1. Introduction

Steel weldability represents how preferably a steel can be welded without weld defects and how satisfactorily a joint welded with a relevant steel performs during service. In the narrow sense, preferable weldability means that steels can be welded with less hardened heat-affected-zones (HAZ) and without a risk of hydrogen-assisted cold cracking. Weldability of a steel has been long evaluated on the empirical basis of welding practices. However, some studies have been carried out for assessing steel weldability from a viewpoint of physical metallurgy. These studies will be reviewed.

2. HAZ Hardenability

A ferritic steel is completely austenitized at the weld heat affected zone (HAZ) during welding. The austenitized HAZ transforms into ferrite, pearlite, bainite, martensite or their mixture depending on the cooling rate after welding. Austenitic grains are most coarsened and most hardened at HAZ near the weld fusion boundary. In 1940, Dearden and O’Neil found a following relation between maximum Vickers hardness (Hv) of HAZ and the steel chemical composition:

\[
Hv \text{ (max)} = 1200\text{CE}_{\text{Dearden}} - 200 \quad \ldots \quad (1)
\]

As seen in Eq. (2), the effect of the chemical composition on the maximum hardness at HAZ is given by a summation of each alloy element content. This is the origin of carbon equivalency to assess steel weldability. This carbon equivalent was modified into the following formula by IIW (International Institute of Welding) and CEIIW has been long used as a weldability index.

\[
\text{CE}_{\text{IIW}} = C + \frac{\text{P}}{2} + \frac{\text{Mn}}{6} + \frac{\text{Cu}}{13} + \frac{\text{Ni}}{15} + \frac{\text{Cr}}{5} + \frac{\text{Mo}}{4} + \frac{\text{V}}{5} \quad \ldots \quad (2)
\]

\[
\text{CE}_{\text{Dearden}} = C + \frac{\text{Mn}}{6} + \frac{\text{Cu} + \text{Ni}}{15} + \frac{\text{Cr} + \text{Mo} + \text{V}}{5} \quad \ldots \quad (3)
\]

As seen in Eq. (2), the effect of the chemical composition on the maximum hardness at HAZ is given by a summation of each alloy element content. This is the origin of carbon equivalency to assess steel weldability. This carbon equivalent was modified into the following formula by IIW (International Institute of Welding) and CEIIW has been long used as a weldability index.

The concept of hardenability used in the welding field differs from that used in the heat treatment. It represents the hardened depth after quenching in the heat treatment while it is related with the welding condition for fully hardened heat-affected-zone (HAZ) in the welding. The effect of steel chemical composition on hardenability is expressed by a multiplying factor for the former and by carbon equivalency for the latter. The metallurgical relation between these two factors can be clarified by a heat conduction analysis of a quenched round bar.

Steel weldability means susceptibility to hydrogen-assisted cold cracking which mostly occurs in the welding of high strength steels. Many carbon equivalents with different coefficients have been proposed to assess the cold cracking susceptibility which is affected greatly by the hardness at HAZ. Since the HAZ hardness is interactively determined by the carbon content and hardenability, carbon equivalency for assessing susceptibility to cold cracking must consider this interactive effect.

Toward the international standardization of the guideline for the avoidance of cold cracking, the methods based on different carbon equivalency are discussed.

KEY WORDS: weldability; hardenability; heat affected zone; cold cracking; hardness; carbon equivalent.
where CRM is the cooling rate (°C/s) at 700°C. Since then, many researchers reported empirical relations between HAZ hardenability and steel chemical composition. The following is one of them:

\[
\ln(CRM) = 5.13.9 - 10.6CE_{\text{Bastien}}
\]

where \(CE_{\text{Bastien}}\) represents a contribution of boron and steel cleanliness to hardenability. The effect of steel cleanliness on HAZ hardenability is rather insignificant, while the effect of boron is markedly significant in very small amount. Boron rapidly diffuses into austenite grain boundaries to prevent ferrite nucleation at the grain boundaries. In other words, the martensite formation is facilitated (the ferrite formation is retarded) and hardenability is raised by boron segregated at the boundaries. Austenite grains are coarsened at HAZ, and thus boron from 3 to 5 ppm is enough to segregate and cover all HAZ austenitic grain boundaries. It should be noted that 10 to 30 ppm of boron is necessary to harden a parent steel with rather fine grains.

In the field of steel heat treatment, steel hardenability is indicated by an ideal diameter of a quenched round bar, \(D_I\), which is of a form of multiplication of each alloying element content. Holloman reported a following relation between the austenitizing temperature of the weld HAZ and the latter being higher than 1500°C. However the austenitizing duration is quite different. That for the former is several hours and for the latter is several seconds.

Kasuya and the present author conducted a heat conduction analysis of the cooling rate at the center of a quenched round bar shown in Fig. 2 and found a following relation between \(t_M\), CRM and \(D_I\):

\[
\ln(t_M) = 5.13.9 - 10.6CE_{\text{Harden}} - 4.8
\]

where \(D_{\text{C}}\) is determined by the carbon content and the austenite grain size, and \(f_B\) is determined by the boron content. The austenitizing temperature of the weld HAZ differs from that of the heat treatment, the former being around 850°C and the latter being higher than 1500°C. However the austenitizing duration is quite different. That for the former is several hours and for the latter is several seconds.

Kasuya and the present author conducted a heat conduction analysis of the cooling rate at the center of a quenched round bar shown in Fig. 2 and found a following relation between \(t_M\), CRM and \(D_I\):

\[
\ln(t_M) = 5.13.9 - 10.6CE_{\text{Harden}} - 4.8
\]

where \(x\) is the concentration of each alloy element. As seen in Eqs. (4), (5), (6) and (7), \(\ln(D_{\text{C}})\) and \(\ln(CRM)\) are described as a linear combination of alloy content. Therefore, \(\ln(D_{\text{C}})\) must be so from the relation of Eq. (9), and thus \(D_{\text{C}}\) is described as the product of some function given by each alloy content alone such as Eq. (8). Substituting Eq. (8) into Eq. (9) gives the coefficients for each element in a linear combination (carbon equivalency). The computed coefficients preferably coincide with those of Eqs. (3) and (7). It is proven that IIW carbon equivalent of Eq. (3) is a hardenability index rather than a hardness index.

3. Hydrogen Assisted Cold Cracking
3.1. Weldability Index

In arc welding, all water in welding consumables and any moisture in arc environments are decomposed into hydrogen due to arc of violently high temperatures and the hydrogen dissolves excessively in the molten weld metal. Dissolved hydrogen diffuses to hardened HAZ of high dislocation density (low chemical potential of hydrogen), causing hydrogen-assisted cracking some hours or some days after welding. Since this cracking occurs after a welded joint completely cools down, it is called cold cracking.

Figure 3 shows one type of hydrogen-assisted cold crack at HAZ. Steel weldability denotes in general the susceptibility to hydrogen-assisted cold cracking. As cold cracking is more likely to occur at HAZ with higher hardness, weldability sometimes means a tendency of higher or lower hardness at HAZ.

Table 1 shows some of carbon equivalents proposed as a steel weldability indicator. The carbon equivalents of Group A include the IIW carbon equivalent which has been long
used as a weldability index as described in the previous section. Group A of carbon equivalency is represented by 1/6 for the coefficient of Mn. Those of Group C include Pcm and CEPLS as represented by 1/20 and 1/16 for the coefficient of Mn. Group C regards the effect of carbon as more significant and the effect of alloying elements as less significant on weldability than Group A. As CEPLS is stated as the carbon equivalency for carbon-reduced pipeline steels, Group C is considered to evaluate weldability of rather modern steels or carbon-reduced steels. On the other hand, Group A of carbon equivalent is considered to evaluate weldability of an old type of steel with a rather high carbon content from 0.15 to 0.30%. Group B is between Group A and Group C, as represented by 1/10 for the coefficient of Mn.

Table 1. Formulas of carbon equivalents.

| Group | Formula                                                                 | Reference |
|-------|-------------------------------------------------------------------------|-----------|
| A     | $CE_{LMS} = C + \frac{Mn}{6} + \frac{Cu + Ni}{15} + \frac{Cr + Mn + V}{5}$ |           |
|       | $CE_{PLS} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni + Cr + Mo + V}{4}$ | 7         |
| B     | $CE_{DTR} = C + \frac{Si}{24} + \frac{Mn + Cr + Nb + V}{10} + \frac{Mn + V}{4}$ | 8         |
|       | $CE_{PL} = C + \frac{Mn}{10} + \frac{Cu + Ni + Cr + Mo + Nb + V}{20}$ | 9         |
| C     | $Pcm = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu + Ni + Cr + Mo + V}{15}$ | 10        |
|       | $CE_{PLS} = C + \frac{Si}{25} + \frac{Mn + Cr + Mo + V}{15}$ | 11        |
|       | $CE_{PLS} = C + \frac{Si}{24} + \frac{Mn + Cr + Mo + Nb + V}{15}$ | 12        |
| D     | $CE_{S} = C + A(C)^{\frac{Si}{24}} + \frac{Mn}{6} + \frac{Cu + Ni + Cr + Mo + Nb + V}{15}$ | 13        |

Figure 4 shows the change in HAZ hardness with respect to welding cooling time for a relatively high carbon steel and a carbon-reduced steel. Hydrogen-assisted cold cracking occurs in a case of the welding with a small heat input. Hydrogen is diffused out from welds in high heat input welding with longer $t_{8/5}$. An important issue is HAZ toughness rather than cold cracking in high heat input welding. In the short $t_{8/5}$ range indicated in Fig. 4, HAZ hardness of a higher carbon steel significantly increases with increasing hardenability, while it increases less significantly in a carbon-reduced steel. HAZ hardness of a low-carbon steel
is determined to a more extent by a carbon content than by hardenability. As discussed in the previous section, Group A of carbon equivalency is an indicator of HAZ hardenability. In other words, weldability of a high-carbon steel is more appropriately evaluated by Group A of carbon equivalent, while that of a low carbon steel is by Group C which regards carbon as more important.

The present author et al.\textsuperscript{13} proposed CEN carbon equivalent taking into account the above interactive effect of a carbon content and hardnenability on HAZ hardness as shown in Fig. 4. The CEN carbon equivalent includes an interactive term of carbon and alloying elements. It approaches Group A of carbon equivalent as carbon increases and does Group C with decreasing carbon. Therefore, CEN is considered to be an index for weldability of a wide variety of steels.

3.2. Avoidance of Cold Cracking

The occurrence of hydrogen-assisted cold cracking is influenced by steel chemical composition (carbon equivalency), a hydrogen content of a welding material and welding heat input (hardness and cooling rate). In addition, the welding residual stress, notch concentration factor, weld thickness, welding pass sequences and ambient temperature are the other important factors to cold cracking. The significance of their influences on cold cracking varies depending on the conditions of welding practices.

The most reliable and fail-safe measure to avoid cold cracking is preheating. Figure 5 shows a result of a finite-difference-method analysis on hydrogen accumulation at the fusion boundary HAZ, indicating an significant effect of the preheating temperature.\textsuperscript{14} Preheating with high temperatures reduces the maximum level of accumulating hydrogen so that hydrogen assisted-cold cracking can be resultantly prevented. It is important to determine the minimum necessary preheating temperature in welding practices of high strength structural steels.

Toward the international standardization of the guideline for the avoidance of cold cracks in arc welding, four methods for determining the minimum necessary preheat are being discussed.\textsuperscript{15} They are the British method\textsuperscript{16} based on CE\textsubscript{EN}, the German method\textsuperscript{9} based on CE\textsubscript{T}, the Japanese method\textsuperscript{17} based on CE\textsubscript{N}, and the AWS (American Welding Society) method\textsuperscript{18} based on Pcm and CE\textsubscript{IIW}. The last method specifies the use of Pcm for steels with carbon contents less than 0.11\% and CE\textsubscript{IIW} for steels not less than 0.11\% carbon.

According to the German method, the necessary minimum preheat temperature, $T_p$ (°C) is simply given by a following equation:

$$T_p = 700CE_T + 160 \tanh \left( \frac{d}{35} \right) + 62 \cdot H_{IIW}^{0.35} + (53CE_T - 32)Q - 328$$ \hspace{1cm} (10)

where, $CE_T$, $d$ (mm), $H_{IIW}$ (ml/100 g) and $Q$ (kJ/mm) are the carbon equivalent of Group B in Table 1, the plate thickness, the diffusible hydrogen content of welding material, and the heat input. The other three methods also consider the above factors although carbon equivalent to be referred to differs among the methods. Only the Japanese method further considers welding residual stresses or the yield strength of weld metal.

Hydrogen-assisted cold cracking is more likely in a weld metal rather than in HAZ when higher strength steels are welded. However, the above four methods are aimed for the avoidance of HAZ cold cracking. This important fact must be reflected in the international guideline of steel welding.

4. Conclusion

Hardenability in the field of heat treatment is represented by the hardened depth and the effect of the steel chemical composition is given in a product form. Hardenability in the field of welding is represented by the welding cooling rate. A heat conduction analysis of a quenched round bar proved that the effect of the steel composition on hardenability in the welding must be expressed in a summation form or carbon equivalency as long as the hardened depth is expressed by the composition of a multiplying form.

Weldability of a steel is represented by carbon equivalency. However, carbon equivalent of a simple summation form cannot evaluate weldability of steels from conventional one to carbon-reduced one because the HAZ harness is
interactively determined by carbon content and hardenable-ty. An index for steel weldability must consider this interactive effect.

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