WELDING RESEARCH

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Reconsidering the Basicity of a FCAW Consumable — Part 1: Solidified Slag Composition of a FCAW Consumable as a Basicity Indicator

A basicity index for a flux cored electrode was developed, taking into consideration the metal sheath, fill ingredients and weld metal composition

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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 two papers, titled Part 1: Solidified Slag Composition of a FCAW Consumable as a Basicity Indicator and Part 2: Verification of the Flux/Slag Analysis Methodology for Weld Metal Oxygen Control. To accomplish this purpose, 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 Part 2, comparison of this innovative methodology with the IIW formula is achieved, as well as with other means reported in the literature for expressing the flux/slag basicity. 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

A flux cored arc welding (FCAW) electrode contains multiple powdered ingredients within a metal sheath. Moreover, the variety of the ingredients that can be used in FCAW is enormous. For these reasons, the intrinsic nature of welding fluxes is rather complex. Also, due to the various chemical reactions involving these ingredients in the arc environment, it is not a simple task to understand how each constituent contributes to the general behavior of the flux with regard to the electrode performance, *i.e.*, the metal transfer stability, the slag viscosity, the slag detachability, the metallurgical properties of the final weldment, etc. Therefore, the multitude of flux ingredients used in a FCAW electrode, each featuring various functions, make the work of formulators rather complex. For a particular FCAW electrode, with proper information on the chemical composition of the deposited weld metal, the composition and nature of the core flux, a simple compositional relationship can be obtained to describe the distribution of each metallic element present in the electrode between the covering slag and the weld metal.

In the present paper, for one particular experimental FCAW electrode, based on a mass balance considering the metal sheath, the electrode fill and the weld metal chemical composition, a simple approach to predicting the composition of the solidified slag is proposed. Hence, a methodology to determine the basicity index of the slag is developed.

FCAW Using CO_2 as Shielding Gas

A flux cored electrode is a composite, tubular electrode that consists of a metal sheath containing a core of flux (Ref. 1). The flux is made up of a mixture of powdered ingredients, both metallic and nonmetallic. The main function of the metallic materials is to alloy the weld metal, together with the alloying elements contained in the metal sheath, in order to increase the strength of the deposited metal and deoxidize it. The non-

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Fig. 1 — X-ray diffraction pattern of slag sample collected after welding with the experimental electrode.

metallic ingredients are often slag formers and arc stabilizers, *i.e.,* helping to produce a smoother arc. They provide a secondary shielding action and help purify the weld metal. The nonmetallic ingredients also help in reducing weld spatter and in controlling the melting characteristics of the electrode.

Proper selection of the core elements is of prime importance for any welding application of acceptable quality. When choosing the ingredients for a new flux design, formulators need to carefully study the physical and chemical characteristics of the raw materials to utilize, *e.g.,* their particle shape and size distribution, their chemical composition and purity, their hygroscopic tendency and their chemical stability. Also, the fill ratio of the electrode, *i.e.,* the ratio of the flux weight over the total electrode weight, has to be closely controlled in order to obtain reproducible weld quality along the weld bead.

Carbon dioxide is certainly the most widely used shielding gas for FCAW steel electrodes that require auxiliary gas shielding. Its selection is mainly due to the possibility of high welding speeds, good weld penetration and, most of all, low cost. At room temperature, carbon dioxide is a relatively inactive gas. When heated to high temperatures in the welding arc, however, part of the CO_2 dissociates to form carbon monoxide (CO), which is more stable than CO_2. Carbon

dioxide can then further decompose into carbon and oxygen (O_2), as indicated by the following reactions:

$$CO_2 \text{ (g)} \rightarrow CO \text{ (g)} + \tfrac{1}{2} O_2 \text{ (g)} \qquad (1)$$

$$CO \text{ (g)} \rightarrow C \text{ (s)} + \tfrac{1}{2} O_2 \text{ (g)} \qquad (2)$$

As a result, a certain amount of oxygen is available in the arc atmosphere to react with the various elements present in the molten metal (metal droplets and weld pool). Therefore, when CO_2 is used as the shielding gas and dissociates during welding, a strong oxidizing effect takes place. That is partly why deoxidizers have to be added to the fill ingredients of the electrode to compensate for the various oxidation sources that include the oxidizing effects of CO_2 and the O_2-containing constituents of the electrode. Also, in the presence of carbon in the molten weld pool, CO_2 can react to form CO according to the reaction below — Boudouard equation (Ref. 2).

$$CO_2 \text{ (g)} + C \text{ (s)} \rightarrow 2 \, CO \text{ (g)} \qquad (3)$$

The simultaneous presence of CO and CO_2 determines the $\dfrac{P_{CO_2}}{P_{CO}}$ ratio, which also controls P_{O_2}, the partial pressure of oxygen of the arc environment, as governed by Equations 1 and 2. Thus, the activity (or partial pressure) of oxygen can

be determined as a function of ΔG_0, the free energy of decomposition of CO_2, and the $\dfrac{P_{CO_2}}{P_{CO}}$ ratio. This reads:

$$a_{O_2} = \rho_{O_2} = \left(\frac{\rho_{CO_2}}{\rho_{CO}} \right)^2 \cdot \exp\left(\frac{-2 \cdot \Delta G_0}{RT} \right) \qquad (4)$$

Furthermore, from the various plasma-metal reactions occurring between the deoxidizing elements and oxygen, oxide compounds are formed, which tend to float to the molten weld pool surface. As solidification of the weld pool proceeds, these oxide compounds become part of the covering slag. A small amount of the oxide products may also be trapped in the solidified weld metal in the form of inclusions.

In the present study, several assumptions are made to simulate the various reactions involving oxygen in welding experiments carried out using an experimental basic-type flux cored wire under 100% CO_2 shielding. A description of the reactions taking place in the arc column is then conceived. As a result, the partition of the various elements present in the constitution of the FCAW electrode between the deposited weld metal and the solidified slag can be determined, as well as the composition of the solidified slag. From this knowledge, a methodology to calculate the basicity index of the FCAW electrode is derived.

Basicity Index of a Flux/Slag System

The concept of basicity was first adopted to answer the needs of the steel making industry. It was used to evaluate the sulfur refinement ability of a slag in steel ladle refining practices (Ref. 3). Later, the use of basicity index was broadened to approximately measure the flux oxidation capacity, and the same principles were applied to the welding technology. Consequently, it has been general practice to use the basicity index to characterize a welding flux with regard to its physical and chemical properties. The slag viscosity and the weldment quality, as represented by the amount of oxygen pickup in the weld metal and the weld metal notch toughness, can both be estimated as a function of the basicity index. Thus, a high basicity slag is considered to be one that exhibits a high concentration (or a high activity) of free oxide ions O^{2-}. It would also tend to exhibit an increased breakdown of the three-dimensional silicate network structure (Refs. 3, 4). Such a slag would therefore be composed of a large quantity of dispersed cations in the broken silicate network, contributing to a more fluid slag

in the molten state. Defining the concept of basicity of slags by means of the O^{2-} activity, however, is virtually not feasible, since activities or concentrations of free oxide ions are impossible to measure experimentally.

In practice, weld metal mechanical properties and weld metal oxygen content are related to the welding fluxes by means of the basicity index, which is usually defined as the following:

$$\text{Basicity Index} = \frac{\Sigma \text{ Basic Oxides}}{\Sigma \text{ Acidic Oxides}} \quad (5)$$

Equation 6 is the most widely used basicity index formula and is recognized by the International Institute of Welding (IIW). It is often referred to as Tuliani's expression (Ref. 5), in which flux component contents are expressed in weight percent.

$$B.I. = \frac{\begin{array}{c} CaF_2 + CaO + MgO + BaO + SrO + \\ Na_2O + K_2O + Li_2O + 0.5 \times (MnO + FeO) \end{array}}{SiO_2 + 0.5 \times (Al_2O_3 + TiO_2 + ZrO_2)} \quad (6)$$

Using the above expression, when the basicity index is less than 1.0, the flux is regarded as acidic, between 1.0 and 1.2, as neutral, and a flux with a B.I. greater than 1.2, as basic.

With time, dozens of empirical or statistical formulas have been developed for the quantitative determination of the basicity of welding fluxes (Refs. 6–8). The degree of successful application of each of these equations depended on the sample population and chemical reactions involved. Nonetheless, problems related to the evaluation of the basicity of welding fluxes/slags have always been a subject of discussion (Refs. 6, 11–14). Thus, other concepts for expressing the flux basicity have been investigated and reported in the literature (Refs. 10, 15–18). In particular, the Bz index, described by Zeke in 1980 (Ref. 16), as well as the optical basicity index, presented by Datta, et al., in 1989 (Ref. 10), are two examples of indexes that were developed to express the basicity of a welding flux. Further explanation of these two basicity theories is provided in Part 2 of the paper, which starts on page 66-s of this issue of the Welding Journal.

Furthermore, Pokhodnya, et al. (Ref. 19), evaluated the oxidizing capacity of submerged arc welding fluxes using a mass spectroscopy technique. As such, these researchers heated and melted typical SAW fluxes. Then, they measured the quantity of oxygen, i.e., the oxygen potential of the gaseous phase generated. Eventually, the weld metal oxygen content could be predicted. This method, therefore, was used as a basicity index to
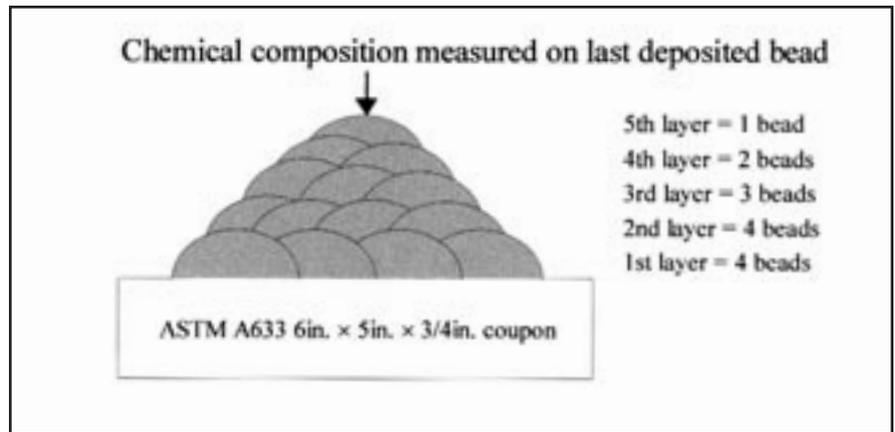

Fig. 2 — Schematic representation of the multilayer deposit.

quantitatively describe the oxidizing capability of the welding fluxes.

For many existing welding consumables, a general trend seems to indicate the weld metal oxygen level decreases as the basicity index increases. In particular, the index is well suited for submerged arc fluxes, which usually contain mostly simple oxides and calcium fluoride, along with ferro-alloys for deoxidization and alloying purposes. However, correlating the basicity index of a flux system based on the amount of all oxides present with its oxygen potential can actually be far from the real deoxidation mechanism that takes place in the weld pool. For example, manganese oxide and iron oxide both have been found to increase the oxygen content in the deposited metal, although their presence increases the basicity of the flux/slag system. In an investigation carried out by Gaspard-Angeli, et al. (Ref. 20), using various SAW fused fluxes, the weld metal oxygen content was found to increase from 427 to 450 ppm as the amount of ferrous oxide (FeO) increased from 2.0% to 4.3%, all other welding parameters being identical. In addition, the same trend related to the effect of magnetite (Fe_3O_4) on the transfer of oxygen in the weld metal could be drawn from data in shielded metal arc welding (Ref. 21). The same conclusion was reached for the influence of FeO flux additions in a systematic study combining several SAW fluxes, various solid wires and two sets of welding parameters (Ref. 22). Some SAW fluxes featuring lower FeO contents, therefore, were found to promote the formation of acicular ferrite in the weld metal, favoring the possibility for higher toughness. Also, some data in this paper showed the effect of MnO on the oxygen content was more complex in that it could actually either help decrease or, on the contrary, increase the oxygen content, as a function

of the welding parameters. Finally, Indacochea, et al. (Ref. 23), studied various manganese silicate fused fluxes in SAW. They came to the interesting conclusion that by holding the SiO_2 content constant at 40%, the weld metal oxygen content increased as the FeO content in the flux was increased. Their results brought about another contradiction to the basicity index theory wherein FeO appears in the numerator of the majority of formulas describing the basicity index.

Therefore, the amount of oxygen in the weld metal is not strictly governed by the value of a basicity index based on the amount of oxides present in the original flux. Defining such a basicity index appears irrelevant since it is always possible to add strong deoxidizers in their metallic form, e.g., Mn, Si, Mg, Al, Ti, ..., which are not included in the basicity index calculation. Nevertheless, these compounds play a major role in the weld pool deoxidization process.

In FCAW, not only do flux formulators use oxides but also ferro-metallic ingredients, e.g., Fe-Mn, Fe-Si and multiple other complex fluorides and minerals, not always reported in the open literature. Hence, because of the many complicated and sometimes unknown reactions taking place in the welding arc environment, it cannot be justifiable to correlate the composition and mechanical properties of the weld metal with a basicity formula based only on the weight percentages of the oxides and calcium fluoride contained in the welding flux. Conversely, the composition of the solidified slag on top of a weld bead is a good indicator of the extent of the slag/metal interactions during welding, and provides substantial information about the various chemical reactions that took place in the weld pool. Therefore, regarding the need for defining the basicity index of a FCAW electrode, it

Fig. 3 — Representation of the distribution of single elements in the solidified slag, as predicted from calculations, and as measured.

should be done based on the chemical composition of the solidified slag collected after welding. As such, this approach is different from most investigations done on slag-metal reactions since they invariably predict the chemical composition of the weld metal instead of that of the solidified slag (Refs. 6, 10, 13, 24, 25). As an example, Mitra and Eagar (Refs. 24, 25) developed a kinetic model to describe the transfer of alloying elements from various submerged arc fluxes to the weld pool. They established a quantitative relationship between the welding consumable composition and the resulting weldment chemical composition. Despite the good agreement between the model and experimental results, no special consideration was given to the solidified slag, which would be in intimate contact with the molten weld pool until solidification.

Proposed Methodology

In the present investigation, an innovative methodology for calculating the basicity index of a FCAW steel electrode is thus conceived by measuring the chemical composition of the solidified slag and applying the expression given by Equation 7.

$$B.I. = \frac{CaF_2 + CaO + MgO + BaO + SrO + Na_2O + K_2O + Li_2O + 0.5 \times (MnO + Fe_2O_3)}{SiO_2 + 0.5 \times (Al_2O_3 + TiO_2 + ZrO_2)}$$

(7)

Equation 7 is identical to the expression proposed in 1969 by Tuliani, *et al.* (Ref. 5), except the mole percentage of each oxide is used instead of the mass fraction. This indeed better accounts for the relative importance of the various oxides, which form from the reactions between the ingredients that dissociate to their metallic forms and the oxygen available in the arc atmosphere. Also, FeO is replaced by Fe_2O_3 in Tuliani's formula since this latter oxide is presumably the iron oxide that forms in a welding slag, on the basis of their Gibbs energy of formation at approximately 2000°C, and confirmed by X-ray diffraction (Ref. 26). Also, the fraction of iron oxide contained in a slag as given by X-ray fluorescence was expressed in the form of Fe_2O_3 in the present investigation. One reason for this practice is the preparation technique employed, which consists of obtaining a fused bead, therefore implying complete oxidation of the iron contained in the slag. This actually opposes results from Medeiros, *et al.* (Ref. 27), who observed Fe_2O_3 initially present in a SMAW coating would tend to reduce to FeO in slags produced in underwater wet welding. Furthermore, Pargamin, *et al.* (Ref. 28), used Mössbauer spectroscopy to determine the coordination of Fe^{2+} and Fe^{3+} ions in quenched silicate melts. They found that at low concentrations of iron oxides in alkaline silicate slags, both Fe^{2+} and Fe^{3+} were actually octahedrally coordinated with oxygen, thus behaving as

network modifiers. The concentration of iron oxide, as well as the melt temperature and the oxygen partial pressure, were also found to affect the reduction of Fe^{3+} to Fe^{2+}. For the sake of simplicity, iron was therefore supposed to be present in the form of ferric oxide (Fe_2O_3) in the slags investigated in the present paper.

In this work, the basicity theory will be utilized to quantitatively characterize each FCAW steel consumable investigated with respect to its oxidation potential and metallurgical quality.

Assumptions

Several assumptions were made in the present study. By doing so, the various reactions taking place during welding are simplified, which allows for the development of the methodology.

1) It is known that silicates and titanates are common in slags found in steel welding systems. They frequently form as solid solutions with variable ratios of Ca, Mn, Mg, Fe, etc. (Ref. 26). Larsenite $-Ca_2SiO_4-$, bustavite $-(Ca,Mg)_3Si_3O_9-$, olivine $-(Fe,Mn)_2SiO_4-$ and fayalite $-Fe_2SiO_4-$ are examples of these compounds. Other constituents determined using X-ray diffraction are $K_2Zr_2O_5$, hematite $-Fe_2O_3-$ or CaF_2. Besides these, many phases found in a welding slag are amorphous, which cannot be determined by X-ray diffraction.

For simplicity's sake, all elements that transfer from the original flux to the slag were assumed to preferentially form oxides in the covering slag.

2) Every ingredient of the original core flux was assumed to dissociate in the welding arc. Recombination of the dissociated flux core elements with oxygen will form the slag that covers the molten weld pool.

Fluorspar, CaF_2, which also participates in the electrode flux formulation, is treated differently in the analysis. CaF_2 originating from the flux was believed to transfer as a whole into the slag. Evidence of its presence as a major constituting phase in the solidified slag was indeed shown through X-ray analysis, in the case of the experimental electrode studied in Part 1 — Fig. 1.

3) In an article published by AWS in 1979 (Ref. 29), data were reported on the weight of fumes per weight of deposited metal for various flux cored steel electrodes, including for two E70T-5 electrodes, *i.e.*, for electrodes somewhat similar to those investigated in the present work. These two sets of data indicated the weight of fumes to constitute exactly 1.79% and 2.36%, respectively, of the weight of weld metal deposit for these two electrodes. On the basis of these

numbers published by AWS, the amount of material carried away in fumes during welding was neglected. No volatile species was considered in the present work. It is assumed, therefore, that when the electrode is heated in the arc atmosphere, only carbon dioxide evolves from the decomposition of the carbonates present in the core flux. The equation below describes the decomposition of carbonates into an oxide and carbon dioxide:

$$E_x(CO_3)_y \,(s) \rightarrow E_xO_y \,(s) + y\,CO_2 \,(g) \quad (8)$$

where $E_x(CO_3)_y$ (s) represents the carbonate of element E (*e.g.*, Ca or Mg, etc.) and E_xO_y (s), the oxide of E that becomes part of the covering slag.

4) The amount of material lost in the form of spatter is neglected.

5) The collected slags were assumed to be homogeneous in composition at any location along the weld bead. Also, no nonmetallic inclusions are assumed to form in the weld metal, which is hypothesized to be fully deoxidized. This assumption implies the resulting oxide compounds float to the surface of the molten weld pool, where they become part of the solidifying slag.

Based on the above assumptions, the overall slag composition, therefore, was expressed in terms of fixed, stoichiometric basic and acidic oxides and calcium fluoride only.

Solidified Slag Composition

From the knowledge of the solidified slag elemental composition, the typical oxidation reaction involving a single metallic element E and its oxide E_xO_y has to be considered, according to the previously stated assumptions and as represented by Equation 9.

$$xE(s) + \frac{y}{2}O_2\,(g) \leftrightarrow E_xO_y\,(s) \qquad (9)$$
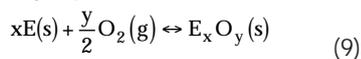
which yields

$$x \times n_{E_xO_y} = n_e \qquad (10)$$

and

$$E_xO_y\%_{slag} + \frac{M_{E_xO_y}}{x \times M_E}E\%_{slag} \qquad (11)$$

In Equations 9, 10 and 11,

n_E = Total number of moles of element E in the slag;

$n_{E_xO_y}$ = Total number of moles of oxide E_xO_y in the slag;

M_E = Molecular mass of E;

$M_{E_xO_y}$ = Molecular mass of E_xO_y;

$E\%_{slag}$ = Total concentration of element E transferred into the solidified covering slag, expressed as a fraction of the total weight of the slag;

$E_xO_y\%_{slag}$ = Total concentration of oxide E_xO_y transferred into the solidified covering slag, expressed as a fraction of the total weight of the slag.

By applying Equation 11 to all elements E of the solidified slag, the slag composition can be determined in terms of stoichiometric oxides and calcium fluoride only. Then, the basicity index of the welding consumable can be computed using the different fractions of oxides calculated from Equation 11. It is noteworthy to point out Equation 12 actually results from the expression given in Equation 7.

$$B.I. = \frac{CaF_2\%_{slag} + \sum\limits_{E=Ca,Mg,Ba,Sr,Na,K,Li}\left(E_xO_y\%_{slag}\right) + 0.5 \times \sum\limits_{E=Mn,Fe}\left(E_xO_y\%_{slag}\right)}{\sum\limits_{E=Si}\left(E_xO_y\%_{slag}\right) + 0.5 \times \sum\limits_{E=Al,Ti,Zr}\left(E_xO_y\%_{slag}\right)}$$

12)

What follows in the present paper will describe a series of experiments that were performed to predict the covering slag composition from the knowledge of the composition and nature of the flux-cored electrode and the chemical composition of the deposited weld metal. In addition, comparison with the actual composition of the collected slag was made.

Experimental Procedure

The experimental 1.2-mm (0.045-in.) diameter basic-type FCAW (E70T-5 AWS grade) electrode investigated in this paper consisted of a low-carbon, low-alloy steel sheath, the composition of which is given in Table 1, and a core flux containing 14 metallic and nonmetallic ingredients, including iron, ferro-silicon, 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 2 lists the ingredients used for manufacturing the electrode.

Multipass welds were prepared on ASTM Type A633 steel coupons using 100% CO_2 shielding gas. These chemical composition pads were prepared using a method equivalent to that specified by AWS A5.29-80 specifications — Fig. 2. As such, the dilution effect caused by the base material could be avoided. The top bead of the multilayer weld pad was ground flat and then analyzed using optical emission spectroscopy. Three runs were performed at different locations on the same weld pad and the average value was reported.

The experimental basic-type FCAW consumable was used at the welding condition of 260 A, 31 V and a travel speed of 7 mm/s (16.5 in./min), which is the best operating performance for this electrode. The contact tip-to-work distance was set and carefully controlled at 20 mm (¾ in.). A Miller Maxtron 450 constant voltage power supply was used. According to the manufacturers' recommended practices, the electrode was welded using direct current electrode negative (DCEN) polarity. Finally, especially due to the nature of the shielding gas, a globular, repulsive type of transfer was observed in the conditions of the experiments.

For the flux cored electrode of Table 2, a method was proposed for the calculation of the composition of the solidified slag using a mass balance technique considering the FCAW fill, sheath and weld metal chemical analyses. Then, a methodology was developed to account for the basicity of the electrode, based on the slag composition. For mass balance, steel coupons used for welding were weighed before and after welding to determine the weight of the deposited weld metal, as well as that of the solidified covering slag. Also, the length of the electrode consumed during a weld test was measured for the calculations of the wire efficiency, *i.e.*, the weight of deposited metal for 100 g of consumed wire.

Furthermore, solidified slag samples were collected from weld beads deposited using the experimental flux cored electrode for subsequent analyses. Ele-

ments such as Si, Mn, Ti, Mg, Fe, Zr, Ca, Al and P present in the slag sample were measured by fusing a bead in a platinum crucible in a propane/oxygen atmosphere. The sample was then analyzed using quantitative X-ray fluorescence. Elements such as Na, K and Li were dissolved in an acidic solution and analyzed using inductance coupled plasma spectroscopy. Fluorine was analyzed in solution after pyrohydrolysis using a specific electrode that featured a monocrystalline membrane (PF4-L type electrode). The activity of free F⁻ anions was measured by immersing the electrode in the solution. The amount of fluorine in slag samples was thus measured as a potential difference, on the basis of Nernst's law. Finally, the sulfur content was estimated using semi-quantitative X-ray spectrometry. This method was selected instead of a combustion technique because of the rather large quantity of fluorine contained in the slag samples. Fluorine evolution would actually damage the measurement cells in a combustion technique such as that employed in a Leco combustion analyzer.

Results and Discussion

Prediction of the Solidified Slag Composition

From the knowledge of the exact formulation of the flux cored electrode, *i.e.*, the chemical analysis of the metal sheath and the exact proportion of the ingredients composing the flux, a method for predicting the composition of the solidified slag was derived.

First of all, when a weld bead is deposited on a steel plate, it is possible to define the arc welding deposition efficiency, as represented by w.e., which corresponds to the actual weight of the weld metal for 100 g of the consumed cored wire. Similarly, s.e., as defined as the "slag efficiency," as well as f.e., the "fume efficiency," and sp.e., the "spatter efficiency," can be determined. The following equations define w.e., s.e., f.e., and sp.e., respectively.

$$\text{w.e.} = \frac{\text{weight of deposited weld metal}}{\text{weight of consumed cored wire}} \times 100 \quad (13)$$

$$\text{s.e.} = \frac{\text{weight of the solidified weld metal}}{\text{weight of consumed cored wire}} \times 100 \quad (14)$$

$$\text{f.e.} = \frac{\text{weight of the fumes produced}}{\text{weight of consumed cored wire}} \times 100 \quad (15)$$

and

$$\text{sp.e.} = \frac{\text{weight of the spatter produced}}{\text{weight of consumed cored wire}} \times 100 \quad (16)$$

It was experimentally found for the experimental flux cored wire of Part 1 that w.e. was equal to 79%, and s.e., to 7.7%. The welding experiments exhibited good reproducibility for this consumable. As for f.e. and sp.e., they were not calculated since neglected, according to the earlier stated assumptions. Notice also the sum of w.e. and s.e. does not equal 100%, clearly indicating the weight of the consumed cored wire does not simply distribute between the weld metal and the slag.

First of all, due to its basic nature, the welding operating characteristics of the FCAW electrode utilized were rather poor, with a harsh arc and significant spatter levels. The weight of the deposited weld metal and that of the collected solidified slag did not include the droplets ejected from the welding arc. Note the use of 100% CO_2 shielding gas was deliberate in the present investigation, as part of a strategy selected for developing a viable 100% CO_2-shielded basic-type FCAW consumable. One can suppose using a more "forgiving" shielding gas, such as a 80%Ar/20%CO_2 or a 98%Ar/2%O_2 shielding gas mixture, would have improved the metal transfer characteristics with a considerable reduction in the amount of spatter during welding. These two gases were not used in this program. However, although featuring a rather high spatter level, the experimental electrode exhibited a high metal transfer stability, as demonstrated by arc voltage and current signals gathered using a high-speed data acquisition system (Ref. 30). Consequently, due to the very stable metal transfer characteristics of the electrode, it was concluded the weld deposit oxygen content would not be greatly affected by the spatter level observed in the present investigation. Neither abrupt changes in the metal transfer mode, nor chaotic transfer events, believed to promote an increase in the oxygen transfer to the weld pool across the arc, was observed.

Secondly, no volatile species are considered in the calculation, which may constitute another source of error. Finally, regarding the slag that results from the multiple reactions that involve gaseous species with the dissociated flux ingredients in the arc column, the quantity of the shielding gas that reacts with the electrode is difficult to evaluate. Consequently, for the above reasons, adding up w.e. and s.e. would not necessarily give a total of 100%.

For the calculation, the concept of mass conservation of a particular element present in the welding system is required. This condition implies the mass of an element E present in the original electrode must also be present in the weld metal, slag, smoke and, eventually,

spatter produced — Equation 17.

$$(E\%_{total} \times 100\%) = (E\%_{weld\ metal} \times w.e.) + (E\%_{slag} \times s.e.) + (E\%_{fume} \times f.e.) + (E\%_{spatter} \times sc.e.) \quad (17)$$

with

$E\%_{total}$ = total concentration of a single element E contained in the flux cored electrode, expressed as a fraction of the total weight of the electrode;

$E\%_{weld\ metal}$ = total concentration of E deposited in the weld metal, expressed as a fraction of the total weight of the deposited weld metal;

$E\%_{slag}$ = total concentration of E transferred into the solidified covering slag, expressed as a fraction of the total weight of the slag;

$E\%_{fumes}$ = total concentration of E lost in the welding fumes, expressed as a fraction of the total weight of the fumes produced during welding;

$E\%_{spatter}$ = total concentration of E transferred into the solidified covering slag, expressed as a fraction of the total weight of the spatter ejected during welding.

Next, since losses in the form of vapors or spatter are ignored according to the earlier stated assumptions, Equation 17 transforms to Equation 18. The equation of conservation reads as follows:

$$(E\%_{total} \times 100\%) = (E\%_{weld\ metal} \times w.e.) + (E\%_{slag} \times s.e.) \quad (18)$$

An expression for calculating the amount of each element that transfers from the original core flux to the solidified slag can thus be derived, as indicated below.

$$E\%_{slag} = \frac{\left(E\%_{total} \times 100\%\right) - \left(E\%_{weld\ metal} \times w.e.\right)}{s.e.} \quad (19)$$

$$E\%_{slag} = \frac{\left\{\begin{bmatrix}(f.r.) \times E\%_{flux} + \\ (1 - f.r.) \times E\%_{metal\ sheath}\end{bmatrix} \times 100\%\right\} - \left(E\%_{weld\ metal} \times w.e.\right)}{s.e.} \quad (20)$$

where f.r. was the fill ratio of the flux cored wire, *i.e.*, ratio of the weight of core flux fill over the total weight of the flux cored electrode fill, per unit length. In addition, $E\%_{flux}$ was the total concentration of element E contained in the core flux, expressed as a fraction of the total weight of the flux, and $E\%_{metal\ sheath}$, the total concentration of E contained in the metal sheath, expressed as a fraction of the total sheath weight.

The complete chemical analysis of the weld metal deposited using the experi-

mental electrode was measured. As such, the values for E%$_{weld\ metal}$ are reported in Table 3.

By knowing the exact constitution and formulation of the flux cored electrode, and by substituting the values for E%$_{weld\ metal}$ from Table 3 into Equation 20, an elemental composition of the solidified slag could be calculated. Additionally, Equation 11 was used to give the composition of the slag as simple oxides. The chemical composition of the solidified slag, expressed both in terms of single elements and oxides, is reported in Table 4.

Predictions from Calculations

From Table 4, it is found the main constituents of the solidified slag are CaF$_2$ (37.4%), SiO$_2$ (21.0%) and TiO$_2$ (16.7%). This agrees well with the fact that most of the matter constituting the slag consists of various silicates, titanates, and calcium fluoride. One can also see from the results in Table 4 the total given by the sum of all oxides is equal to 108.8%, which is greater than 100%. This discrepancy certainly arises from shortcomings in the assumptions, particularly the negligence of the amount of material carried away in the form of spatter and welding fume. Also, it was assumed that CaF$_2$ completely transferred from the core flux to the solidified slag. Even though X-ray analysis showed evidence of the presence of CaF$_2$ in the solidified slag of the electrode, it is probable this ingredient reacts differently when transferred across the welding arc. Finally, in order to explain the discrepancy of Table 4 regarding the total chemical composition of 108.8%, assuming the slag is made up only of simple oxides is less than rigorous. For example, when a compound such as olivine –(Fe,Mn)$_2$SiO$_4$– forms in the slag, fewer oxygen equivalents are needed than what is required for the formation of Fe$_2$O$_3$, 2MnO and SiO$_2$ (4 O equiv. vs. 7). Likewise, assuming the formation of 3CaO, 3MgO and 3SiO$_2$ instead of bustavite –(Ca,Mg)$_3$Si$_3$O$_9$– requires three extra oxygen equivalents (12 vs. 9). Therefore, the discrepancy of Table 4 is most likely due to the assumption the slag forms stoichiometric oxides instead of complex oxides.

Analysis of the Solidified Slag Composition

Slag chips were collected from the welds produced for complete analysis. The analysis allowed for the determination of the slag composition in terms of single metallic elements. Also, Equation 11 was applied to this analysis in order to get the composition of the slag in terms of stoichiometric oxides. The results of the analysis are compiled in Table 5.

Results from Actual Slag Chemical Analysis

Table 5 compares well with Table 4. Additionally, Fig. 3 presents both sets of data that describe the composition of the covering slag, expressed as a function of the single elements present in it.

First of all, it is important to observe that the total given by the slag composition expressed in terms of oxides is very close to 100%, as indicated in Table 5. This shows that the assumption that all elements transferring from the original flux to the slag form oxides and CaF$_2$ in the covering slag was reasonable. This assumption allowed for good predictions of the overall slag composition. Besides, it is apparent from these results that a rather good agreement is obtained between the calculated and the measured slag compositions. The five main elements constituting the slag, i.e., Ca, F, Mn, Si and Ti, were predicted with a fairly acceptable match. Therefore, the methodology proposed for predicting the composition of the covering slag was reasonable. Furthermore, from the constitution of the slag expressed in terms of stoichiometric oxides and CaF$_2$, the basicity was calculated in each case. As shown in Tables 4 and 5, the experimental FCAW steel electrode was assigned a basicity index approximately equal to 1.9. Both calculated and measured slag compositions led to this basicity index value with an excellent agreement.

Figure 3 also shows all of the predicted concentrations are larger than those given by the slag analysis — except for zirconium, aluminum and iron. One of the reasons for this may be the vaporization of flux ingredients and reaction products during welding. For each element, the magnitude of the difference between the predicted and the measured values might be attributed to the losses in vapors of the corresponding compound of the element present in the flux at the high temperatures in the welding arc. In particular, as seen in Fig. 3, only about half of the predicted Li, Na and K were actually measured in the slag. These results are not surprising considering these elements feature high volatility. Consequently, a large proportion of these ele-

ments would be concentrated in the fumes, which were neglected according to the assumptions. Notice here, if Li, Na and K constituted a large percentage of the slag-forming ingredients of the electrode, as would be the case in many metal-cored electrodes, then the predicted slag composition, assuming no fume losses, would be considerably different from the actual slag composition. Notice, however, in the case of the present electrode, Li, Na and K represented only 3.2% of the total flux weight. Thus, vaporization losses of these elements certainly had a minor effect on the final outcome of the analysis. Finally, as to the presence of Al and Zr in the solidified slag, both of them are believed to originate from "impurities" contained in the core flux — in particular, from $CaCO_3$ and CaF_2 — since no compound of these two elements was actually present in the core flux of the experimental electrode.

From these results, with a silicon content equal to 0.23% and a manganese content equal to 1.26% in the weld metal deposited using the electrode of Part 1, it was found 80% of the total amount of silicon originally contained in the flux cored electrode was transferred into the solidified slag, and only 44% of the manganese did. As for the constituents of the core flux other than those containing Si and Mn, *i.e.*, elements such as Ti, Ca, Zr, Li, Mg, Na, K and Al, they were virtually not found in the weld metal. They indeed exhibited only minor or null effect on the final chemical composition of the weld metal.

Finally, one of the drawbacks of the present model is that no Fe can be predicted in the covering slag since the method employed consists in a mass balance in which iron is the base element. However, the analysis showed 2.7% Fe was actually present in the covering slag.

Conclusions

The achievements of the investigations carried out in Part 1 of the present paper can be summarized as follows:

1) Knowing the constitution of an experimental basic-type FCAW electrode and the chemical analysis of the weld metal deposited with it, a simple method for predicting the composition of the solidified slag was developed. Rather good agreement was obtained with the composition obtained from a slag analysis.

2) A conceivable approach to quantitatively characterize FCAW electrodes by means of a basicity index based on the chemical analysis of their collected slag was developed using a derivative of the well-known Tuliani's formula. The different steps of this methodology consisted of collecting the solidified slag on top of the weld bead for a complete analysis, calculating for each metallic element present in the slag the number of oxygen equivalents consumed for the formation of its most stable stoichiometric oxide, expressing the overall composition of the solidified slag in terms of molar fractions of the constituting oxides together with CaF_2 and calculating the basicity index of the slag using a derivative of Tuliani's formula from the molar fraction of each oxide and CaF_2 present in the slag.

3) One of the main advantages of this innovative basicity theory is that the slag basicity index is always predictable from a mass balance considering the exact formulation of the FCAW consumable. Prior to welding, the slag basicity index can be estimated from calculations.

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