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:

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

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:

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

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.

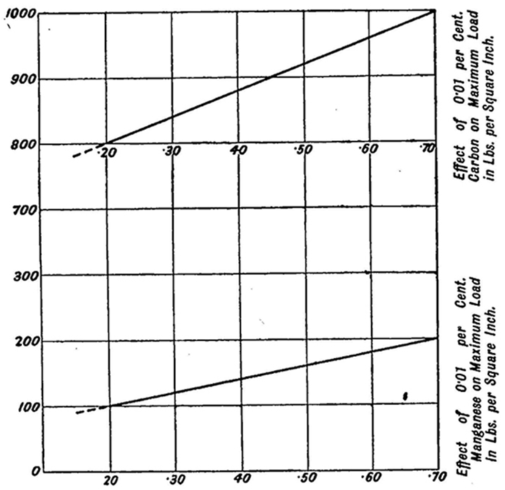

Figure 1. Strengthening effect from C and Mn in steel.

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:

$$\mathrm{CE} = \mathrm{C} + \mathrm{Si}/6 + \mathrm{P}/0.8 + \mathrm{Mn}/5 \qquad (3)$$

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.

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

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.

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

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:

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

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

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

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

[1] McWilliam, A., "The Influence of Some Elements on the Tenacity of Basic Steel, with a New Formula for Calculating the Maximum Load From the Composition", *The Journal of the Iron and Steel Institute,* Vol. XCVIII, pp. 43-58, 1918.

[2] Reeve, L., "Metallurgy of Ferrous Welding", Note on Cambridge Welding Conference, *Transactions of the Institute of Welding*, Vol. II, pp. 7-18, 1939.

[3] ~~Dearden, J. and O'Neill, H., "A Guide to the Selection and Welding of Low Alloy Structural Steels", *Transactions of the Institute of Welding*, Vol III, pp. 203-214, 1940~~.

[4] Wickhorst, M.H., "Formula for Deflection of Rails in Drop Test", *American Railway Association*, Bulletin 170, 1914.

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