} + 0.012 - C)$$ (A3)

The relationship between $CE_{eq}(s)$ and CE(IIW) was examined for various types of steel, including those listed in Tables 2 and 3 and others. It is seen in Fig. 14 that equation (A3) holds for steels having Nb less than 0.02% and Si ranging from 0.24 to 0.48%.

Equation (A3) implies that CE(IIW) values equal to $CE_{eq}(s)$ significantly increase in the region of lower carbon content as shown in the dotted lines in Fig. 13. The present study showed that $CE_{eq}(s)$ is more appropriate in assessing steel's susceptibility to cold cracking than CE(IIW). It follows that steel with a low carbon content is considered less susceptible to cold cracking, even when the CE(IIW) of the steel is high.

References