Commentary on GMAW Parameter Selection Paper

I wish to comment on the paper titled "Selecting Parameters for GMAW Using Dimensional Analysis," by Paul E. Murray, which was published in the July 2002 issue of the *Welding Journal*.

Concerned with the empirical methods that are used by industry when developing welding procedures, Murray developed a "dimensional analysis of experimental data to obtain analytical relationships between welding parameters and welding variables." For this, he used nondimensional numbers of mass and heat transfer. Then he went on to develop "a method for selecting welding parameters to obtain a welding geometry."

Chosen for studying the parameters and variables was the gas metal arc welding (GMAW) process with $98Ar/2O_2$ shielding and 308 stainless wire. No consideration seems to have been given to controlling the mode of transfer. The experimental deposits were beads on plate. Preselected for the experiments were two plate thicknesses (but not included in the analysis), two wire diameters, three travel speeds, and three contact tip-to-work distances. Not explained was the selection of the wire feed speed or the power supply settings. I'm speculating that, cleverly, Murray tied the wire feed speed (U) to three preselected areas of the weld reinforcement (A_{dep}). With the following equation, this provided a logical way to preset the wire feed speed. Confirmation of these assumptions would be appreciated.

$$U = A_{dep}S/\pi r_e^2 \qquad (1_L)$$

Remaining, it seems, was the question of how to set the constant potential power supply. Welders having experience with GMAW and argon-rich shield gases generally set the arc length to be slightly longer than that at which a slight crackling sound is emitted, about 5 mm. At this length, the spray mode arc is stiff, spatter-free, and produces the lowest amount of fume. And, should the current be below transition, the large drops (globular transfer) would be free to fall without short-circuiting. Longer spray arcs become sluggish, produce more fume, and, if too long, can produce meltbacks. Shortened a bit, slight (although audible) short circuits produce pressure fluctuations in the arc that, in turn, cause air to be aspirated into the shield gas. Unlike shields containing significant amounts of CO_2 or He, additional shortening in the selected gas results in more fume and lots of spatter — a mess. Recognizing this, instead of spending time with arcs that have no useful function, a current above transition and a fixed arc length of about 5 mm should have been used. With the same number of experimental welds, about twice as much information would have been obtained. Comment, please, about the reasons for not controlling the arc length or transition current.

A second option would be to preset an arc voltage. That's fine if the welder had been there before and has an approximate idea of where he should be. Not to be forgotten is that both the arc and power supply voltages are dependent on the welding current (increasing for the arc and decreasing for the power supply output). The third option would have been to preset the open circuit voltage at the power supply. This really is flying blind because other voltage drops such as those in the welding cable and connectors become hidden variables. Unfortunately, the report does not mention the approach used to set the power supply, something that should be addressed. Incidentally, one of the requirements of peer-reviewed papers is that others should be given enough information to be able to reproduce the results.

Twenty-seven beads were deposited, the results of which are reported in Table 1 of the paper. Measured or observed were arc volts, arc length, welding current, metal transfer mode, and bead cross sections (depth of penetration, width, and cross-section area). Not mentioned was the penetration configuration, particularly the presence of central spikes, which characterize spray transfer (presuming they were found). Photographs of these sections would be very helpful — at the very least those of the extremes in size of each of the transfer modes (spray, mixed, and short circuiting).

The short circuiting mode was reported to have occurred with arcs shorter than 3.5 mm. Spray was not found with arcs shorter than 4.5 mm. The mixed mode, however, was reported with the shortest arcs (2.6 mm) and close to the longest (9 mm). This raises some question about the meaning of the mixed mode.

The interactions of the data assembled in the table were correlated with two nondimensional numbers, a mass transfer number "A" and a heat transfer number "B." Unfortunately, he did not discuss or define the purpose of either.

$$A = M/\mu r_e \qquad (1)$$

$$B = V_{arc}IS/\Delta H\alpha^2 \qquad (2)$$

Students of dimensionless numbers probably understand why such an approach was helpful (if not essential) for this study. My limited understanding has been that dimensionless numbers are used to simplify complex interactions of parameters. An example is one of the Reynolds' numbers, which is used to show how physical constants of gases and their velocity in tubes interact to maintain laminar flow. Determined empirically, the number needs to be less than 30. This has been useful for designing the gas shielding nozzles of GMA and GTA apparatus.

The M in the mass transport number (Equation 1) is defined as the electrode melting rate (kg/s). Nothing new here since the parameters involved were explained in a paper I had written in 1958.

$$M = aI + bI^2L_e/A_e \qquad (2_L)$$

Very simple — the wire is melted with heat generated by the anode and resistance drops. This relationship was made dimensionless by introducing the viscosity of the weld pool (a blend of melted wire and melted base plate?) and the radius of the wire. Equation 1 explains that in maintaining a given mass transport number (for whatever the reason) an increase in deposition rate requires a proportional increase in wire feed speed. I am having difficulty believing that or that the number is proportional to the viscosity of the weld pool. An explanation would help.

Another quandary surfaced with the energy transfer number B in Equation 2. It contains the same parameters as another ancient arc energy input equation that has been used for years by welding metallurgists when concerned about martensite in the HAZ of hardenable steels. It defines the quantity of arc energy distributed along the length of a weld, decreasing, of course, as the travel speed increases.

$$E = VI/S \qquad (3_L)$$

It appears to have been made dimensionless by introducing the enthalpy change and thermal diffusivity of the base plate, and by moving S from the denominator to the numerator. According to Equation 2, to maintain a given heat transport number, an increase in current must be accompanied by a proportional decrease in travel speed. This might make sense if the reasoning behind the heat transfer number (B) was explained and how that differs from energy input (E).

I apologize for a bit of nitpicking about the V_{arc} in the dimensionless number for heat transfer. V_{arc} is a summation of voltage drops produced at the anode, cathode, and across the plasma. However, because of the way voltmeter connections have to be made, the measured voltage across the arc also includes V_e (the drop along the wire extension) and V_a (the drop across the wire tip), both of which are the b_0 and b_1 in the equation for mass transfer. To be accurate, the voltage term in B should be a summation of only V_p and V_c (the drops across the plasma and at the plate surface).

Continuing with the process of developing the dimensionless analysis, A and B were combined by multiplying them together. Being mathematically disadvantaged, I would have added these energies. However, with dimensionless numbers, such manipulations probably are acceptable and offer unexplained advantages. Obviously I'm missing something and, as before, an explanation would be helpful.

At the same time, however, another travel speed and another thermal diffusivity constant (S and α) were introduced, apparently to make the relationships dimensional. Followed by some more mathematical manipulations, a set of equations evolved with which the weld bead cross-sectional dimensions (width, penetration, and area) could be calculated (Equations 3–5). By incorporating Equations 7 and 9, recognizing that $A_e = \pi r_e^2$, and combining the two Ss, the following general relationship was established.

$$\left(d, w \text{ or } \Omega^{1/2}\right) = \eta_a \left(\frac{v_a I}{r_e} + \frac{\sigma L_e I^2}{\pi r_e^3}\right)^b \frac{\left(v_{arc} I\right)^c}{S^{\left(1-c\right)}} \qquad (4_L)$$

Each of the dimensions has its own set of empirically derived constants. In my opinion, the necessary math probably is beyond the capabilities of most welding engineers — those who the author wanted to help. If the results of this work are expected to find general use, it seems the author should help by explaining the procedures that were used.

Often troubling to me when reading papers about modeling is that the correlating equations often are not consistent with what is commonly understood about the effects of arc welding variables. As an example, welding people have learned the cross-sectional areas of the deposited welds follow the relationship $A_d = c/S$. In Equation 4_L, however, the relationship is more like $\Omega^{1/2} = c/S^{(1-c)}$, which is much more complex. But this complication appears to be justified because this measurement includes the fused base metal as well as the deposited metal.

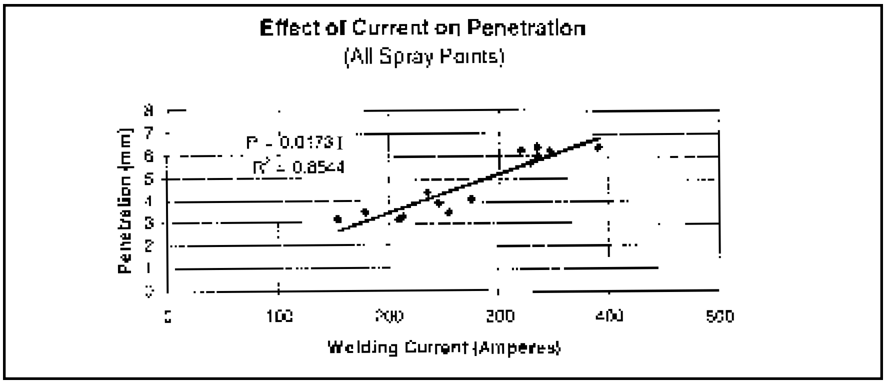

Fig. 1L — Effect of current on penetration.

As questioned earlier, the presence of the additional r_e in the numerator is difficult to understand dimensionally or even functionally. It's also difficult to believe the electrode extension can affect penetration, at least to the degree expressed here. We know from experience longer arcs don't provide the deeper penetration that this equation tells us we should expect. If anything, based on my experience, longer arcs reduce penetration. Comments from the author about these aspects would be appreciated.

The expressed purpose of the three calculations summarized previously is to allow a designer to select specific dimensions for welds without having to resort to additional trials. To be remembered, however, is that none of this work is applicable to joints into which the metal is deposited. Nevertheless, the calculations could be useful for simple butt joints and cladding. And, because of the very high correlation coefficients shown in the paper, excellent results should be anticipated when designing welds for different applications. I'm not sure, however, the equations permit the independence of the bead dimensions that is necessary.

Let's assume the need to clad a carbon steel with a stainless. This means low dilution, achieved with low penetration and a sizeable reinforcement (large Ω and wide d). Examining summary Equation 4_L for the best way to obtain low penetration, it's evident low current is mandated, although higher than transition. Since low transition currents mean small wire diameters, wire diameter is defined. Helpful, too, would be to decrease L (the electrode extension) and keep the arc short (although, to be realistic, not much can be done about arc length). The selection process for low penetration is completed by picking the highest travel speed that allows uninterrupted beads (experience counts here).

The next step is to pick conditions for the large, flat claddings. According to the equations that define Ω and w, that means high current. But current has been defined already. It means a long electrode extension. But that, too, has been defined. Apparently it's not possible to obtain the conditions needed for large deposits without increasing penetration. In other words, contrary to expectations, these equations do not appear to be independent. It seems the dimensions defined are not the least bit independent. All of the dimensions are proportional. The desired independence does not exist.

Life could be simplified by recognizing the depth of penetration is dominated by current, as illustrated in Fig. 1_L. The points were taken from the data of Table 1, but only those associated with the spray transfer mode. Even though each of the points represents welds made with different travel speeds, wire diameters, electrode extensions, plate thicknesses, etc., the linear relationship of penetration to current is obvious. Considering the parametric differences associated with each of the points, the correlation coefficient is not bad. Clearly, penetration is dominated by current. At currents higher than used in this study, penetration is not linearly related to current but follows the relationship $(aI + bI^n)$. And, unlike wire melting rate, penetration is strongly affected by the shield gas.

Of course other variables have an effect, although slight. A quick analysis of the paper's data showed a 43% change in travel speed resulted in only a 6% change in penetration. I suppose the paper's equation for Ω might have yielded the same results, but I didn't attempt that exercise. I hope someone will take the challenge. Other variables such as the wire diameter and electrode extension also have a sizeable effect on the weld width and area although a negligible influence on penetration. Unfortunately, too little effort has been given to studying, or perhaps only documenting, the interactions of these important variables of arc welding, probably because such investigations are dull and mundane. With apologies for this digression, I would appreciate any comment.

The paper ends with a discussion about the use of nondimensional, three-dimensional graphs from which "operating points" are obtained. Sorry to say, but this discussion was difficult to follow. Considering that Murray claims to have gone to all of this trouble because he wanted to simplify the development of welding procedures, I was disappointed. Since all of the graphs appear to be based on wire feed speed and contact tip-to-work distance, I'm assuming they are the only way to proceed. I wonder about the reason for including six such plots when only the one that defines arc length seems to be necessary. The others seem only to add to the confusion and clutter.

Considering the effort needed to develop the critical three equations, I was surprised to see the author had abandoned the one for Ω (the sum of melted plate and melted wire). It was replaced by the simpler $A_{dep} = \pi r_e^2 U/S$. The reason for this was not explained but, considering the change in attitude regarding bead areas, it should be.

At this point, considering that weld area is being defined by wire feed speed and travel speed alone and that penetration can be defined by current alone, only one of the set of three equations remains to be calculated (Equation 4): the weld width. Apparently not considered important, it was barely mentioned in the paper.

Getting back to the analytical method proposed in the paper, the steps appear simple enough.

1) Pick a desired depth of fusion and deposited metal area; select a wire diameter.

2) Develop the operating points for the combination of arc length, wire feed speed, and contact tip-to-work distance (such as the three-dimensional plots shown in Fig. 8 of the paper). The techniques for doing that appear to be out of reach for the average guy in industry. Assuming the operating point concept to be necessary for this type of analysis, the methods used for their development need to be explained. The only direction given is — quoting the author — "Equations 1–10 augmented by specific constraints must be solved to obtain a reduced set of operating points."

3) Calculate the travel speed with the equation $S = \pi r^2 U/A_{dep}$. But, hadn't this equation been used to calculate the weld area?

One more point. Even if the required relationships can be solved with relative ease, the information given is based on one alloy and one shield gas. Changing to another ferrous alloy might not present a problem, but changing to another shield gas will. And the gas used for this study is not the gas most commonly used at this time. With such a change, would it be necessary to go through this entire exercise — 27 welds, multiplicity of calculation, and new graphs of operating points — again?

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In my recent AWS paper, I proposed an analytical method to select welding parameters leading to a desired operating condition and demonstrated how the method may be used to control bead shape. Much of the difficulty of modeling welding processes and ascertaining the effect of welding parameters stems from the complex interrelationship among process variables and the inability to independently vary one variable while holding all other variables constant. Welding parameter selection is often based on observing cause and effect relations without clearly identifying how a change in one variable leads to changes in others. This underscores the need to examine controllable machine settings as well as those process variables controlled indirectly by the welder.

The experiment was designed to control deposited metal area by selecting the wire size and setting the wire feed speed and travel speed to those values required to produce the selected amount of deposited metal. The open circuit voltage was set to produce a desired arc length, which required several trials. An experimental weld matrix was developed to include high, moderate, and low values of deposited metal area and short, medium, and long values of arc length, leading to an experimental data set encompassing a wide range of operating conditions using a minimum number of welds. Although some welds may be nonoptimal because of the presence of short circuits, it was necessary to expand the range of operating conditions in order to obtain a statistically significant sample. The wire feed speed and open circuit voltage are examples of welding parameters that are controlled directly, whereas deposited metal area and arc length are process variables that are controlled indirectly by adjusting the welding parameters. Moreover, a welding parameter is important insofar as its effect on process variables such as current and arc voltage that directly affect bead shape.

Consider the comment that bead shape is primarily affected by heat input per unit length of weld. The analysis given in my paper suggests bead shape and heat input do not correlate well inasmuch as beads made at similar heat inputs and different deposited mass have a much different size and shape. Here, I use deposited mass to denote the melting rate of the electrode per unit length of weld. For example, consider the experimental data given in Table 1 of my paper. Weld No. 9 has heat input equal to 900 J/mm, deposited mass equal to 0.12 g/mm, depth of fusion equal to 1.4 mm, and arc length equal to 9.1 mm. Weld No. 18 has heat input equal to 850 J/mm, deposited mass equal to 0.16 g/mm, depth of fusion equal to 3.7 mm, and arc length equal to 5.8 mm. Note that both welds have a travel speed equal to 4 mm/s and the same mode of mass transfer. This data suggests bead shape is affected by deposited mass, which was confirmed by regression and correlation of the experimental data. Photographs of these and other weld beads may be found in Reference 12 cited in my paper.

Consider the comment that bead depth is affected by arc length. The data from weld No. 9 and weld No. 18 support this assertion inasmuch as beads made at similar heat inputs and different arc lengths have a much different depth of fusion. Increasing arc length while maintaining constant heat input leads to decreasing bead depth. The comment that my equations suggest the opposite effect appears to neglect other variables that are changing simultaneously with a change in arc length. The total variation in bead depth with respect to arc length includes the variation in bead depth with respect to each variable that depends on arc length. It is difficult to isolate the effect of one variable on bead shape without knowing its effect on all other variables. This remark underscores an important issue. Is the observed effect on bead shape due to a change in arc length or a change in deposited mass? Is there another way to combine variables into a nondimensional quantity that can be used to correlate experimental data and succinctly describe the observed effect that is apparently related to mass transfer and independent of heat input?

The preceding observations are the basis for using dimensional analysis in welding parameter selection. Moreover, dimensional analysis simplifies the correlation of experimental data and reduces the number of variables needed in the analysis. In my paper, two nondimensional variables were introduced: the mass transfer number A *and heat transfer number* B. *The meaning of the mass transfer number may be explained in terms of the ratio of time scales associated with the physical processes governing mass transport from the electrode and momentum transport in the weld pool. Generally the most difficult part of developing nondimensional variables is selecting the proper scales, which* *is often guided by intuition.*

Consider a droplet of filler metal having a characteristic length r_e and a characteristic velocity U, where r_e is the electrode radius and U is the wire feed speed. The time scale associated with transfer of droplets is r_e/U. The time scale of momentum transport in the pool is $\rho r_e^2/\mu$, where ρ is the weld metal density and μ is the weld metal viscosity. Taking the ratio of time scales and multiplying by p, I obtain $A=\rho\pi r_e^2U/\mu r_e$. Since the melting rate M is equal to $\rho U\pi r_e^2$, I obtain $A=M/\mu r_e$. Note the nondimensional mass transfer number is different from deposited mass per unit length of weld, which is defined as M/S, where S is the travel speed.

A similar approach may be used to deduce the heat transfer number, which is the ratio of length scales associated with the physical processes governing heat transfer in the arc and heat transfer in the pool. The length scale associated with heat transfer in the arc is $V_{arc}I/\Delta H\alpha$, where V_{arc} is the arc voltage, I is the current, ΔH is the quantity of heat needed to melt a unit volume of weld metal, and α is the weld metal thermal diffusivity. The length scale of heat transport in the pool is α/S, where S is the travel speed. Taking the ratio of length scales, I obtain $B = V_{arc}IS/\Delta H\alpha^2$. This nondimensional variable has been used previously to correlate welding parameters and bead shape, and I refer the reader to references cited in my paper for a thorough discussion of the effect of heat transfer on bead shape. Note the nondimensional heat transfer number is different from heat input per unit length of weld, which is defined as $V_{arc}I/S$.

I used regression and correlation of experimental data to establish nondimensional relationships for bead shape. These relations included both A and B since I observed bead shape is affected by mass transfer as well as heat transfer. A correlation is found by assuming a functional relation between bead shape and the variables A and B. Generally, I assume nondimensional bead depth, bead width, and bead area are functions of $A\,B^p$, where p is an exponent determined empirically. This is the simplest way to represent the observed behavior that nondimensional bead size increases with an increase in either A or B. The exponent is introduced so that one variable may have a stronger influence on bead shape than the other variable. Linear regression was used to determine the precise form of the correlation, and I refer the reader to my paper for details. Finally, the accuracy of the correlation was demonstrated by statistical analysis of the experimental data. Statistics may also be used to assess the importance of each physical variable in the correlation, which would be a useful extension of my analysis.

I presented a set of equations that includes the analytical relations for bead shape as well as auxiliary relations needed to compute the desired operating parameters. Ten equations are needed. These equations, augmented by process constraints, may have one solution, multiple solutions, or none at all if the equations are overconstrained. The comment that these equations may be overconstrained is valid, so I suggest applying constraints one at a time until a reduced set of operating points is obtained. Using incompatible constraints such as high current and low deposited mass is not advised.

The following procedure was used to compute an operating point. I wrote a computer program to evaluate each of the equations described in my paper. The inputs to the program are welding parameters and the outputs are process variables. In this way the program simulates the operation of the actual welding equipment. I input the open circuit voltage, wire diameter, wire feed speed, contact tip-to-work distance, and travel speed. The program computes the current, arc voltage, arc length, and electrode extension as well as the depth, width, and area of the weld bead. The computed current is compared to the transition current to determine the mode of transfer. The simplest way to show the solution is with three-dimensional graphs as given in my paper. Twenty to thirty data points are usually enough to construct a graph. I reduce the set of operating points by choosing only those points that satisfy desired constraints on the process. That is easily done using the graphs.

The example given in my paper was designed to demonstrate the method in a way that may be understood by most welding engineers. In fact, I underconstrained the equations by requiring only an optimal arc length and a desired bead depth without constraining bead width or bead area. I included multiple graphs to demonstrate how a reduced set of operating points is obtained by applying constraints one at a time. This particular example is apparently the reason for the comment suggesting my method can be simplified considerably. However, this simplification leads to a loss of generality. The commentary also includes an application of my method to stainless steel weld claddings. In this case, it is necessary to choose constraints on bead depth and bead width in a way that does not overconstrain the equations. I encourage further research to extend the analysis to other materials, shielding gases, and weld joints. However, it will be necessary to develop a new set of experimental data and follow the procedure described in my paper to obtain the empirical coefficients needed in the equations.

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Commentary on Carbon Pickup Paper

In the article "Carbon Pickup from Argon-CO_2 Blends in GMAW," which ran in the December 2001 issue of the *Welding Journal,* Damian Kotecki carried out a detailed study of the effect of the shielding gas CO_2 content on the stainless steel weld metal carbon content during gas metal arc welding. It was found the carbon content is proportional to the square root of the CO_2 content of the shielding gas. However, the reaction mechanisms considered by him could not explain the above relationship. The following is an analysis of the possible reactions taking place at the weld pool in order to explain the experimental observations.

At the welding temperature of about 1600°C, the shielding gas CO_2 is stable except in the presence of elements like Al, Cr, Mn, Si, Ti, etc., whose oxides are more stable (also CO), as can be determined from the Ellingham's diagrams[1]. In order to explain the experimental observations, the reaction between CO_2 in the shielding gas and the molten weld metal should result in two gaseous products, one of them being carbon monoxide (CO). From a study of the chemical compositions of the various electrode materials given in Table 1 of Kotecki's paper, the second gaseous product of the reaction was assumed to be SiO, silicon monoxide. A study of the Ellingham's diagram shows the line representing the standard free energy of formation of SiO lies between those of CO_2 and CO. From the diagram, the approximate standard free energy changes due to the reaction of one mole of oxygen with carbon and silicon to form, at 1600°C, the three gases CO_2, SiO, and CO were found to be –95, –120 and –138 kcals, respectively. Moreover, during slag metal reactions in the blast furnace gaseous SiO aud CO are known to form[2], i.e., the two gases can coexist.Therefore, the weld pool reac-

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[1] *Lankford, Jr., W. T., Sermays, N. L., Craven, R. F., and McGannon, H. E., eds. 1985.* Making, Shaping and Treating of Steel. *United States Steel Corp., Pittsburg, Pa. 10th ed., p. 442.*

[2] *ibid., p. 446.*

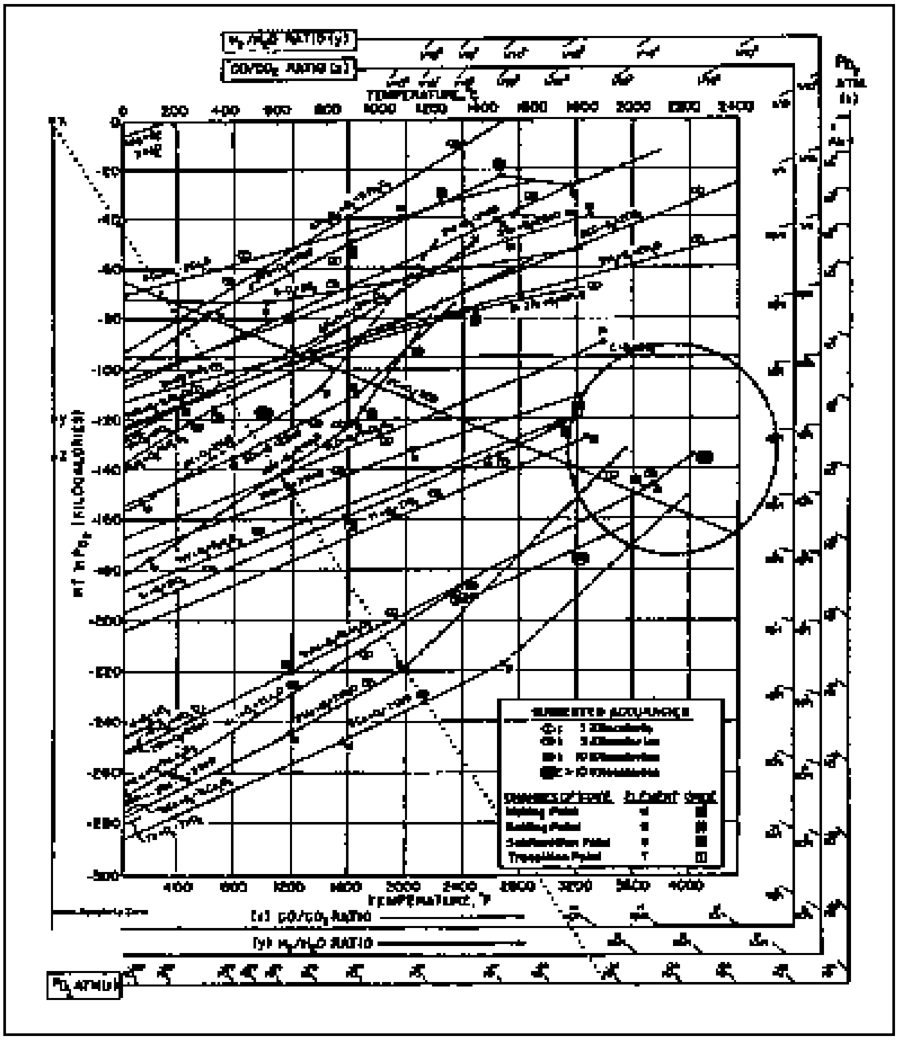

Fig. A — Ellingham/Richardson and Jeffes plot for metal-metal oxide equilibria. (F. D. Richardson and J. H. E. Jeffes, Journal of the Iron and Steel Institute*, Vol. 160, The Metals Society, 1943, p. 263.)*

tions are considered to be

$$CO_2 + \underline{Si} \Leftrightarrow CO + SiO \tag{A}$$

And CO + *weld metal* $\Leftrightarrow \underline{C}$ + *slag* (B)

From Equation A,

$$K = \frac{pCO \times pSiO}{a\underline{Si} \times pCO_2} \tag{A1}$$

$$K' = K \times aSi = \frac{pCo \times pSiO}{pCO_2} \tag{A2}$$

Assuming ideal behavior of the gases and $pCO = pSiO$,

$$K' = \frac{p^2CO}{pCO_2} \tag{A3}$$

or, $$p^2CO \propto pCO_2 \tag{A4}$$

i.e., $$pCO \propto \sqrt{pCO_2} \tag{A5}$$

$$\therefore pCO \propto \sqrt{\%CO_2} \tag{A6}$$

where $\%CO_2$ is the carbon dioxide content of the shielding gas.

From Equation B,

$$\underline{C} \propto pCO \tag{B1}$$

where $\underline{C} = \%C$ in the weld metal. Therefore, from Equations A6 and BI,

$$\%C \propto pCO \propto \sqrt{\%CO_2}$$

Thus, the experimental observation of the dependence of carbon content of the weld metal on the square root of the CO_2 content of the shielding gas can be understood. Therefore, the above assumptions and the weld pool reactions are justified.

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As thermodynamics is not my strongest suit, I forwarded Rao's commentary to Professor Steve Liu at Colorado School of Mines. It seems we can't be sure, but there is a possibility that Rao has a plausible explanation for the phenomenon I observed. Liu's comments follow.

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Thanks for allowing me to see the interesting derivation from Rao intended to explain your experimental data. After considering his reasoning, I arrived at the following conclusions. Indeed, the formation of gaseous SiO had been proposed and reported for submerged arc welding a few decades ago. However, it typically occurs as a decomposition of SiO_2*, instead of partial oxidation of silicon. Nevertheless, Equation A (*$CO_2 + \underline{Si} \Leftrightarrow CO + SiO$*) is plausible. Equation B (*CO + weld metal $\Leftrightarrow$ C+slag*) also appears to be reasonable, at first view. For example, Al, Ti, etc., in the weld metal would reduce CO to form carbon, while they themselves would be oxidized and incorporated into the slag. Examining the Ellingham/Richardson diagram, however, showed Equation B may not exhibit negative* ΔG*. At temperatures between 1700 and 2200°C, generally accepted droplet and weld pool temperature, the CO line (with negative slope) may actually intersect the oxide lines (with positive slope). That is, the CO line will be below the oxide lines such as TiO and* Al_2O_3 *(see region within the circle in Fig. A). The crossover indicates that at these high temperatures, CO may actually be more stable than many oxides, which implies in the reduction of the oxides and oxidation of* $\underline{C}$ *to CO, i.e., the reverse direction of Equation B. If the above reasoning is accepted, then the remaining derivation of Rao must be revised. Nevertheless, if one considers that the temperatures of the steel weld pool and metal droplets transferred across the arc are lower than 1800°C, then Equation B is possible and the rest of the derivation adequate to describe the carbon pickup behavior you observed.*

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