

The Great Minds of Carbon Equivalent

Part I: Invention of the Carbon Equivalent

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Modern steels made using complicated alloying strategies and thermomechanical rolling processes have exhibited unprecedented weldability since World War II. Using this advantage, steel structure designers and fabricators have achieved many modern marvels from machinery to deep-water oil and gas platforms. Through extensive research on the integrity of steel structures, rigid qualification welding tests have evolved for various fabrication codes. Weldability testing, for example, is no longer focused only on producing crack-free welds as was the case in the early part of the last century. Testing now emphasizes the robustness of the weld. As a result qualifying steels and welding procedures to build important structures, such as oil and gas pipelines, well heads, and offshore platforms, is significantly more challenging. To streamline this process, fabricators need a method of effectively evaluating the robustness of steel base-materials and welding consumables before the start of a fabrication project. Carbon equivalent (CE) equations are capable of predicting the cold-cracking tendency of steels and have recently been receiving significant attention, leading to this retrospective work on their evolution.

In the early 20th century before traveling to a steel plant in India, Scottish metallurgical inspector Andrew McWilliam [1] pioneered the idea for an equation that could predict the tensile strength of steel using its chemical composition. At that time, steels were rather simple, and were mainly strengthened by C, Mn, and P. After McWilliam arrived in India, he explored his database on steel strength and chemical composition. He found that tensile strength had a linear relationship with concentrations of C, Mn, and P. For steels with 0.20-0.26% C, he formulated the following equation:

$$\text{UTS (psi)} = 38,000 + 800C + 100\text{Mn} + 100P \quad (1)$$

The effect of Si was overlooked in McWilliam's equation because steels at that time only contained minimal amounts. When the carbon content in steel was increased to 0.5%, the predicted tensile strengths from equation (1) were significantly lower than those measured, hence; McWilliam updated the equation by adding the Si term as follows:

$$\text{UTS (psi)} = 38,000 + [800 + 4(C-20)] + 120\text{Si} + [100 + 2(C-20)]\text{Mn} + 100P \quad (2)$$

It is important to note that equation (2) already includes the effect of the interaction between C and Mn.

In 1918, McWilliam[1] presented a figure clearly showing that the strengthening effect of C was five to eight times greater than that of Mn (Figure 1). Indeed, equation (2) weighed the strengthening effects of C, Mn and P differently and addressed their contributions in a linear function. This equation is significant as it introduced a prototype CE equation describing the strengthening effects of alloying elements.

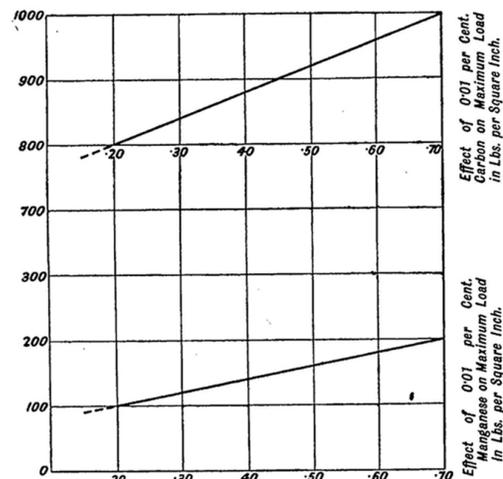


Figure 1. Strengthening effect from C and Mn in steel.

In 1939, after decades of extensive research on steel strengthening, metallurgist Louis Reeve [2] presented the following conclusions to Subcommittee R11 of the Research Committee of the Institute of Welding at a welding conference in Cambridge:

1. If the heat affected zone (HAZ) hardness was lower than 350 HV, no cracking would occur.
2. If the HAZ hardness exceeded 400 HV, cracking was almost certain on a restrained joint; however, no cracking would occur if the joint was not restrained.
3. Welds with small cross-sectional areas were more prone to cracking.
4. Certain welding consumables could promote more cracking than others.

In brief, the above addressed the importance of carbon content, thermal stress, weld size, cooling rate, and diffusible hydrogen as it relates to welding consumables.

In October 1940, less than a year after the Cambridge conference, Dearden and O'Neill [3] invented the concept of carbon equivalent and published their equation, stating that CE "means the influence of any one element is expressed in terms of the amount carbon which would have the same result." Dearden and O'Neill studied Wickhorst [4] and McWilliam's results on the strengthening effect of C, Si, Mn, and P on pure steels, and used their strengthening coefficients to formulate the following initial CE equation:

$$CE = C + Si/6 + P/0.8 + Mn/5 \quad (3)$$

Dearden and O'Neill then plotted the known tensile strengths of 50 steels against their calculated carbon equivalents per Equation (3) and drew a best-fit straight line to acquire the following tensile strength equation.

$$UTS \text{ (tons/in.}^2\text{)} = 16 + 40CE \pm 2 \text{ tons/in.}^2 \quad (4)$$

This linear Equation (4) was used as a mathematic model to determine the coefficients used in the CE equation. For example, a steel with a 39.6 tons/in.² tensile strength was composed of 0.25% C, 1.50% Mn, 0.14% Si, and 0.036% P. Using the given coefficients of C, Si, and P in Equation (3), the following could be calculated:

Element	Calculation	Carbon Equivalent %
C	0.250 × 1	0.250
Si	0.140 × 1/6	0.023
P	0.030 × 1/0.8	0.045
Subtotal		0.318

Since Equation (4) gave a 0.590% carbon equivalent with respect to a 39.6 ton/in.² tensile strength, the difference between the above subtotaled carbon equivalent (i.e. 0.318%) and the 0.590% total carbon equivalent from Equation (4) was the contribution from Mn. Therefore, the coefficient of Mn could be deduced as follows:

Element	Calculation	Carbon Equivalent %
Mn	(0.590-0.318)/1.50	5.5

The same process was applied to other steels with different Mn contents. The mean value was used as the coefficient of Mn in Dearden and O'Neill's updated CE equation. This process was applied to other elements until the following equation was developed based upon the tensile strength data on steels with 0.2% C, 0.4-0.8% Mn, 0.4-0.65% Mo, <0.08% P, and <0.5% Cu, resulting in the following equation, to be used with equation (4) to predict strength.

$$CE = \frac{C + Si/6 + Mn/8 + Cr/7 + Ni/16 + Mo/4 + Co/16 + P/0.8}{1} \quad (5)$$

To simplify the testing method, Dearden and O'Neill used the Vickers hardness test to replace tensile and yield strength tests and determine the coefficient of each element. This yielded the

following classic carbon equivalent equation based on hardness:

$$CE = \frac{C}{1} + \frac{Mn + Cr}{5.5} + \frac{Ni}{15} + \frac{V}{5} + \frac{Mo}{4} + \frac{Co}{150} + \frac{P}{2} \quad (6)$$

This equation can then be used with the following linear equation (7), which is an important application of the CE equation to predict hardness:

$$H_v = 120CE - 200 \quad (7)$$

As long as the predicted hardness was lower than the “maximum weld hardness”, cold cracking could be avoided. Based upon their results from Reeve’s-type tests, Dearden and O’Neill confirmed the “maximum weld hardness” to be 350 HV; the same value that was announced in 1939 by Louis Reeve himself [2].

It should be noted that the “maximum weld hardness” mentioned by Dearden and O’Neill refers to the hardness adjacent to the fusion line on the parent steel side, as opposed to the hardness in the weld metal. As such, the term “maximum weld hardness” is actually referring to maximum HAZ hardness. The same is true of Dearden and O’Neill’s use of the term “weld cracking” in Part (6) of their paper [3]. Here they state “...the area in which cracking is liable to occur is in the parent plate and just alongside the weld bead.” Here, the term “weld cracking” is actually referring to HAZ cracking.

Equations (5) through (7) suggest that the steel strength or hardness can be designed by manipulating contents of alloying elements at a low carbon level to prevent HAZ cracking after welding. This strategy laid the foundation for the development of modern steels featuring good weldability.

References

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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:

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

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

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

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:

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

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:

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

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 Warsaw, announcing the birth of P_c. 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:

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

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:

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

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

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

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

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:

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

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

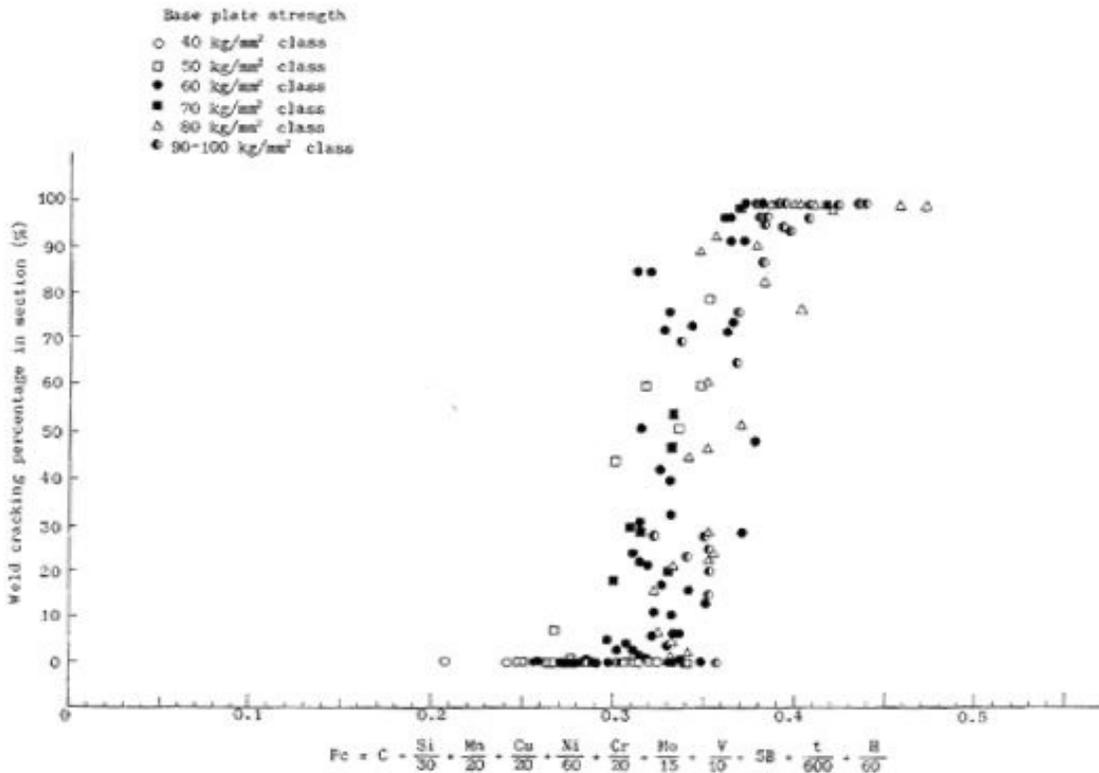


Figure 1: Effect of steel grade on the relationship between the cracking parameter and weld cracking test results.

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

$$P_{cm} = \frac{C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B}{t/600 + B/60} \quad (10)$$

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

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

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

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

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The Great Minds of Carbon Equivalent

Part III: The Evolution of Carbon Equivalent Equations

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In welding, carbon equivalent (CE) calculations are used to predict heat affected zone (HAZ) hardenability in steels. These CE equations can be used to establish criteria to predict cold-cracking, as they can predict maximum hardness. Dearden and O'Neill believed that the following critical hardness guidelines could be used to judge the cold-cracking tendency of steels [1][2].

- If the HAZ hardness is less than 350HV, no cold-cracking would occur.
- If the HAZ hardness is greater than 400HV, the steel would be prone to cold-cracking.

Dearden and O'Neill realized that the cold cracking tendency wasn't determined only by the steel's chemical composition. They understood that the welding consumable, plate thickness, and weld size would all have an effect. However, the effect of diffusible hydrogen, which can cause cold cracking in the HAZ even when the hardness is lower than the critical 350HV, was not further explored.

In the summer of 1968, Yoshinori Ito and Kiyoshi Bessyo [3] submitted a paper to Commission IX of the International Institute of Welding (IIW) in Warsgawa to propose P_{cm} as a new carbon equivalent equation:

$$P_{cm} = \frac{C+Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (1)$$

Due to widespread application of the carbon equivalent in Japan, the Japanese Welding Engineering Society (JWES) published its own carbon equivalent equation in 1973:

$$CE_{Wes} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14} \quad (2)$$

It should be noted that specification WES-135 of the Japanese Welding Engineering Society lists P_{cm}

as an alternative method of calculating the carbon equivalent of HSLA steels.

In Germany, 1973, Beckert [4] considered that the maximum hardness was related not only to the linear addition of the hardening terms commonly used in carbon equivalent equations, but also to the interaction between carbon and the remaining alloy elements. Hence, he presented a unique carbon equivalent equation (3) and an equation (4) to calculate the maximum hardness, both of which take these interactions into account:

$$CE_{Beckert} = \frac{C+Si}{11} + \frac{Mn}{2.9} + \frac{Ni}{17} + \frac{Cr}{3.2} + \frac{Mo}{3.4} + \frac{Cu}{3.9} \quad (3)$$

$$Hv = (A-B)\exp(-bt)^2 + B \quad (4)$$

Where:

$$B = 167(CE_{Beckert})^{2.42} + 137 \quad (5)$$

$$A = 939C + 284 \quad (6)$$

$$b = \exp(-0.013B + 0.8) \quad (7)$$

$$t = \Delta t_{8/5}$$

The importance of equation (4) is that it was the first to incorporate the cooling rate $\Delta t_{8/5}$ (the time that a weld cools from 800°C to 500°C) into a hardness equation, providing inspiration for later researchers.

Three years later, Stout [5] developed a slot test to check the weldability of pipeline steels in the field. Like Ito et al. [3] and Beckert [4], he presented a new carbon equivalent equation by considering the effect of Cu based upon his testing results:

$$CE_{stout} = C + \frac{Mn}{6} + \frac{Ni}{20} + \frac{Cr+Mo}{10} + Cu \quad (8)$$

Stout concluded that as long as CE_{stout} was less

than 0.35, the pipeline steel would not crack. It is interesting to note that this number agrees well with Ito's 0.35 P_{cm} .

One year after Stout's work, Seyffarth [6] was inspired to develop an equation to predict the maximum hardness by combining CE_{WES} , P_{cm} , the interaction between C and Cr, and cooling rate:

$$H_{v-30} = \begin{aligned} & 323.6 - 114.6(\text{Ln}\Delta t_{8/5}) + 11.33(\text{Ln}\Delta t_{8/5})^2 + \\ & 123.7(\text{Ln}\Delta t_{8/5})CE_{WES} - 15.88(\text{Ln}\Delta t_{8/5})^2CE_{WES} \\ & - 1299C - 79.11Si - 120.7Mn + 79.22Ni \\ & - 539Cr + 2830C*Cr + 620.8CE_{WES} \\ & + 875.4P_{cm} \end{aligned} \quad (9)$$

Owing to their excellent strength and toughness performance, niobium-alloyed large-diameter pipe steels have been popular for transporting oil and gas since the 1980's. Welding on these large pipes featured a shorter cooling time, which greatly affected the microstructure and hardness of the welds. In 1981, Lorenz and Düren [7] found significant variation between the weldability predictions generated by the IIW carbon equivalent equation and cracking observed in real-world specimens. Since the CE_{IIW} equation was developed from the results of controlled thermal severity (CTS) type weldability testing using fillet welds, it was quite different from pipe welding. Lorenz and Düren believed that cooling rate, microstructure, and testing method were all essential variables which should be investigated together. They conducted an implant test on pipe steels. They first developed a "pipeline steel formula" (i.e. PSL) to replace CE_{IIW} and successfully narrowed the hardness scattering comparing to that resulted from the CE_{IIW} prediction.

$$CE_{PSL} = \frac{C+Si/25+(Mn+Cu)/16+Cr/20+Ni/60}{+Mo/40+V/15} \quad (10)$$

Using the results of their implant test, Lorenz and Düren established a model to correlate maximum hardness and cooling rate (Figure 1). It should be noted that this figure includes three microstructure zones: HV_M (martensite), HV_X (martensite + bainite), and HV_B (bainite).

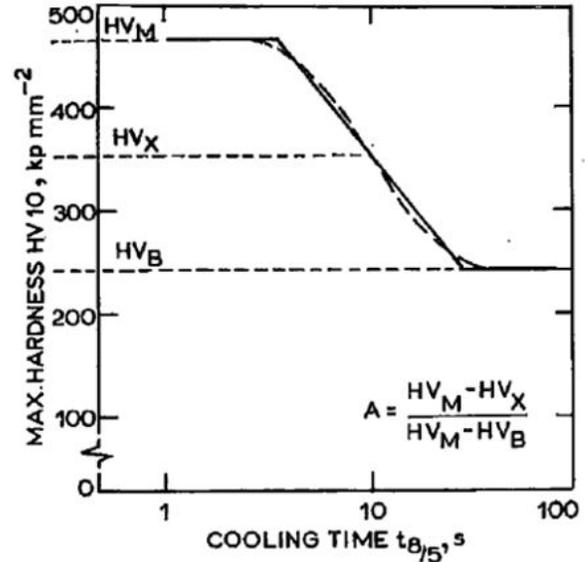


Figure 1: An illustration of the relationship between maximum hardness and cooling rate with three microstructure zones

Using the microstructural distributions illustrated in Figure 1, Lorenz and Düren developed the following maximum hardness equation by integrating the effects of chemical composition, microstructure, and cooling rate:

$$HV_c = 802C - 452C*A + 350A(CE_b * C) + 305(1-0.67A) \quad (11)$$

Where:

$$A = \frac{(HV_m - HV_x)}{(HV_m - HV_b)} \quad (0 < A < 1) \quad (12)$$

To calculate "A," the following hardness equations were used:

Martensite hardness equation:

$$HV_m = 802C + 305 \quad (13)$$

Bainite hardness equation:

$$HV_x = \frac{(C+Si/11+Mn/8+Cu/9+Cr/5+Ni/17)}{+Mo/6+V/3} + 101 \quad (14)$$

Martensite and bainite hardness equation:

$$HV_x = \frac{2019(C[1 - 0.5\log \Delta t_{8/5}])}{+ 0.3[CE_b - C]} + 66(1-0.8\log \Delta t_{8/5}) \quad (15)$$

Where:

$$CE_b = C + Si/11 + Mn/8 + Cu/9 + Cr/5 + Ni/17 + Mo/6 + V/3 \quad (16)$$

$$t_{3/5} = K_1 * 1000HI / [1/(500 - T_p) - 1/(800 - T_p)] \quad (17)$$

$$K_1 = 0.55 - 4.3 \times 10^{-4}$$

HI = heat input

By incorporating HV_M , HV_X , and HV_B into the term "A," Lorenz and Düren's model (11) separately covered three microstructure zones dominated by martensite, martensite + bainite and bainite. Usually, a combination of bainite and martensite dominates in the HAZ of high-strength graded pipe (such as X70 or X80). As such, CE_b is regarded as the carbon equivalent $CE_{Lorenz-Düren}$. In Figure 2, Lorenz and Düren divided the carbon equivalent CE_b (16) into two parts, with carbon on the x-axis and the remaining terms on the y-axis. This allows the martensite percentage in the HAZ to be predicted at different cooling rates.

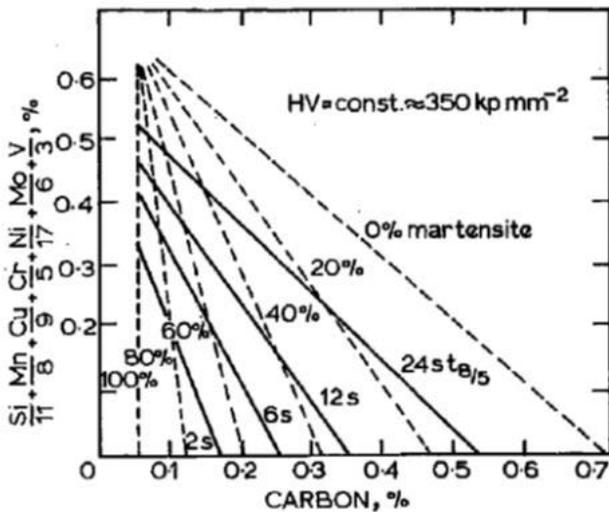


Figure 2: Permissible C and metal alloying elements contents to control the HAZ hardness at 350HV per different cooling rates

In the same year in Japan, Yurioka, Oshita and Tamehiro [8] were also studying pipeline steels welded with high cooling rates. They classified

carbon equivalent equations into two groups. The carbon equivalent equations in Group I considered the metal alloying elements to be more important than carbon. These equations were considered to be more suitable for steels where the carbon level was greater than 0.16%. Examples of equations that fall into this group are CE_{WES} and CE_{IIW} .

CE equations in Group II considered carbon to be more important, and were more suitable for low-alloy steels. Examples of equations that fall into this group are CE_{Ito} , $CE_{Graville}$, $CE_{Düren}$.

Yurioka et al. realized that it was difficult to create a carbon equivalent equation that could cover a wide range of carbon contents for cold-cracking assessment. They reviewed the works of Beckert [8], Stout [9] and Sayffarth [10] to integrate all non-linear contributions and developed new equations for carbon equivalent and maximum hardness for steels with a carbon content between 0.01 and 0.30% :

$$CE_{Yurioka} = \frac{C + A(C)(Si/24 + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + Nb + V)/5 + 5B)}{1} \quad (18)$$

Where:

$$A(C) = 1/4 \left\{ 3 + \frac{(1 - \exp[-40(C - 0.12)])}{(1 + \exp[-40(C - 0.12)])} \right\} \quad (19)$$

$$H_{v-10} = \frac{406C + 164CE_I + 183 \log \Delta t_{3/5} - 2.822CE_{II} + 0.262}{-(369C - 149CE_I + 100) \tan^{-1} \frac{0.526 - 0.195CE_{II}}{}} \quad (20)$$

Where:

$$CE_I = C + \frac{Si/24 + Mn/6 + Cu/15 + Ni/40 + Cr/5}{Mo/4 + (Nb + V)/5 + 10B} \quad (21)$$

$$CE_{II} = C - Si/30 + Mn/5 + Cu/5 + Ni/20 + Cr/4 + Mo/6 + 10B \quad (22)$$

In 1983, Yurioka, et al [9] modified the "Cu+Ni" term in equation (18) and officially published it in the Welding Journal. Their carbon equivalent equation was the famed CEN:

$$CEN = C + A(C) \frac{[Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr + Mo + Nb + V)/5 + 5B]}{1} \quad (23)$$

Where:

$$A(C) = 0.75 + 0.25 \tanh[20(C - 20)] \quad (24)$$

The introduction of the term A(C) presents the interaction of the alloying elements with the carbon. Generally speaking, if the carbon content is lower than 0.08% (Group II), A(C) is calculated to be approximately 0.5, suggesting that the contribution of carbon is significantly more than that of the alloying elements. If the carbon content is about 0.18% (Group I), A(C) is approximately 1.0, suggesting that the contribution from the alloying elements is more than that of the carbon.

Yurioka, et al. [9] made another important contribution by proposing the critical cooling rate at 100°C, i.e. $(t_{100})_{cr}$, as a criterion to determine a steel's cold-cracking tendency. To formulate this equation they considered:

- The maximum hardness as calculated from the chemical composition
- The welding electrode's diffusible hydrogen content
- The restraint stress of the joint
- The groove geometry

Yurioka, et al. then established the critical cooling rate equation as the following:

$$(t_{100})_{cr} = \exp(67.6CI^3 - 182CI^2 + 163.8CI - 41) \quad (25)$$

Where:

$CI = CE + 0.15\log[H]_{JIS} + 0.30\log(0.017K_t\sigma_w)$
[H]_{JIS} is the diffusible hydrogen content per JIS, K_t is the groove parameter and σ_w is the restraint stress factor.

Whenever a cooling rate at 100°C is higher than $(t_{100})_{cr}$, cold-cracking is more than likely. In other words, the pre-heat temperature should be carefully controlled to avoid cold-cracking.

After extensive research and application of the carbon equivalent, it became obvious that lowering carbon and the resulting carbon equivalent could improve crack tip opening displacement (CTOD) toughness, cold-cracking resistance, and hardness. As a result, steel mills and welding consumable manufacturers began making low-carbon HSLA steels and filler metals to satisfy the market demand; however, this low-carbon

approach encountered an unexpected problem in fabrication.

In 1983, Ohshita, et al. [10] found that low-carbon steels welds were susceptible to solidification cracking if they were welded using filler metals with carbon levels less than 0.05%. In this case, the concern over cold-cracking was replaced with a concern over hot-cracking. A Tekken-type test was conducted on plate and pipe steels containing different levels of carbon. Welding was completed using cellulosic SMAW electrodes and gas metal arc welding (GMAW) wire electrodes; each with different carbon contents. Considering the metallurgical effect on the $\delta \rightarrow \gamma$ phase transformation from the alloying elements, Al, Cr, Si, Ti, Mo, V, W and Zr promote δ -ferrite formation and are therefore known as ferrite stabilizers. On the other hand, C, Ni, Mn, and Cu are considered to be austenite stabilizers as they facilitate the formation of austenite. Due to the difference in their thermal expansion coefficients, the phase transformation from δ -ferrite to γ -austenite generates lateral shrinkage, resulting in increased solidification cracking susceptibility. By lowering the amounts of δ -ferrite, the hot-cracking tendency can be reduced. As a result, Ohshita suggested an austenite carbon equivalent equation:

$$CE_{\gamma} = C + Ni/28 + Mn/110 + Cu/83 - Si/15 - Mo/21 - Cr/76 \quad (26)$$

Obviously, C is considered to be the most effective element in steels to prevent hot-cracking. As a result, Ohshita suggested that the carbon content in steels and welds should be 0.05-0.10%.

In 1983 it was discovered that interstitial elements also contributed to the carbon equivalent. Hart [11] indicated that the effective carbon equivalent could be higher than that calculated when the sulfur content of a steel was low. Mckeown [12] also published work proving that high nitrogen and low sulfur could increase the effective carbon equivalent. The effect of N and S led to Cottrell's idea on the hardness equivalent (HE) and the weldability equivalent (WE). By integrating the effects from metal alloying elements, interstitial

elements, and the cooling rate, Cottrell [13] proposed the following HE and WE equations in 1984:

$$HE = 80 + 800(C + 3N + 0.29) \exp \left\{ - \left\{ 0.25(r) \left[C + \frac{Mn}{6} + \frac{Cr+Mo}{5} + \frac{V}{3} + \frac{Nb}{4C} + \frac{0.0001}{S} + \frac{Ni}{Mn^2} \right]^{-1} \right\} \right\} \quad (27)$$

$$WE = (C + 3N + 0.29) \exp \left\{ - \left\{ 0.25(r) \left[C + \frac{Mn}{6} + \frac{Cr+Mo}{5} + \frac{V}{3} + \frac{Nb}{4C} + \frac{0.0001}{S} + \frac{Ni}{Mn^2} \right]^{-1} \right\} \right\} \quad (28)$$

After calculating the WE at a 40°C/s cooling rate ($\Delta t_{8/5}$) on the steel he used, Cottrell found WE to be superior to CE_{IIW} for predicting cold-cracking.

Unsatisfied with the accuracy of The Welding Institute's (TWI) prediction of the critical arc energy (or heat input) required to avoid HAZ hydrogen cracking, Cottrell [14] proposed the "Compound Welding Index" (CWI) in April, 1990:

$$CWI = H^{1/2} (1 - p/300) (CE_w)_e^{-IE/40CE_w} \quad (29)$$

Where:

p = pre-heating temperature
H = diffusible hydrogen

$$CE_w = C + \frac{Mn/14 + Ni/30 + Cr/10 + Mo/10}{V/6 + Nb/2.5 + Cu/30} + 3N + 20B \quad (30)$$

$$IE = 60S + 5Si - 5Si^2 + 100Al - 18Al^{1/2} - 7000Al^3 + 40Ti \quad (31)$$

Using the CWI concept, equations for the critical arc energy were derived:

For a finite plate thickness:

$$E_{Cr} = 0.07(t_c + 80/t_o) [CWI - 0.00227(t_c + 80/t_o)] \quad (32)$$

For an infinite plate thickness:

$$E_{Cnf} = 7.5(CWI)^2 \quad (33)$$

Figure 3 shows a good agreement between the predicted critical arc energy and the observed critical arc energy.

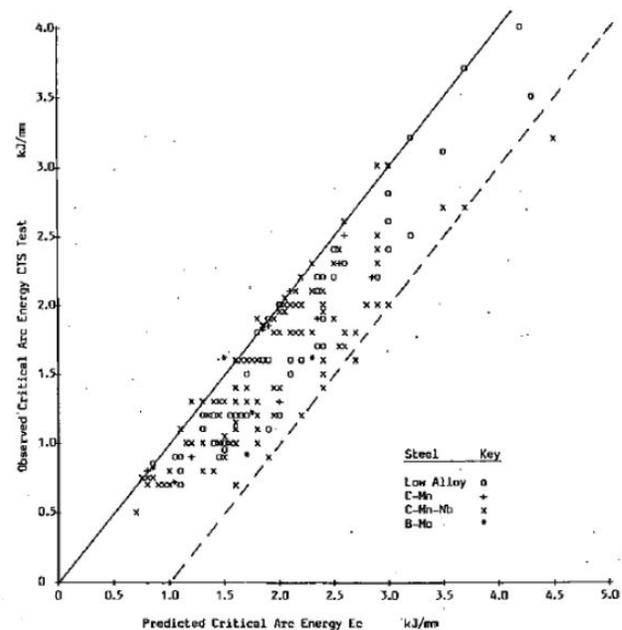


Figure 3: Predicted critical arc energy vs. observed critical arc energy

In May, 1990, a select conference named *Hardenability of Steels* was held in Derby, UK. It celebrated the success of carbon equivalent equations and brought about a collection of papers to summarize their evolution [15]. In the same year, Liu and Olson [16] derived the linear functionality of carbon equivalent from the viewpoint of thermodynamics in the 9th International Conference on Offshore Mechanics and Arctic Engineering in Houston, Texas.

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*Part I of Great Minds of Carbon Equivalent: Invention of the Carbon Equivalent can be found [here](#).
Part II of Great Minds of Carbon Equivalent: The Adoption of Carbon Equivalent can be found [here](#).*

Wesley Wang is a senior engineer in EWI's Materials group. His expertise includes ferrous and nonferrous welding materials (selection, development, evaluation/analysis, and qualification), WPS design, welding processes, weldability evaluation, failure analysis, microstructure and phase transformation, similar/dissimilar alloys welding, corrosion, pipeline welding, underwater welding, and hardfacing. He possesses an in-depth understanding of welding metallurgy and strategies to optimize welding performance and weldment mechanical properties.

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Future Trends on Carbon Equivalent Research

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Introduction

In my blog series The Great Minds of Carbon Equivalent, Parts I, II, and III, I've discussed the value and evolution of carbon equivalent (CE) equations in the prediction of heat affected zone (HAZ) hardenability in steels. In this blog, I discuss two future CE research trends.

Applying Carbon Equivalent Equations to Higher-strength Steels for the Oil & Gas Industry

Higher strength steels (\geq X80 grade) are being increasingly used in deep-water exploration by the offshore oil and gas industry. In offshore structure fabrication, post-weld heat-treatment (PWHT) is used on the welding joint to lower the hardness of the heat-affected-zone (HAZ) and weld metal to below 250HV10 or 22HRC. While this method can effectively be used to meet the corrosion-control requirements of industrial codes and standards such as NACE MR0175 and MR0103, it is well-known that PWHT could significantly deteriorate crack tip opening displacement (CTOD) toughness and reduce cold-cracking resistance. The mechanism of CTOD toughness deterioration by PWHT is not completely clear, warranting an in-depth investigation. To better control the hardness in both the HAZ and the weld metal, the welding cooling rate, PWHT, microstructure, and steel composition (i.e. carbon equivalent) must be correlated. The pseudo graph provided in Figure 1 correlates cooling rate, the balance of carbon and other alloying elements, and the predicted percentage of martensite in the microstructure. This allows fabricators to select base materials and welding procedures to effectively control hardness.

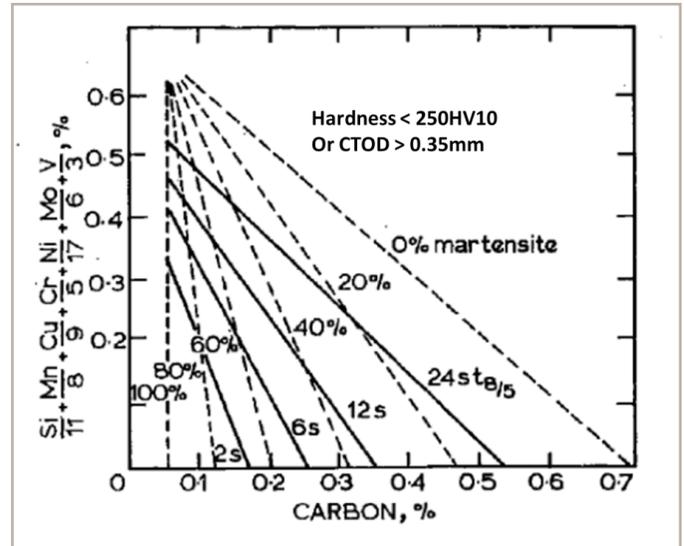


Figure 1: An example of mapping the correlation between carbon content, alloying elements, cooling rate, and microstructure in as-welded and PWHT conditions

The Future Role of Carbon Equivalent in Additive Manufacturing

In addition to conventional fabrication, additive manufacturing (AM) is receiving increased attention from various industries. While significant research is being conducted on building AM components, these parts and assemblies may need to be joined to conventional base materials as part of assembly. As a result, weldability testing will be essential for AM materials. For example, the cold-cracking tendency of AM components made of 4140 or 4340 should be evaluated for arc- and laser-welding processes. AM component weldability evaluations will again explore the use of carbon equivalent to provide necessary guidance to

industrial fabricators. Extensive research and experimental efforts will be required to re-visit the carbon equivalent application, adapt it to these applications, and establish new codes and standards.

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