# The Effect of SAW Parameters on Weld Metal Chemistry

*Weld deposit chemistry is shown to be primarily dependent on flux composition although seemingly insignificant operating parameters may produce notable changes in weld chemistry*

BY C. S. CHAI AND T. W. EAGAR

ABSTRACT. A parametric study of manganese silicon, carbon and oxygen recovery during submerged arc welding has been made using two commercial fluxes. Both fluxes were designated as neutral in chemical behavior; however, the results indicate that wide variations in weld metal chemistry may occur depending upon the choice of operating parameters. In the case of oxygen, in particular, the recovery level varies from 210 ppm to 580 ppm when using a calcium silicate flux, while the variation for a manganese silicate flux is 670 ppm to 1740 ppm.

Such changes in oxygen content have a profound effect on the cleanliness of the weld metal, and this, in turn, affects the fracture toughness. Variations in Si and Mn content were of similar magnitude. It is concluded that any assessment of the fracture behavior of high quality weldments should be based upon a consistent set of operating conditions. Furthermore, the results suggest that the "oxygen potential" of a flux is not a uniquely definable quantity and that such a parameter would not provide a useful method of classifying fluxes.

A statistical analysis of the effect of operating conditions on several other parameters, including weld geometry, has also been performed. While many of the relationships were known previously, several new factors are illustrated. Generally, the results indicate the great complexity of the welding process and the difficulty of isolating the effect of changes in a single parameter.

Of the 176 combinations of independent and dependent variables, only nine gave correlation coefficients greater than 0.70. Most of these were familiar ones such as increased weld penetration with increasing welding current, or oxygen recovery vs. flux composition; however, some less obvious correlations were also noted. Several correlations relating to recovery of manganese, silicon and oxygen in the weld metal were noted, although no correlations were found for the carbon recovery. Many of the chemical reaction effects can be explained in terms of possible kinetic processes operating between the slag and the molten weld pool.

## Introduction

It has long been known that the high temperature attained during flux shielded arc welding promotes chemical reactions between the slag and the metal, although the very short times and the large thermal gradients involved in the process prevent the attainment of an overall slag-metal equilibrium. Nonetheless, numerous investigators have attempted to quantify the changes, which do occur, by determining which flux components are of most importance in establishing the final weld metal chemistry. Unfortunately, the results are sometimes contradictory and a great deal of confusion still exists. It would be very worthwhile if one could develop a framework with which to predict the manganese, silicon and oxygen content to be expected from a given combination of electrode, flux and base metal chemistries. The present study was performed in order to determine which process parameters need to be controlled when studying slag-metal reactions during welding.

Christensen and Chipman[1] in a study of shielded metal arc welding using acidic fluxes noted that the weld travel speed had by far the greatest effect on manganese recovery. In a similar study of submerged arc welding, North[2] found that there was no effect of travel speed on the manganese recovery. This conclusion conflicts with the work of Christensen[3] who found that manganese recovery in SAW could best be related to the product of the heat input and the travel speed.

Belton *et al.*[4] in a study of silicon recovery during SAW found that an effective equilibrium temperature of 2000°C (3632°F) was attained. No equilibrium was noted for the FeO reaction which is usually thought to control the oxygen potential of these fluxes.

While studying more basic fluxes, Kubli and Sharav[5] and Lewis *et al.*[6] found that the cleanliness and fracture toughness of the weld metal could be improved by reducing the $SiO_2$ content of the flux. This concept was extended by Tuliani *et al.*[7] who showed that oxygen recovery decreases as the flux basicity is increased. Recent papers by Eagar[8,9] have indicated that this is due to the reduced thermodynamic activity of $SiO_2$ in

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**Table 1—Experimental Results Obtained Using the Independent Variables of Table 2, and the Trial Design of Plackett and Burman[12]**

| Trial | Penetration, mm | Height, mm | Width, mm | Arc stability | Contact angle, deg | Flux consumption, g/s | Melting rate, g/s | Oxygen % | Mn, % | Si, % | C, % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 10.5 | 6.0 | 16.0 | 1 | 125 | 1.094 | 2.87 | 0.085 | 1.28 | 0.40 | 0.1 |
| 2 | 1.5 | 4.0 | 16.0 | 3 | 138.8 | 1.958 | 1.784 | 0.102 | 1.07 | 0.38 | 0.05 |
| 3 | 3.0 | 2.5 | 12.0 | 1 | 137.5 | 0.718 | 1.17 | 0.054 | 0.98 | 0.32 | 0.12 |
| 4 | 4.0 | 5.5 | 10.0 | 5 | 91.8 | 0.811 | 2.824 | 0.086 | 1.03 | 0.33 | 0.14 |
| 5 | 7.0 | 2.0 | 17.0 | 1 | 150.0 | 2.032 | 1.558 | 0.043 | 0.92 | 0.33 | 0.16 |
| 6 | 9.0 | 3.0 | 13.5 | 1 | 145.0 | 1.373 | 1.88 | 0.088 | 1.23 | 0.35 | 0.10 |
| 7 | 7.5 | 3.5 | 24.0 | 1 | 150 | 1.92 | 1.787 | 0.026 | 1.05 | 0.32 | 0.10 |
| 8 | 4.0 | 2.0 | 11.5 | 1 | 141.5 | 1.489 | 0.965 | 0.058 | 0.58 | 0.11 | 0.13 |
| 9 | 7.0 | 6.5 | 9.0 | 5 | 90 | 0.732 | 2.06 | 0.027 | 0.97 | 0.42 | 0.11 |
| 10 | 3.5 | 3.0 | 12.0 | 3 | 134 | 1.69 | 1.06 | 0.033 | 0.85 | 0.44 | 0.12 |
| 11 | 8.5 | 8.5 | 8.0 | 5 | 50.0 | 0.615 | 2.615 | 0.087 | 1.23 | 0.64 | 0.12 |
| 12 | 2.5 | 4.5 | 14.0 | 3 | 119 | 0.38 | 1.98 | 0.143 | 1.19 | 0.92 | 0.07 |
| 13 | 3.0 | 4.0 | 11.0 | 5 | 119.5 | 0.9 | 1.117 | 0.033 | 0.91 | 0.37 | 0.12 |
| 14 | 3.0 | 2.5 | 15.0 | 1 | 125.5 | 0.993 | 1.257 | 0.174 | 1.21 | 0.77 | 0.15 |
| 15 | 3.0 | 2.0 | 11.5 | 5 | 135 | 0.904 | 1.006 | 0.150 | 1.11 | 0.64 | 0.06 |
| 16 | 7.0 | 6.5 | 7.0 | 5 | 83.5 | 0.496 | 2.337 | 0.022 | 1.09 | 0.40 | 0.12 |
| 17 | 7.0 | 5.0 | 18.5 | 3 | 128 | 1.99 | 2.475 | 0.021 | 0.82 | 0.30 | 0.12 |
| 18 | 2.0 | 2.5 | 14.0 | 3 | 142.5 | 1.56 | 1.52 | 0.133 | 1.11 | 0.75 | 0.06 |
| 19 | 4.5 | 6.5 | 9.0 | 5 | 264.0 | 3.08 | 2.23 | 0.067 | 1.11 | 0.42 | 0.13 |
| 20 | 3.5 | 3.0 | 15.0 | 1 | 142 | 0.94 | 1.044 | 0.028 | 0.90 | 0.36 | 0.07 |

these fluxes. North[10] has claimed that the oxygen recovery during submerged arc welding depends upon the CaO content of the flux, although his conclusions were based primarily on blended carbonate fluxes and hence may not be applicable to fused fluxes.

Despite the above studies, it is still not possible to predict weld metal chemistry based upon the composition of the starting materials. Nonetheless, some progress has been made in the case of fused neutral fluxes, where the thermodynamic approach taken by Eagar[8] shows promise of being able to predict the direction, if not the magnitude, of changes in weld metal composition.[11] The failure to quantify the extent of the reaction is to be expected, because a thermodynamic approach is only capable of determining the equilibrium state; it tells nothing about the rate of approach to that equilibrium.

The final composition of the weld metal is determined by the kinetics of the slag metal reactions operating within the limits placed upon the system by the thermodynamics. Hence, if a true understanding of flux shielded weld chemistry is to be obtained, both the thermodynamics and kinetics of the process must be studied. The present work represents an attempt to determine which parameters are of greatest importance in controlling the kinetics of these reactions.

## Experimental Program

In order to accurately assess the significance of the many welding process variables, a screening experiment based upon a two-level, twenty-run Plackett-Burman design[12] was performed—Table 1. The choice of 11 independent variables permitted a statistical estimate of the significant interactions between both the independent and the dependent variables through the remaining eight degrees of freedom of the experiment.[13]

The independent variables and their selected values are given in Table 2. The compositions of the electrodes, base plates and fluxes are given in Table 3. All materials were supplied by commercial vendors. The two fluxes were chosen due to their widely varying basicity and expected differences in manganese, silicon and oxygen recovery. Both are classed as fused neutral fluxes. In the present case, a neutral flux is defined as one in which the manganese and silicon recovery does not depend upon the weld voltage. As will be seen subsequently, each flux was found to be "neutral" in this sense, although neither flux was found to be non-reactive.

All welds were run in random sequence in order to reduce the effect of external, uncontrolled variables. The welding was performed with an 800 ampere (A) constant potential power supply. This particular power supply has a very large inductor in the circuit which improves arc stability.

**Table 2—Independent Variables Chosen for the Screening Equipment**

| Variable | Level (−) | Level (+) |
|---|---|---|
| Voltage, V | 20 | 30 |
| Current, A | 300 | 500 |
| Travel Speed, cm/s | 0.50 | 0.81 |
| Electrode diameter, mm | 2.3 | 3.1 |
| Plate thickness, cm | 1.25 | 2.5 |
| Flux height, cm | 2 | 4 |
| Flux composition | Calcium silicate | Manganese silicate |
| Electrode tilt, deg | 0 | +15 |
| Polarity | Electrode (+) | Electrode (−) |
| Electrode extension, cm | 1.5 | 2.5 |
| External shield | None | Argon |

**Table 3—Flux, Electrode and Base Metal Chemistries Used in This Study**

| | C | Mn | Si | O |
|---|---|---|---|---|
| Plate (2.5 cm) | 0.13 | 1.40 | 0.37 | 0.0026 |
| Plate (1.25 cm) | 0.13 | 1.37 | 0.37 | 0.0026 |
| Electrode (3.1 mm) | 0.12 | 0.81 | 0.27 | 0.016 |
| Electrode (2.3 mm) | 0.11 | 1.02 | 0.26 | 0.011 |

| Fluxes | $SiO_2$ | CaO | MnO | $CaF_2$ | $Na_2O$ |
|---|---|---|---|---|---|
| Calcium silicate | 36 | 47 | 0.14 | 9.8 | 5 |
| Manganese silicate | 50 | 3 | 40 | 5 | — |

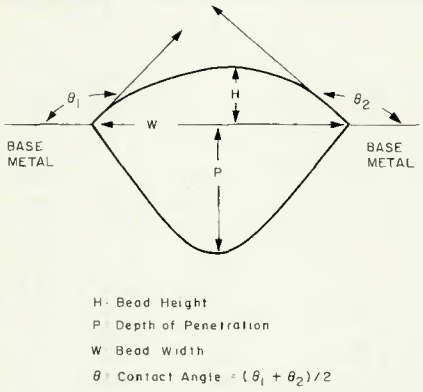


*Fig. 1—Schematic defining the weld bead shape parameters measured in this study*

Eleven dependent variables were monitored, viz., penetration, height, width, arc stability, contact angle, flux consumption, electrode melting rate and manganese, silicon, oxygen and carbon content. The definitions of penetration, height, width and contact angle are illustrated in Fig. 1.

Arc stability was monitored by a technique suggested by G. Uttrachi of Union Carbide Corporation's Linde Division. His technique uses a storage oscilloscope operated in the X-Y rather than the usual Y-time mode. The current oscillations of the dc arc are input to the X-axis and the dc arc voltage is input to the Y axis. This results in a plot as shown in Fig. 2. The smaller the region of voltage-current oscillations, the greater is the arc stability.

For purposes of this study, arc stability was given values of 1, 3 or 5 depending on the extent of the variations, with 1 being the most stable arc. This technique of quantifying arc stability is similar to the approach of Olsen *et al.*, who used the total voltage oscillation range.[11]

Manganese and silicon contents were measured by atomic absorption spectroscopy. Oxygen content was measured by a vacuum fusion technique, and carbon was analyzed with a Leco analyzer.

**Table 4—Measured Range of Dependent Parameters as Produced by the Independent Parameters Shown in Table 1**

| Dependent parameter | Minimum | Maximum |
|---|---|---|
| Penetration, mm | 1.5 | 10.5 |
| Contact angle, deg | 50 | 150 |
| Height, mm | 2.0 | 6.5 |
| Width, mm | 7 | 24 |
| Flux consumption rate, g/s | 0.38 | 3.08 |
| Electrode melting rate, g/s | 0.97 | 2.87 |
| Oxygen, ppm | 210 | 1740 |
| Manganese, % | 0.58 | 1.28 |
| Silicon, % | 0.11 | 0.92 |
| Carbon, % | 0.05 | 0.16 |

## Experimental Results

The range of measured dependent parameters is given in Table 4. By comparing Tables 2 and 4, it is seen that changes in the independent parameters produce even greater changes in the dependent parameters. In most cases, the dependent variables show at least a factor of three variation between maximum and minimum values; hence the experiment is considered to have produced a wide range of possible welding conditions. This indicates that the initial choice of experimental limits (Table 2) was effective in separating the dependent variable responses.

The correlation coefficients for all binary combinations of the independent-dependent and dependent-dependent variables are given in Table 5. The underlined values are those responses which have been determined to be correlated with 95% confidence. Correlation in this sense means that a change in one parameter is expected to produce a proportionate change in the other parameter. For example, a correlation coefficient of 0.84 between welding current and depth of penetration means that increases in welding current will most likely lead to increased penetration.

Perfect correlation is given by a correlation coefficient of one, while random responses are given by a correlation coefficient of zero. Negative correlation coefficients indicate that an increase in one parameter will produce a decrease in the other parameter. For example, an increase in weld bead height is expected to decrease the weld contact angle. Any two parameters which have a correlation coefficient with an absolute value close to one will produce a pleasing graph. However, the physical interpretation of the graph is not always apparent.

## Discussion

Of the 176 correlations presented in Table 5, 44 are correlated within 95% confidence limits yet only nine have correlation coefficients above 0.7. The large number of correlated variables indicate the complexity of the interactions during flux shielded welding, yet the small number of strongly correlated variables shows that the effects of process changes, although real, are often subtle.

Discussion of each of the 44 correlations would be tedious and probably repetitive. For example, the fact that weld penetration has been found to be dependent primarily upon welding current, but also upon electrode diameter and polarity is not new. The correlation of weld penetration with weld

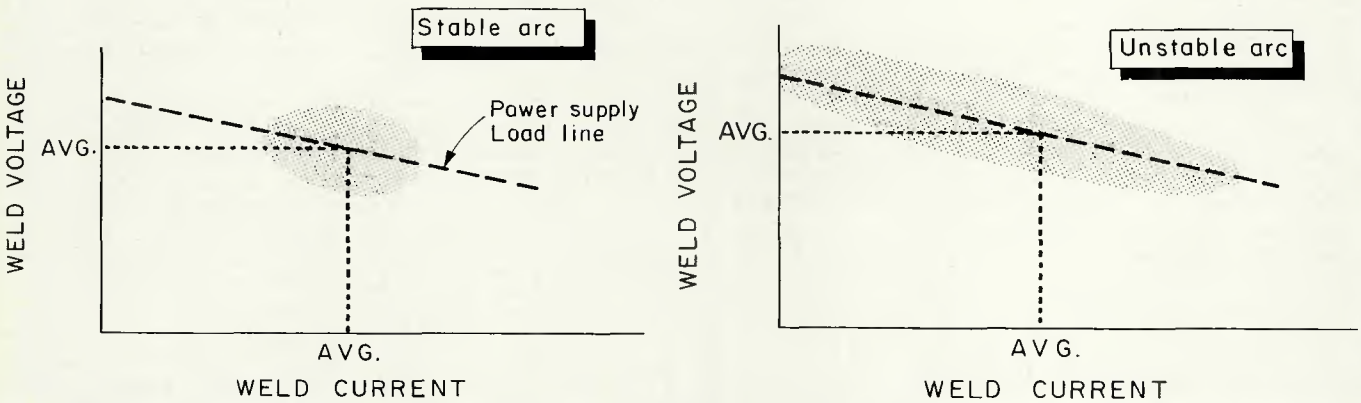


*Fig. 2—Schematic of the oscillographic image of dc arcs used to monitor arc stability. Note that unstable arcs often are completely extinguished and may approach double the average welding current on re-ignition*

**Table 5—Correlation Coefficients**

| | Penetration | Height | Width | Arc stability | Contact angle | Flux composition | Melting rate | Oxygen | Manganese | Silicon | Carbon |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Voltage | 0.16 | −0.33 | 0.63 | −0.52 | 0.59 | 0.40 | 0.02 | 0.00 | −0.13 | −0.10 | 0.2 |
| Current | 0.84 | 0.62 | 0.00 | 0.17 | −0.45 | 0.20 | 0.79 | −0.39 | 0.25 | −0.30 | 0.4 |
| Travel speed | −0.14 | −0.33 | −0.37 | 0.06 | 0.07 | 0.20 | −0.20 | 0.01 | −0 19 | −0.21 | 0.2 |
| Electrode diameter | −0.21 | −0.30 | 0.38 | −0.06 | 0.29 | 0.12 | −0.05 | 0.19 | −0.03 | 0.04 | 0.0 |
| Plate thickness | 0.06 | −0.03 | −0.04 | −0.17 | 0.10 | −0.15 | 0.15 | −0.02 | −0.07 | −0.40 | 0.2 |
| Flux thickness | −0.04 | 0.00 | 0.14 | 0.06 | 0.06 | 0.10 | 0.01 | −0.01 | 0.23 | 0.17 | −0.1 |
| Flux composition | −0.08 | 0.19 | −0.13 | 0.17 | −0.25 | −0.01 | 0.36 | 0.83 | 0.75 | 0.59 | −0.3 |
| Electrode tilt angle | 0.06 | 0.05 | 0.01 | −0.06 | −0.11 | 0.28 | 0.02 | 0.00 | 0.06 | 0.13 | 0.4 |
| Electrode polarity | −0.33 | 0.35 | −0.29 | 0.64 | −0.34 | 0.12 | 0.26 | −0.14 | −0.10 | 0.13 | −0.1 |
| Electrode extension | 0.16 | 0.24 | −0.27 | 0.17 | −0.19 | −0.43 | 0.20 | 0.11 | 0.02 | 0.22 | −0.2 |
| Argon shielding | 0.0 | 0.1 | 0.0 | 0.2 | −0.2 | 0.3 | 0.0 | 0.0 | −0.1 | 0.0 | 0.1 |
| Penetration | — | 0.48 | 0.11 | −0.12 | −0.22 | 0.01 | 0.60 | −0.37 | 0.26 | −0.29 | 0.3 |
| Height | — | — | −0.43 | 0.60 | −0.88 | −0.14 | 0.82 | −0.21 | 0.36 | 0.07 | 0.1 |
| Width | — | — | — | −0.67 | 0.70 | 0.37 | −0.10 | −0.03 | −0.04 | −0.10 | −0.2 |
| Arc stability | — | — | — | — | −0.74 | −0.15 | 0.32 | −0.01 | 0.12 | 0.22 | 0.0 |
| Contact angle | — | — | — | — | — | 0.16 | −0.60 | 0 05 | 0.30 | −0.18 | −0.3 |
| Flux composition | — | — | — | — | — | — | −0.01 | −0.19 | −0.22 | −0.33 | 0.1 |
| Melting rate | — | — | — | — | — | — | — | −0.6 | 0.46 | 0.01 | 0.1 |
| Oxygen | — | — | — | — | — | — | — | — | 0.58 | 0.75 | −0.3 |
| Manganese | — | — | — | — | — | — | — | — | — | 0.63 | −0.2 |
| Silicon | — | — | — | — | — | — | — | — | — | — | −0.3 |

height and electrode melting rate probably has not been noted previously. However, this is not surprising when one considers that the welding current strongly affects both bead height and melting rate as well as penetration depth. Hence these dependent parameters are all interrelated through the welding current, and the positive correlation results of weld penetration are not surprising.

The data also indicate that weld penetration is not affected by any of the other parameters within the limits of this study. Specifically, the finding that electrode tilt angle does not affect depth of penetration is surprising as electrode tilting does change the penetration characteristics of some GTA welds. An explanation of why tilting does not affect SAW weld penetration is lacking. It is seen that the lack of a correlation is often of as much interest as if a correlation had been found.

Similarly, the parameters affecting weld bead height, width, contact angle and flux consumption, as indicated in Table 4, are not unusual. One correlation which may be of interest is the finding that weld travel speed has as much effect on electrode melting rate as electrode extension. This is curious because it is generally assumed that the phenomena occurring at the electrode tip are the only factors controlling electrode melting rate. This study indicates that the condition of the base plate may have an effect as well.

Although the correlation between melting rate and travel speed is weak, it is as strong as the effect of electrode extension on melting rate which is commonly cited (after welding current) as the primary factor controlling melting. In the present study, flux composition was found to have a stronger effect on melting rate than electrode extension. This is no doubt due to changes in the ionization potential of the fluxes, which influences the heat transported to the electrode tip.

It is interesting to note that flux burden thickness and electrode tilt angle were not found to be significant parameters. As with all the correlations presented, this is true only within the limits of this experiment. In other situations, these parameters may be significant. For example, electrode tilt angle is known to be important in multiple electrode welding; however, the present study is only valid for single electrode SAW.

**Table 6—Weld Metal Chemistry Variations Observed with Each Flux**

| | Flux type | |
|---|---|---|
| | Manganese silicate | Calcium silicate |
| C | .05–.15 | .07–.16 |
| Mn | 1.03–1.28 | .58–1.09 |
| Si | .33–.92 | .11–.44 |
| O | .067–.174 | .021–.058 |

The oxygen, manganese and silicon contents of the weld metal show relatively little correlation with any parameters other than weld current, flux composition and overall weld chemistry. Manganese content was found not to be dependent upon travel speed; this agrees with the work of North.[2] The carbon content was not found to correlate with any parameter. The correlation of silicon with welding current and plate thickness suggests that the silicon reaction kinetics may be dependent upon convection and cooling in the molten weld pool.

The strong correlation between silicon and oxygen in the weld metal is in agreement with the mechanism of oxygen transfer proposed by Eagar.[8,9] The correlation of melting rate with weld manganese content is not explained. The other chemistry correlations are not unusual considering the fact that the manganese, silicon and oxygen reactions are all interrelated.

One of the most surprising findings of this study is the wide range of weld metal chemistries obtained with operational changes in the welding process. This is particularly true when the major chemistry variable, flux composition, is separated. Table 6 gives the range of observed chemistries for each flux.

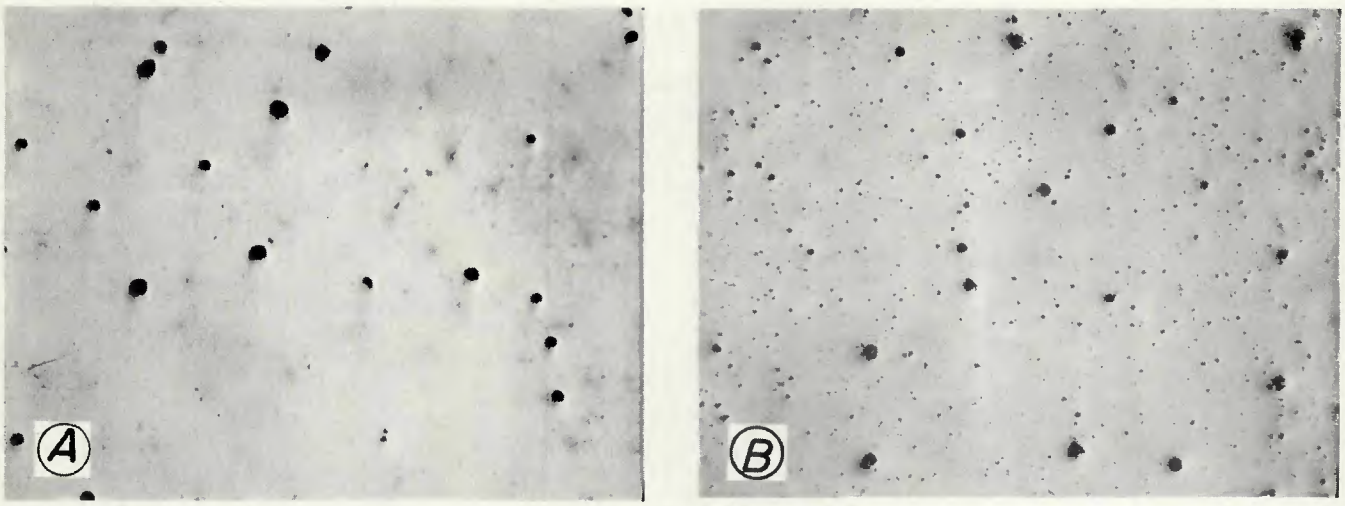


*Fig. 3—Inclusion distribution in weld metal produced with manganese silicate flux: A—670 ppm oxygen; B—1740 ppm oxygen. X230 (reduced 26% on reproduction)*

Carbon, silicon and oxygen are found to vary by a factor of three with a given flux. Hence, even though no single parameter other than flux composition appears to control weld metal chemistry, changes in seemingly insignificant parameters may produce wide variations in weld metal chemistry. This illustrates the difficulty and complexity of trying to determine weld metal chemistry based upon starting material compositions and provides a caution to those claiming specific chemistry properties of a flux.

The actual values obtained are dependent upon the process parameters chosen. This finding further illustrates the need for a more fundamental understanding of the kinetic processes controlling weld metal chemistry. Only by understanding the mechanism of silicon, manganese, oxygen and carbon transfer between the slag and the metal will it be possible to understand the variations observed here.

A practical consequence of these variations in weld chemistry is illustrated in Figs. 3 and 4. In each, the inclusion population of the lowest oxygen and the highest oxygen welds of each flux are compared. It is apparent that the cleanliness of each weld is affected by the operating parameters; hence any comparison of weld mechanical properties should be made with identical weld procedures. Although commonly required by welding codes, this is seldom practiced in the welding literature.

Finally, it should be noted that even though external argon shielding was not found to affect weld metal chemistry significantly, atmospheric contamination of SAW metal is still a likely possibility.[8] In the present study, the effect of atmospheric contamination appears to have been overshadowed by other factors. Studies by North *et al.*,[10] confirmed in our laboratory, indicate increased weld metal oxygen when using pure $CaF_2$ as a flux. These changes are commonly on the order of 100 to 300 ppm oxygen, which although not insignificant, were probably too small to be separated in the present study.

## Conclusions

A parameteric study of the factors controlling weld metal chemistry during SAW has shown that the weld deposit chemistry is primarily dependent upon flux composition; however, other, seemingly insignificant operating parameters may produce notable changes in weld chemistry.

It is concluded that the oxygen potential of the flux is not a uniquely definable quantity nor can the weld metal mechanical properties be determined solely by the base plate, flux and electrode chemistries. Some of the studies in the literature claiming significant correlations of weld fracture toughness with weld microstructure appear to have overlooked the variations in weld chemistry which may occur when the operating procedures are changed.

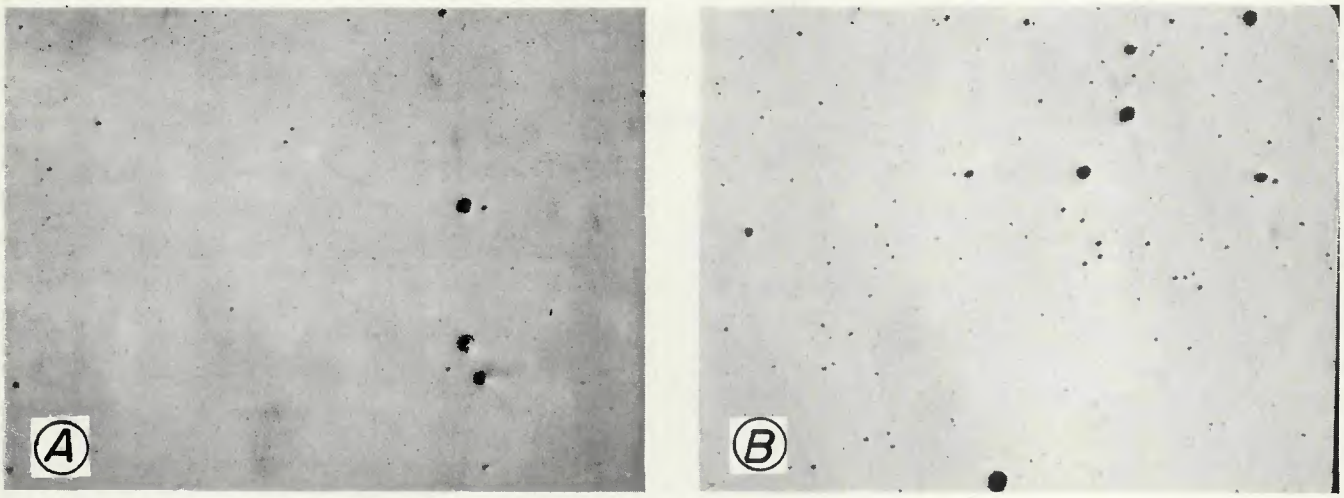


*Fig. 4—Inclusion distribution in weld metal produced with calcium silicate flux: A—210 ppm oxygen; B—580 ppm oxygen. X230 (reduced 26% on reproduction)*

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## WRC Bulletin 253
## October 1979

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Through the courtesy of G&W Taylor-Bonney Division, the 1949 Taylor Forge book, *Development of General Formulas for Bolted Flanges,* by E. O. Waters, D. B. Rossheim, D. B. Wesstrom and F. S. G. Williams has been reprinted.

The historical importance of this book is enhanced by the fact that the material is current and still forms the basis of the rules in the ASME Codes for the design of raised faced flanges. Additionally, the book continues to appear as a reference in technical papers published in the United States and abroad.

The price of this book is $18.00. Please send payment with orders to the Welding Research Council, 345 East 47th St., Room 801, New York, NY 10017.