Reconsidering the Basicity of a FCAW Consumable — Part 2: Verification of the Flux/Slag Analysis Methodology for Weld Metal Oxygen Control

The prediction model is verified by experimental results

BY E. BAUNÉ, C. BONNET AND S. LIU

ABSTRACT. Based on an investigation performed using a set of five experimental FCAW electrodes, an improved version of the IIW basicity index formula is developed. This new methodology is described in a series of two papers — Part 1 and Part 2. The partition of the various elements contained in the formulation of one FCAW electrode is studied and modeled in Part 1. Correspondingly, the composition of the solidified slag is predicted for this particular electrode. To verify the model, the prediction of the slag chemical composition is compared with experimental measurements. Good accordance is found, which shows the model is applicable. Also, a new way of defining the basicity of a FCAW consumable based on the chemical composition of the slag is derived. In the present Part 2, comparison of this innovative methodology with the IIW formula is achieved, as well as with other means for expressing the flux/slag basicity reported in the literature. The newly defined basicity index is found to offer superior correlation with the weld metal oxygen content, demonstrating the validity of the assumptions made in the present investigation.

Introduction

In Part 1 (Ref. 18), a methodology was reviewed for predicting the chemical composition of the solidified slag produced using an experimental basic-type FCAW (E70T-5 AWS grade) electrode. Then, a "slag basicity index" could be calculated on the basis of the slag composition and a derivative of the IIW formula that defines the basicity of a flux system. In Part 2, the same methodology is used as a tool to predict the weld metal oxygen content. The theory is then tested on a set of five experimental FCAW electrodes including the electrode of Part 1 and consisting of various amounts of the same fill ingredients. Finally, the validity of this methodology is established by comparing it with various other means for expressing the slag/flux basicity, in particular Tuliani's basicity index, the optical basicity index as defined by Datta and Parekh in 1989, and the B_Z basicity index as defined by Zeke in 1980.

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KEY WORDS

Basic Slag
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Oxygen Content
Weld Metal
Consumable

Effect of Weld Metal Oxygen Content on Weldment Properties

Oxygen is introduced to the weld pool at high temperatures by 1) the presence of oxide components in the flux, which dissociate in the arc; 2) the slag-metal reactions in the weld pool; and 3) the atmosphere that surrounds the arc plasma environment. Under these conditions, oxygen directly reacts with alloying elements in the weld pool, modifying their prevailing role, depressing hardenability and promoting deoxidation through the production of inclusions (Ref. 1).

Throughout the years, the effect of oxygen on weld metal microstructure has received a great deal of attention (Refs. 2–8). Correspondingly, the relationship between weld metal oxygen content and mechanical properties of the weldment has also been much investigated. As an example, Ito, *et al.* (Ref. 9), in an exhaustive study on factors affecting impact properties of submerged arc weld metal, observed that both weld metal oxygen contents higher than 500 ppm and lower than 200 ppm would lead to poor toughness. According to their results, formation of fine acicular ferrite structures was observed to take place at intermediate oxygen levels only, *i.e.*, between 200 and 500 ppm. At sufficiently high oxygen levels, coarse-grained ferrite was formed and was characteristic of poor low-temperature toughness. At extremely low oxygen levels, however, bainitic structures were observed to appear, causing somewhat similar fracture properties. Furthermore, Abson, *et al.* (Ref. 10), showed that the formation of acicular ferrite took place in weld samples featuring oxygen contents in the range 200–300 ppm. Also, from laser remelting experiments, they concluded that a reduction in the weld deposit oxygen level down to about 130 ppm caused a drastic reduc-

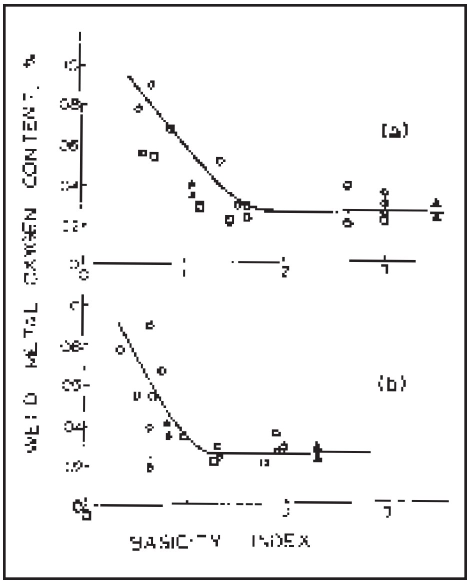

Fig. 1 — Weld metal oxygen content as a function of flux basicity in SAW. A — Case where CaF_2 is included in the IIW formula; B — case where CaF_2 is not included in the IIW formula (after Ref. 14).

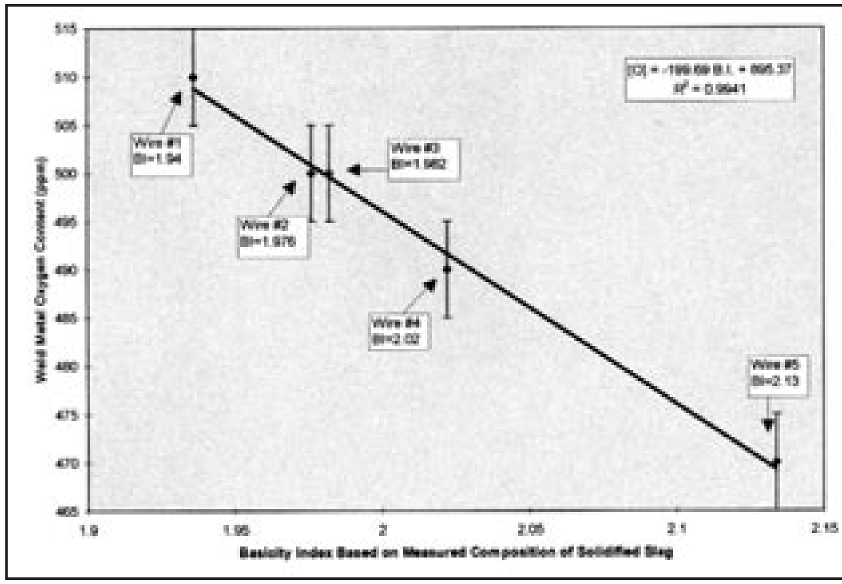

Fig. 2 — Dependence of the weld metal oxygen content upon the basicity index value of the FCAW electrode, based on the measured composition of the solidified slag. Dependence plotted for a set of five experimental FCAW electrodes containing the same core ingredients in various ratios.

tion in the acicular ferrite content in the welds produced, close to 0%. Finally, as another significant example, Cochrane, *et al.* (Ref. 11), in their investigation reporting on the effect of oxygen on weld metal microstructure in submerged arc welds, observed that increasing the weld metal oxygen content was responsible for an abrupt microstructural change from fine, interlocking laths of acicular ferrite at 200–400 ppm of oxygen to a coarse "bainitic ferrite" at oxygen levels greater than 500 ppm.

As reported in the first part of this article, a general trend suggests a decrease in the basicity of the welding flux gives rise to an apparent increase in weld metal oxygen content. This relationship is often encountered for most of the basicity theories based on Tuliani's formula (Ref. 12). Correspondingly, the higher the flux basicity, the fewer the nonmetallic inclusions generally found in the weld metal, *i.e.*, the cleaner is the weldment. This relationship was indeed reported in submerged arc welds by various authors such as Tuliani, *et al.* (Ref. 12), and Almqvist, *et al.* (Ref. 13), whose investigations showed rutile fluxes tended to produce higher inclusion contents in the weld metal, with a reduced toughness. Also, Eagar (Ref. 14) investigated various submerged arc welding fluxes and found that weld metal oxygen content would decrease with basicity indexes up to approximately 1.5 and would reach a plateau value around 250 ppm at larger basicity values. Figure 1 shows the correlation between the weld metal oxygen content and flux basicity in submerged arc welding, as reported by Eagar.

Furthermore, other basicity theories have been employed to correlate the flux basicity with weld metal oxygen content. As an example, Zeke (Ref. 15) proposed in 1980 a new way of expressing the flux basicity index, utilizing the ionic theory of slags. The index by which the degree of basicity was expressed, B_z, was defined as the ionic fraction of free O^{2-} anions in the dissociated slag over the sum of all anions and cations of the flux system. Equation 1 gives an expression for B_z in the case of a flux system including various metallic oxides of elements E and F, E_2O and FO respectively, as well as Al_2O_3, CaF_2, SiO_2 and TiO_2.

$$\mathbf{B_z} = \frac{\left[\mathbf{n_{O^{2-}}}\right]}{\sum\left(\mathbf{cations} + \mathbf{anions}\right)} = \frac{\left[\sum \mathbf{n_{EO}} + \sum \mathbf{n_{F_2O}} - \left(3\cdot\mathbf{n_{Al_2O_3}} + 2\cdot\mathbf{n_{SiO_2}} + 2\cdot\mathbf{n_{TiO_2}}\right)\right]}{\sum \mathbf{n_{EO}} + \sum 2\cdot\mathbf{n_{F_2O}} + 3\cdot\mathbf{n_{CaF_2}} + 2\cdot\mathbf{n_{Al_2O_3}} + \mathbf{n_{SiO_2}} + \mathbf{n_{TiO_2}} + \left[\mathbf{n_{O^{2-}}}\right]} \quad (1)$$

where n represents the number of component moles per 100 g of slag. For a B_z value superior to zero, the flux/slag system was considered to be basic, and acidic when B_z was negative. Zeke found the weld metal oxygen content would continuously decrease as B_z increased to zero. Instead, for positive values of B_z, *i.e.*, fluxes basic in nature, the oxygen content remained constant independent of the basicity.

Attention has also been given to the optical basicity index since Datta and Parekh (Ref. 16) carried out a comparative investigation of the IIW and the optical basicity indexes. The optical basicity was defined as the ratio of the electron donor power of oxygen in an oxide system over the electron donor power of free oxide anions. An expression defining the optical basicity is given in Equation 2.

$$\textbf{Optical Basicity} = \sum_{\text{All Cations}}\left[\frac{\mathbf{z_c}\cdot\mathbf{R_c}}{\mathbf{2.78}\cdot\left(\mathbf{X_c} - \mathbf{0.26}\right)}\right] \quad (2)$$

In Equation 2, z_C is the coordination number (or number of charges associated with) of the cation, R_C is the ratio of the number of moles of the cation over the total number of moles of oxygen in the flux system and X_C is the Pauling's electronegativity of the cation. This method for calculating the flux basicity presented a considerable advantage in that the optical basicity index could be measured using a spectroscopic technique. In addition, its correlation was found to be rather good with both the weld metal oxygen content and the impact toughness. The general trend indicated higher basicity indexes would lead to lower oxygen levels in the deposited weld metal.

Under these circumstances, the validity of the slag basicity index defined in Part 1 (Ref. 18) using the chemical composition of the slag collected after welding is verified in Part 2. The correlation between the so-defined basicity index of the FCAW electrode with the corresponding

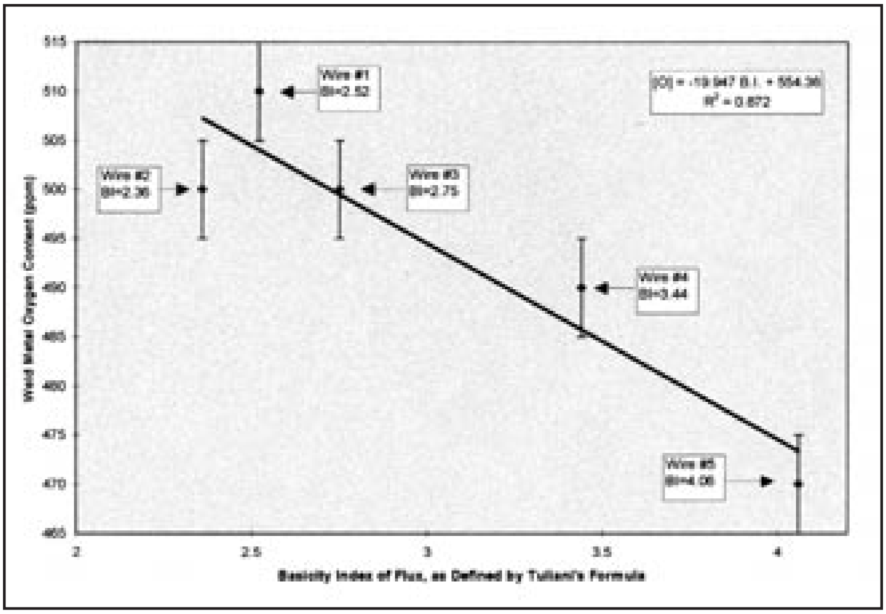

Fig. 3 — Dependence of the weld metal oxygen content upon the basicity index value of the FCAW electrode, as defined by Tuliani's formula. Dependence plotted for a set of five experimental FCAW electrodes containing the same core ingredients in various ratios.

weld metal oxygen level will be investigated. Comparison with other existing basicity theories will be performed.

Experimental Procedure

The five experimental 1.2-mm (0.045-in.) diameter basic-type FCAW (E70T-5 AWS grade) electrodes drawn for the present study consisted of a low-carbon, low-alloy steel sheath, the composition of which is given in Table 1 of Part 1, and a core flux containing 14 metallic and nonmetallic ingredients, which included iron, ferro-silicon and ferro-manganese powders, SiO_2, TiO_2, $CaCO_3$, CaF_2, ZrO_2 and various other oxides and minerals that contained Na, K, Mg, Li, Al and Zr. Table 1 lists the ingredients that were used for manufacturing all five experimental electrodes, together with the corresponding fill ratios.

The five experimental basic-type FCAW electrodes were welded according to the procedure specified in Part 1 (Ref. 18). All metal transfer characteristics described in Part 1 remain the same in Part 2.

The methodology reviewed in Part 1 to calculate the slag basicity based on the slag composition was applied to the five flux cored electrodes in Part 2. With regard to the weld metal oxygen analyses performed throughout the present paper, top beads were machined from multipass welds to obtain all-weld-metal chips for oxygen analysis using a Leco oxygen analyzer. Five specimens were prepared for each FCAW electrode to be tested and the average value was computed and used as representative of the wire tested. This was performed with an accuracy estimated to ± 5 ppm of oxygen.

Results and Discussion

Weld Metal Oxygen Content vs. Slag Basicity Index

A methodology for quantitatively characterizing a FCAW electrode by means of a basicity index based on the chemical composition of the collected slag has been previously described (Refs. 17, 18). Figure 2 shows how this way of expressing the basicity of a FCAW electrode relates to the weld metal oxygen content for the five experimental basic-type FCAW electrodes welded under pure CO_2 shielding gas. Recall that these five flux cored electrodes consisted of the same core ingredients in different proportions.

As expected from results obtained in previous works (Refs. 12–16), the weld metal oxygen content diminishes as the basicity of the slag system increases. The insignificant scatter observed in Fig. 2 shows that this method of characterizing the nature of flux cored electrodes by means of a basicity index based on the chemical composition of their solidified slag is highly satisfactory in that it provides a good quantitative indication of the oxygen level in the weld metal. Also, it is obvious from Fig. 2 that for the same family of wires, of which the core fluxes are composed of the same ingredients, the weld metal oxygen content relates extremely well with the slag basicity index. This observation further demonstrates the validity of the basicity index as defined in the present investigation and indicates that the knowledge of the physical and chemical characteristics of the raw materials to utilize in the flux core is of prime necessity.

Likewise, Fig. 3 shows the dependence of the weld metal oxygen level for the same set of experimental electrodes upon the basicity value using Tuliani's index (Ref. 12).

The regression coefficient for the correlation between the weld metal oxygen contents and the IIW index is 0.87, vs. 0.99 for the correlation between the same oxygen contents and the basicity defined as a function of the slag composition — Fig. 2. Even though the scatter for both plots is rather low, the plot with the slag basicity proves to exhibit a much superior scatter, close to perfect correlation. Correspondingly, the slag basicity constitutes a more correct form of the basicity index to be used. This way of expressing the basicity for a welding consumable, in particular for a FCAW electrode, seems to better account for all contributions brought about by the numerous core constituents for oxygen control.

Also, based on this innovative way of calculating the slag basicity, a commercial rutile-based electrode (typical AWS E70T-1 grade) was found to exhibit a slag basicity index equal to 0.56. This electrode was welded under the same conditions as those previously stated, with the difference that direct current electrode positive (DCEP) polarity was used, as a general practice. As expected, using this rutile-based electrode featuring a basicity index smaller than the basic-type electrodes previously described, the weld metal oxygen content was 600 ppm. Consequently, the methodology presented herein for quantitatively characterizing a FCAW electrode by means of the slag basicity index can be used as a tool to roughly estimate the weld metal oxygen content of a particular electrode. Also, from the knowledge of the chemical analysis of a sufficient amount of slag chips collected after welding, it is possible to establish a ranking between several electrodes as a function of their oxidation potential.

Furthermore, as mentioned previously, the IIW index is determined from the knowledge of the mass fractions of the various oxides of the flux. On the other hand, the slag basicity takes into consideration the molar fractions of all oxides present in the solidified slag. The basicity calculated from the slag composition not only gives a better description of the welding consumable basicity than Tuliani's index but also that of the actual deoxidization mechanism. Also, it should be pointed out that whether the slag basicity as defined in this investigation or Tuliani's flux basicity is manipulated, different ranges of basicity index may be obtained, both describing the oxygen potential of the same welding consumables. For example, for the set of five flux cored wires studied in the present work, the slag basicity was found to range from 1.94 to 2.13. The flux basicity as defined by Tuliani's formula, however, was comprised between 2.36 and 4.06. This observation is important in that a number of investigators (Refs. 5–7) classify the nature of the welding fluxes that they used by means of their relative basicity index values. Therefore, following up on this investigation, it would certainly be meaningful that the methodology presented herein be applied to other welding consumables.

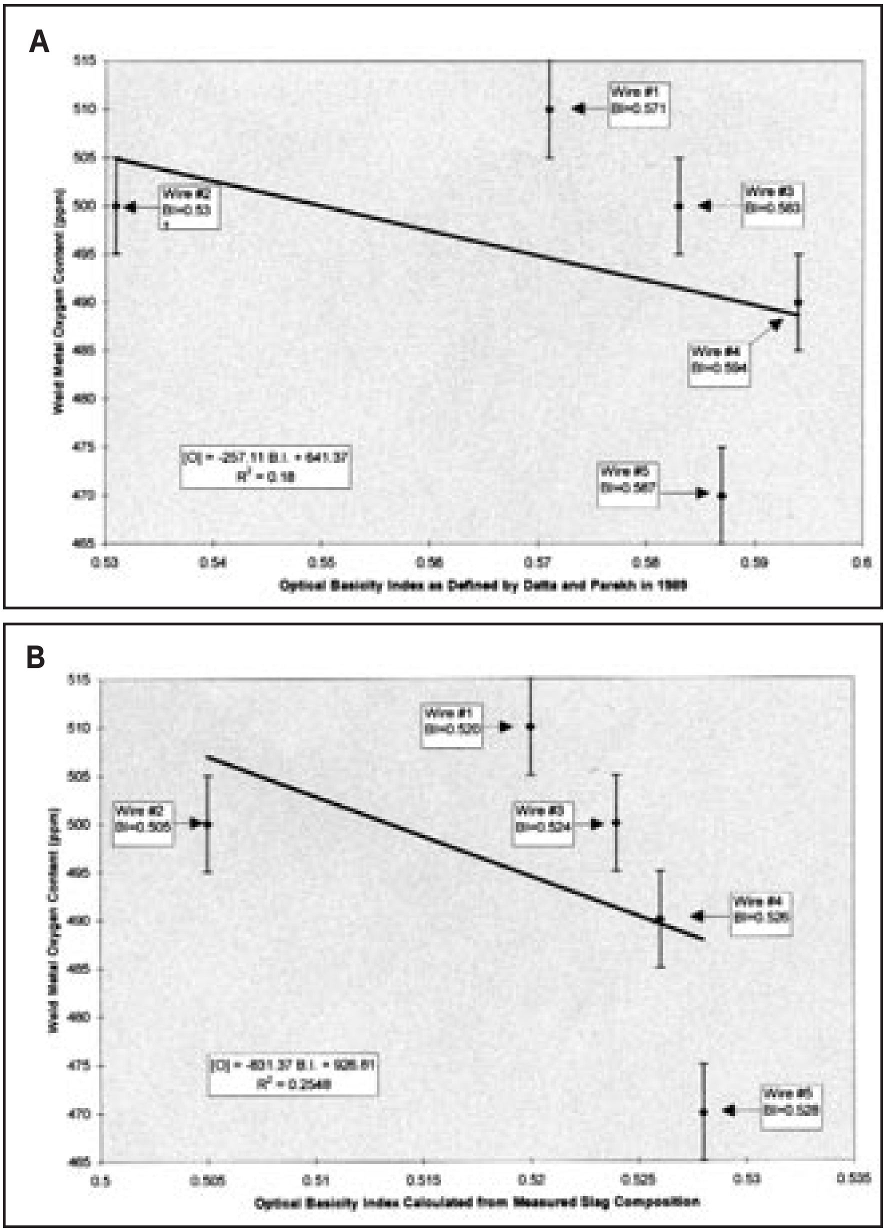

Fig. 4 —A — Dependence of the weld metal oxygen content upon the optical basicity index, according to Datta and Parekh's theory (from flux formulation); B — dependence of the weld metal oxygen content upon the optical basicity index, using the measured solidified slag compositions.

Various Basicity Approaches to Correlate with Oxygen Content

Figures 4A and 5A show the dependence of the weld metal oxygen level for the set of five experimental electrodes upon the optical basicity index as defined by Datta and Parekh (Ref. 16), and the B_z basicity index as defined by Zeke (Ref. 15), respectively (*i.e.*, applied to the flux formulation of the electrodes). For comparison, Figs. 4B and 5B illustrate the dependence of the weld metal oxygen level of the same electrodes using the optical basicity and the B_z index, applied to the measured solidified slag composition.

First of all, data presented in Figs. 4A and 5A show the optical basicity index and the B_z coefficient as defined by Zeke did not offer strong correlations with the weld deposit oxygen level. Both the slag basicity and Tuliani's index appeared to be more effective in describing the slag/weld metal oxygen behavior. This can be seen when comparing the regression coefficient values. Secondly, when comparing the data in Figs. 6A and 7A with those in Figs. 4B and 5B, it seemed that better correlations could be obtained when using both the optical basicity index and the B_z coefficient computed from the measured slag compositions.

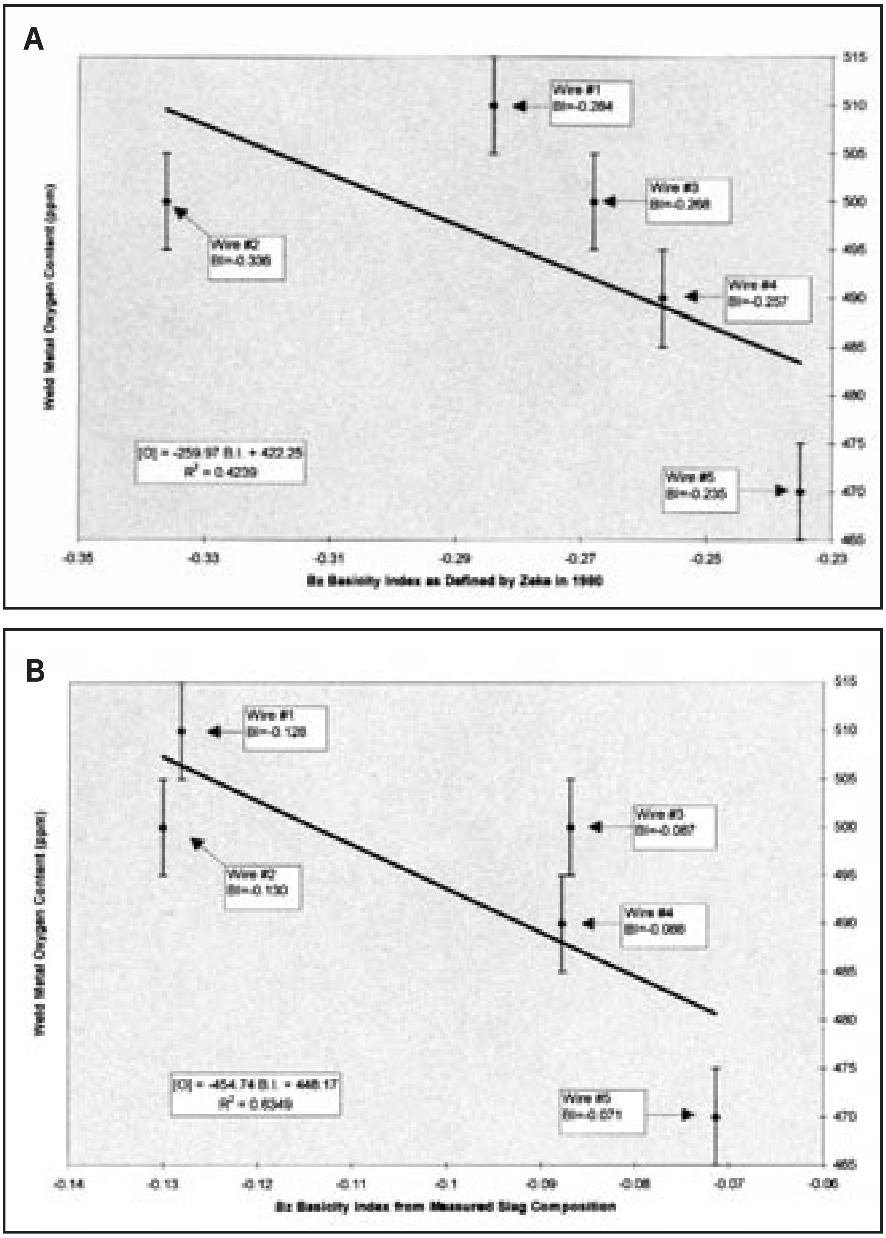

Fig. 5 — A — Dependence of the weld metal oxygen content upon the B_z basicity index, according to Zeke's theory (from flux formulation); B — dependence of the weld metal oxygen content upon the B_z basicity index, using the measured solidified slag compositions.

This finding could in fact be expected since the slag composition actually reveals the extent of slag/metal interactions that take place during welding. In the case of the FCAW electrodes studied herein, expressing the basicity from the composition of the solidified slag better estimated the weld metal oxygen content than the flux formulation.

Finally, it should be noted the determination of the slag basicity only relies on the availability of adequate techniques for determining the solidified slag composition. The fact that the slag basicity is therefore easily accessible for any welding consumable also constitutes a considerable advantage of the slag basicity over most existing basicity theories, which often are based on the uncertain composition of the fill ingredients in the flux.

Conclusions

In Part 1, a methodology was developed to predict the solidified slag chemical composition and to define a slag basicity index based on the slag composition. In Part 2, the usefulness of this innovative basicity theory was shown by correlating the newly defined index with weld metal oxygen content data. The achievements of the investigations conducted in Part 2 can be summarized as follows: Comparative studies of the slag basicity, as defined in Part 1, with Tuliani's index, Datta's optical basicity and Zeke's B_Z index were done to test the validity of the proposed basicity index. Weld metal oxygen content data were plotted against the various indexes for a set of five experimental FCAW electrodes. The slag basicity gave a much better correlation with the oxygen level. Tuliani's index, which only considers oxides present in the original welding flux, does not account for all effects contributed by the various flux ingredients.

Finally, it was shown that expressing the basicity of a FCAW consumable from the composition of the solidified slag better correlates the weld metal oxygen content than using the flux formulation.

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