Note on the Carbon Equivalent

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1. Introduction

Measuring the hardness in the heat affected zone of welds is often considered as a convenient means to obtain easily information relative to the weldability of structural steels and or to the behaviour of weldments in service. A general association developed over the years between excessive harness levels in the weld zone and difficulties that were encountered during welding with cold cracking and/or during service with weldment performances.

The maximum possible hardness of a steel depends primarily on its carbon content. The actual maximum underbead hardness depends not only on the carbon content of the steel but also on its hardenability under the welding thermal cycles, as influenced also by many other factors. In order to evaluate the effects of chemical elements, other than carbon, present in the steel composition on its hardenability during welding, formulae of the carbon equivalent have been introduced. Higher underbead hardnesses are associated with higher values of the carbon equivalent.

As a consequence, it has now become a widespread practice also to specify a maximum carbon equivalent content when ordering steels for welded constructions and/or to introduce a limiting value for the maximum underbead hardness as an evaluation criterion when working out welding procedures.

Sub-Commission IX-B feels it is appropriate to re-express now in a short note its opinion on these practices, especially on the concept of the carbon equivalent in the light of the most recent results of the continuous research effort in this field. This document is an updating of the former notes on carbon equivalent [1] and on underbead hardness and cold cracking susceptibility [2], whose general philosophy is still considered valid even though they were published some 20 years ago.

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The methods for underbead hardness measurement have been critically reviewed elsewhere by Videau [3]. The scatter of measured values between laboratories is also under current evaluation through round-robin tests within the Sub-Commission.

2. Prediction of the underbead hardness

The hardness of a steel after cooling depends upon its chemical composition and its microstructure at the time of decomposition of the austenite during cooling and the cooling rate. Therefore, in order to predict accurately the hardnesses in the heat affected zone in welds of a given steel, one should not only know its complete chemical composition but also fully take into account its initial microstructure resulting from its processing history and understand the evolution of the microstructures under the influence of the welding thermal cycles, i.e. maximum temperatures and dwell times, the imposed cooling rates and also any reheating due to subsequent welding passes or post-weld heat treatment. The maximum underbead hardness occurs in the immediate vicinity of the fusion line because at that location the cooling rate is fastest, the maximum temperature reached is highest and times at high temperatures are longest. The latter two facts induce grain coarsening and more complete solution and diffusion of carbides and other particles, thereby increasing the hardenability of the microstructure.

Even though great progress has been accomplished in the physical metallurgy of welding, the prediction of the hardnesses in the heat affected zones cannot yet be made with sufficient accuracy through zones cannot yet be made with sufficient accuracy through calculation methods based on models of the actual weld thermal cycles coupled with models of the metallurgical phenomena occurring in the welds. The best predictions at the present time are obtained through statistical correlations of experimental results obtained under carefully controlled welding conditions.

It is now generally recognized that it is not possible to predict with sufficient accuracy the maximum underbead hardness, even for simple bead-on-plate test specimens, by only taking into account the chemical

Table 1. Recent formulae to predict maximum underbead hardness

1. Formula proposed by Düren [4,6]/Formule proposee par Düren [4,6]

$$HV = 2019\ [C(1 - 0.5 \log t_{8/5}) + 0.3\ CE_B + 66\ (1 - 0.8 \log t_{8/5})]$$

where/où $CE_B = C + \frac{Si}{11} + \frac{Mn}{8} + \frac{Cu}{9} + \frac{Cr}{5} + \frac{Ni}{17} + \frac{Mo}{6} + \frac{V}{3}$

and/et $HV_M \geq HV \geq HV_B$

If/si $HV \geq HV_M$, $HV = HV_M = 802\ CE_B + 305$ (100% martensite).
If/si $HV \leq HV_B$, $HV = HV_B = 305\ Ce_B + 301$ (0% martensite).

2. Formula proposed by Suzuki [14]

$$HV = H_\infty + K/([1 + \exp(\alpha(\log t_{8/5} - Y_5))]$$

where/où $H_\infty = 884\ C + 287 - K$
$K = 237 + 1633\ C - 1157\ P_{CM}$
$\alpha K = 566 + 5532\ C - 2880\ P_{CM}$
$Y_5 = -0.03 - 6.00\ C + 7.77\ P_{CM}$

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

3. Formula proposed by Yurioka [13]

$$HV = 406\ C + 164\ CE_I + 183 - (369\ C - 149\ CE_I + 100)\ \text{artan}\ X$$

where/où $X = \frac{(\log t_{8/5} - 2.822\ CE_{II} + 0.262)}{(0.526 - 0.195\ CE_{II})}$

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

$$CE_{II} = C + \frac{Si}{30} + \frac{Mn}{5} + \frac{Cu}{5} + \frac{Ni}{20} + \frac{Cr}{4} + \frac{Mo}{6} + 10B$$

Field of validity. These formulae have been tested by H. Suzuki for 70 steels with chemical composition in the following ranges [14]: C<0.33; 0.48<Mn<2.06; Si<0.65; Cu<0.47; Cr<1.06; Ni<2.06; Mo<0.66; V 0.07; Nb<0.06; Ti<0.02; B<0.0020. It must be noted, however, as it has been indicated by C. Duren [6], that these ranges of chemical compositions should be limited to C<0.22 and Cr<0.5. Aluminium also should remain below 0.06. Moreover, the formulae proposed by Duren should not be applied to titanium or boron containing steels since this formula does not take into account the influences of these elements.

composition of the base material expressed in a single carbon equivalent formula. The relative effect of individual alloying and residual elements on the maximum underbead hardness is greatly influenced by the cooling rate, usually characterized by the cooling time between 800°C and 500°C [4,5].

The most recent formulae proposed for predicting the maximum underbead hardness of bead-on-plate test specimens under various welding conditions can be found in Table 1. Even though they neglect a number of possible factors of influence, other than the chemical composition and cooling rate, it appears they give under normal welding conditions reliable predictions provided they are applied within the validity range for which they were originally derived [8,9]. The scatter (standard deviation) between calculated and measured values has been evaluated to be approximately 20 HV 10.

It may be observed that, if the cooling time between 800°C and 500°C is fixed to a given value, the maximum underbead hardness as predicted by the formulae mentioned above depends only on the chemical composition of the steel. This means that, in this particular case, a single carbon equivalent formula can be used to predict the maximum underbead hardness. The coefficients (dividing factors) for each individual element in the carbon equivalent formulae so calculated do, however, depend on the selected cooling rate. They increase when the cooling time decreases [4,5,10].

3. Carbon equivalent

The calculation of a carbon equivalent level represents an attempt to describe the chemical composition by means of a single number in order to show how changes in composition affect material behaviour. Carbon equivalent formulae have been derived for a number of purposes. Among them, one must mention especially their use to evaluate :

— hardenability;

— cold cracking sensitivity of steels or derived quantities in direct connection with this phenomenon, such as minimum recommended preheating temperature or tolerance to diffusible hydrogen;

— evaluation of service properties for which a correlation is found or expected with the hardness, such as, for example, sulfide cracking and stress corrosion cracking.

It cannot be expected that all of these various behaviour patterns of material or welded joints can be reliably described by one single number related only to the chemical composition. Therefore, the significance of any carbon equivalent formula must always be restricted to its initial purpose. Many of the the proposed formulae found in the literature are primarily hardenability formulae.

The use of a carbon equivalent formula to predict a specific behaviour pattern of a steel or of a weld can be criticized for several reasons :

1. As to predicting the maximum underbead hardness, a number of factors other than chemical composition can influence the observed microstructures. Even the influence of chemical composition is only taken into account in a perhaps too simple way though a single number calculated most often according to a linear formula.

2. It is not obvious that values of calculated carbon equivalent and the property or behaviour of interest are singularly related. In fact, it is not true even for microstructure and hardness. A steel can be heat-treated to obtain different microstructures, all of which display identical hardnesses but which possess different toughness, ductility, corrosion resistance or other properties. Similarly two steels of different composition can be heat-treated to the same harness level, perhaps even by the same cooling method, yet their microstructures and properties may differ significantly.

3. Many properties of practical interest do not depend only on the composition and on the microstructures present in the welded joints. For instance, the risk of cold cracking is also influenced by the welding process and the welding procedure, including or not preheating and/or postheating, by the stresses during and after welding, by the hydrogen content, by the thickness, etc.

It must be recognized that it has not always been clear whether proposed carbon equivalent formulae were established directly through correlations between chemical composition and a specific material or weldment behaviour pattern for which they were intended, or only indirectly through correlations between this behaviour and the hardness of microstructures. In this last case, the formula should be primarily used for hardnesses prediction and the complementary aspect of the relevance of maximum underbead harness limits to avoid specific difficulties during and/or after welding is another important problem which is not treated here. In the sequel, the discussion is restricted to the significance carbon equivalent with regard to the risk of cold cracking.

The reliability of a great number of carbon equivalent formulae in evaluating the risk of cold cracking of structural steels has been reviewed [5,10]. According to the most recent review [10], it may be stated that:

1. The well known IIW carbon equivalent formula, first proposed by Dearden and O'Neil in 1940 [11],

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

may be used for higher carbon steels of more than 0.18, or, in the case of welding conditions requiring slow cooling, $t_{8/5}$ longer than about 12 sec.

metal arc

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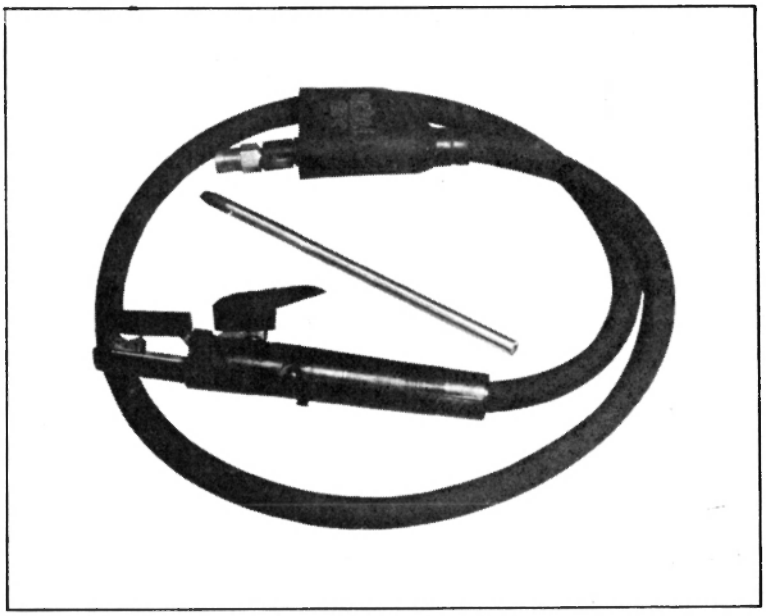
metal arc GOUGING TORCH WITH 360° FREE REVOLING CABLE



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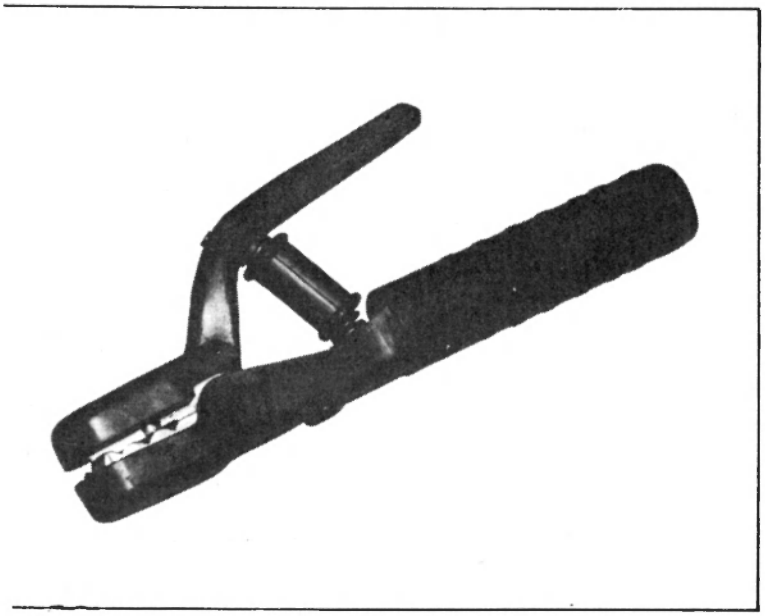

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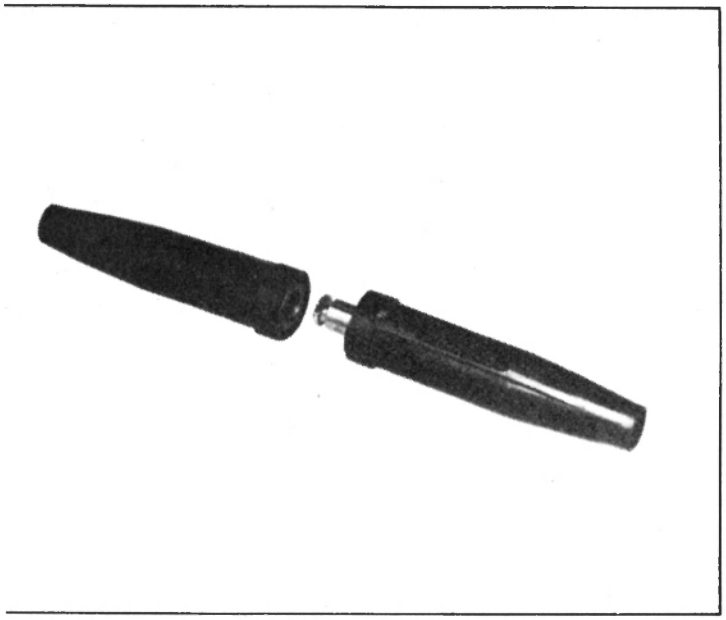
* For better cable connection 3 alien screws provided with D shape grip plate



metal arc CABLE CONNECTORS 600 AMPS

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* Heavy duty cable connector suitable for high capacity usage and efficient operation to perform at nominal voltage drop and at high duty cycles.
* Interlocking parts made of high conductivity brass machined for close tolerance and perfect fit.
* The male and female ends of the connector have quick locking arrangement for positive engage/ disengage by 180° twist.
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* Better and quick cable connection at each end by alien screws and D shape grip plate.
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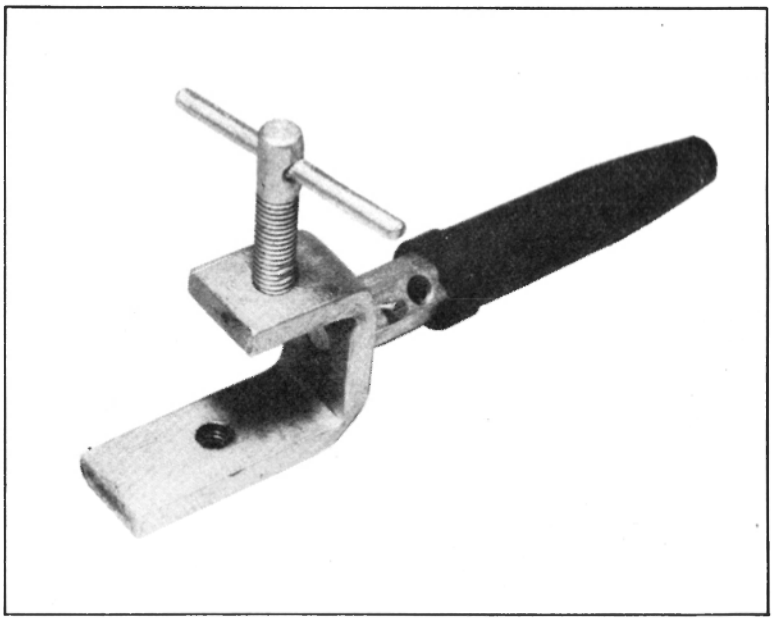

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2. Formulae like the P_{CM} proposed by Y. Ito and K.Bessyo in 1968 [12],

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

or the CE_{MW} proposed by Duren in 1981 [4,5],

$$CE_{MW} = C + \frac{Si}{25} + \frac{Mn+Cu}{20} + \frac{Cr}{10} + \frac{Ni}{40} + \frac{Mo}{15} + \frac{V}{10}$$

may be preferred for steels with carbon contents of less than approximately 0.22% and, in the case of rapid cooling, $t_{8/5}$ shorter than about 6 sec.

3. The formula proposed by Yurioka in 1981 [13],

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

where $A(C) = 0.75 + 0.25 \tanh \{ 20 (C - 0.12)\}$,

appears to give acceptable evaluations for steel of carbon contents up to 0.25%. It can easily be verified that this last formula can be reduced to expressions very similar to CE_{IIW} or P_{CM} and CE_{MW} for higher and lower carbon steels since the accommodation factor A(C) varies with carbon content.

4. Conclusions

1. Reliable predictions of the maximum underbead hardness for bead-on-plate specimens require the influence of the cooling rate to be taken into account. The maximum underbead hardness can be evaluated through a single carbon equivalent formula only when the cooling time between 800°C and 500°C is given. The formula must then be adapted according to this cooling time.

2. The relevance of maximum underbead hardness limits to avoid difficulties encountered during and after welding has not been thoroughly discussed here. It may be criticized for may reasons and it is there fore always recommended to carry out tests, as closely representative as possible of the actual application, to qualify the welding procedures whenever specific difficulties may be suspected to occur during or after welding.

3. With all these restrictions in mind, the practical usefulness of the carbon equivalent concept to limit the risk of cold cracking cannot be denied. In the present state of knowledge in welding technology, such formulae can only be used to select steels which, under given and well controlled welding technology, such formulae can only be used to select steels which, under given and well controlled welding conditions, including welding procedure and weld geometry, can be used with a limited risk of cold cracking. Alternatively, they can be used for a given steel in order to orient the choice of an appropriate welding procedure limiting the risk of cold cracking.

   The calculation of the carbon equivalent should always be made on the basis of product analysis rather than ladle analysis, or worse still, maximum contents specified, and should include residuals.

   In any case, the use of any carbon equivalent formula cannot be extended either beyond the ranges of chemical compositions for which it was established or for any other evaluation than the purpose intended.

4. Since carbon equivalent formulae can only be used for a quick and easy but incomplete evaluation of the fitness of a steel for use, a too strict application of a limiting value criterion on any formula may constitute an obstacle to the development of new qualities of steels or improvement of welding procedures.

   Appropriate welding qualification tests are always preferable and can give relevant and reliable information on the quality of weldments.

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SAFETY IN WELDING AND CUTTING

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expulsion of acetone. Acetylene forms an explosive compound with copper, and the use of copper pipes in acetylene handling systems must be avoided. Acetylene is a highly flammable and explosive gas, and readily forms explosive mixtures with from 2 to 82% air. Acetylene is not toxic but is mildly anesthetic and in high concentrations can replace air, resulting in asphyxiation.

Flashback. A problem known as 'flashback' may occur with oxy-fuel cutting and welding systems. This situation arises when oxygen mixes with acetylene in the acetylene supply line and ignites. The extremely high flame speed causes the ignited mixture to travel rapidly back down the supply line to the acetylene cylinder. This results in rupture of the hose or, more seriously, explosion of the cylinder. To prevent this all oxy-acetylene equipment should be fitted with 'flashback arrestors'. The risk of flashback may also be reduced by :

- Using correct gas pressures.
- Using correct nozzle sizes.
- Maintaining the equipment in good (clean) working order, and
- Using the correct lightup and shutdown procedures.

Propane is heavier than air and is stored in liquid form of 6.5 bar. It is very flammable (mixtures of between 2.2-9.5% propane in air are explosive). Propane is mildly anesthetic and will cause asphyxia at high concentrations. Propane should not be used in confined spaces due to its tendency to collect at the lowest point of the space, causing a potential explosion risk.

Oxygen is non flammable but supports vigorous combustion in any flammable material. Oil, grease, paper, cloth etc. all burn explosively in an oxygen enriched atmosphere. The following precautions should be observed in handling and storage of oxygen :

- Do not store in the same area as flammable materials including gases, solvents, paint, oil.
- Store in well ventilated area.
- Never use oil or grease on valves or gas equipment.
- When using oxygen keep clothing clean and free from grease.

Inert Gases

The inert gases (e.g. argon and helium) are non toxic, non flammable and will not support combustion. (Carbon dioxide is not chemically inert and can exert a toxic effect). The main problem, however, with these gases, particularly those that are heavier than air, is that they may cause asphyxiation. If used in confined spaces the excess inert gas must be effectively ventilated and in some cases breathing apparatus may have to be worn.

Toxic Substances

Small amounts of toxic gases such as sulphur dioxide and chlorine have been used in welding environments under special, carefully controlled circumstances. They must only be used under very strict control.

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