The Great Minds of Carbon Equivalent

Part II: The Adoption of Carbon Equivalent

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In 1958, eighteen years after Dearden and O'Neill's initial proposal on carbon equivalent (CE), the concept was accepted by British Standard BS2642[1]. The standard was then amended to include the following modified version of their equation:

$$CE = C+Si/24+Mn/6+Cr/5+Ni/13+V/5+Mo/4+Cu/15 \quad (1)$$

In 1961, Winterton[2] reviewed twelve CE equations and presented his own:

$$CE_{Winterton} = C+Mn/6+Cr/10+Ni/20-V/10-Mo/50+Cu/40 \quad (2)$$

It is interesting to note that Winterton considered V and Mo to be softening elements instead of hardening elements, which was unique in the evolutionary history of CE equations. In the same year, Kihara, Suzuki and Tamura[3] published their version of the CE equation in Japan:

$$CE_{Kihara} = C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4 \quad (3)$$

After twenty-seven years of extensive research and application of Dearden and O'Neill's CE equation, the International Institute of Welding (IIW) officially published its own version in 1967:

$$CE_{IIW} = C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5 \quad (4)$$

From then on, CE equations were further explored in Britain, Germany, the United States, and Japan, resulting in the widespread adoption of carbon equivalent throughout the world.

In the summer of 1968, Yoshinori Ito and Kiyoshi Bessyo[4] submitted a paper to Commission IX of the IIW in Warsgawa, announcing the birth of Pcm. Ito and Bessyo thought that the Reeve's-type test that Dearden and O'Neill used did not provide sufficient restraint to induce weld cracking. Instead, they used the "y"-groove Tekken-type test to determine the cold-cracking tendency of the weld. Ito and Bessyo ran an orthogonal matrix with 32 combinations of steel chemical composition, plate thickness, and diffusible hydrogen content from different types of shielded metal arc welding (SMAW) electrodes. By correlating the cracking percent along the weld thickness with chemical composition, plate thickness, and diffusible hydrogen content, the following equation was proposed to predict the probability of 0% cracking:

$$\mu I\ (\%) = 235.8-600C-20Si-30Mn-30Cu-10Cr-40Mo-210V-6000B-t-8H \quad (5)$$

where "t" is the plate thickness and "H" is the diffusible hydrogen content. Ito and Bessyo also proposed the following equation to predict the probability of 100% cracking:

$$\mu II\ (\%) = -171.7+800C+10Si+30Mn+30Cu+10Cr+50Mo+210V+3600B+0.4t+14.1H \quad (6)$$

By converting the effect of each element with respect to carbon, equations (5) and (6) became the following:

$$P_c\ (0\%) = C+Si/30+Mn/20+Cu/20+Cr/60+Mo/15+V/3+10B+t/600+H/75 \quad (7)$$

$$P_c\ (100\%) = C+Si/30+Mn/27+Cu/27+Cr/80+Mo/16+V/4+4.5B+t/2000+H/57 \quad (8)$$

where P_c is called the "cracking parameter". After investigating 200 types of steel and making numerous modifications to the equations above, Ito and Bessyo's famous P_c equation was established to be:

$$P_c = C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B+t/600+H/60 \quad (9)$$

The use of equation (9) to predict the cold-cracking tendency is illustrated in Figure 1.

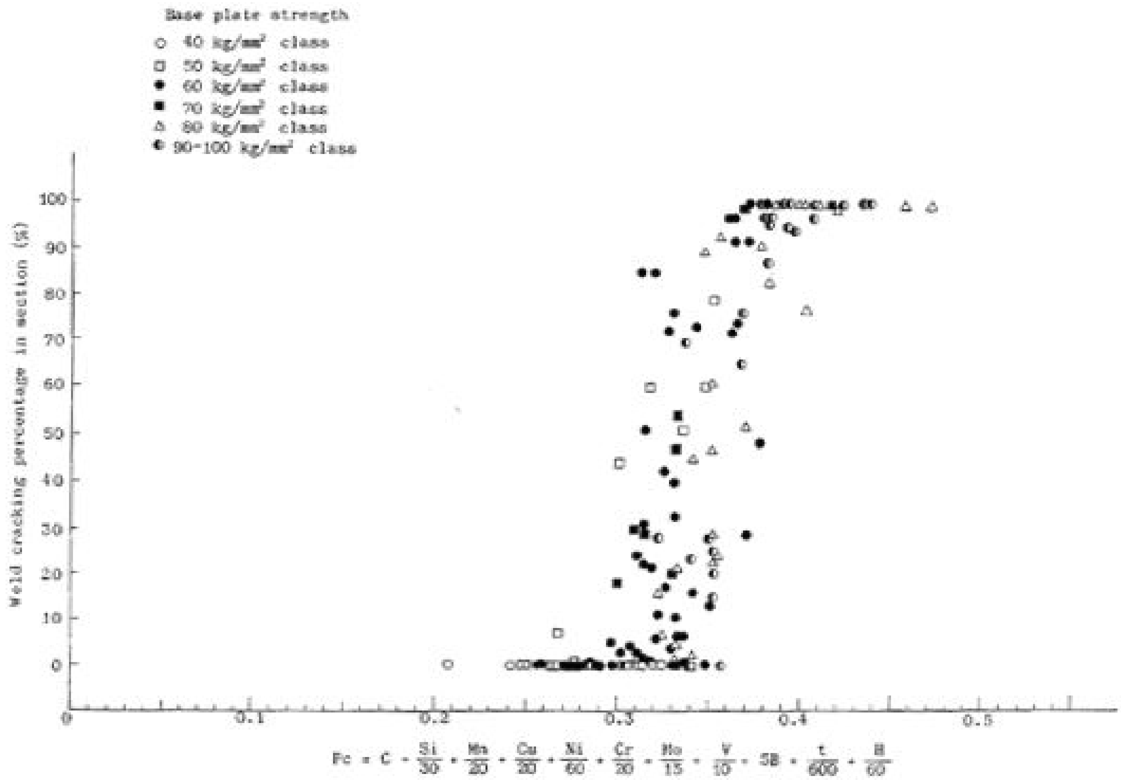

Figure 1: Effect of steel grade on the relationship between the cracking parameter and weld cracking test results.

As a material parameter, $P_{cm,}$ (the so-called weld cracking parameter) was proposed to be:

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

More importantly, Ito and Bessyo developed a linear function between the pre-heating temperature and the cracking parameter for field applications:

$$T_{pre\text{-}heating} = 1440Pc - 392 \quad (11)$$

However, the cracking parameter equation developed by Ito and Bessyo reflects the ratio of a nominal crack length (including portions in both weld metal and parent metal) to the thickness of the weld metal. It did not differentiate the crack length located in the weld metal from the crack length located in the parent steel. Therefore, the cracking tendency of the parent steel was blurred by omitting the cracking contribution from the weld.

In 1973, due to the wide application of carbon equivalent in Japan, the Japanese Welding Engineering Society (JWES) officially included a CE equation by adding the term “V/14” to Kihara, Suzuki, and Tamura’s equation (3):

$$CE_{Wes} = C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14 \quad (12)$$

Since then, this equation has been well-proven in Japan. With the publication of $P_{cm,}$ JWES carried out extensive tests to confirm its use in predicting the weldability of steel. P_{cm} was then included in the WES-135 specification as an alternative calculation of carbon equivalent for high-strength low-alloy (HSLA) steels in 1973.
It is worth noting that P_{cm} can still be effectively used to predict the cracking tendency of high-strength low-alloy (HSLA) offshore-grade steels.

Generally speaking, as long as P_{cm} is less than 0.35, cracking in steel isn't a concern.

References

[1] British Standard BS2642:1958, “General requirements for the arc welding of steel to BS968 and similar steels”.

[2] Winterton, K, 1961, “Weldability prediction from steel composition to avoid HAZ cracking”, Welding Journal, Vol. 40, p253s-258s.

[3] Kihara, H. et al, 1962, “Weld cracking tests of high-strength steels and electrodes”, Welding Journal, Vol. 41, p36s-48s.

[4] Ito, Y. and Bessyo, K., 1968, “Weldability formula of high strength steels related to heat-affected zone cracking”, IIW Document No. IX-576-68.

*To read Part I of **Great Minds of Carbon Equivalent: Invention of the Carbon Equivalent** click here.*

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