Mathematical Modeling of Melting Rates for Submerged Arc Welding

Models of melting rates take into account the effects of welding variables

BY R. S. CHANDEL

ABSTRACT. The effects of welding current, arc voltage, wire diameter, electrode extension (EE), electrode polarity, power source type and flux classification on melting rates (MR) have been evaluated. For the submerged arc welding process, the results show that for a given heat input, greater melting rates are obtained when higher current, longer electrode extension, smaller diameter electrodes and electrode negative polarity are used. Arc voltage, power source type and flux classification do not have any significant influence on melting rates. Mathematical models to correlate process variables and melting rates have been computed from the data.

Introduction

Researchers and welding engineers have been trying to increase productivity by increasing melting rates since the inception of the submerged arc welding process. Historically, welding current has been found to have the greatest influence on the melting rate and weld bead geometry (Refs. 1-4). However, it is also recognized that when welding current is increased to enhance the melting rate, there is a corresponding increase in heat input, which may influence the weld metal toughness. Alternatively, travel speed can be increased to maintain the same heat input; however, this can increase the propensity for defects such as centerline cracking and incomplete penetration (Ref. 5). However, melting rate can be increased for a given heat input and welding current by using electrode negative polarity, longer electrode extension, and smaller diameter electrodes (Refs. 6-9). In order to predict and control the melting rate, the quantitative effect of all the variables must be known. Wilson and Jackson (Ref. 9) formulated the following mathematical relationship between welding variables and melting rate in Imperial units, which are converted here to the following SI units:

\[
\text{MR (kg/h)} = \frac{1}{1000} \left[ 9.45 + \frac{0.042 D^2 + 2.906 	imes 10^{-4}}{I^2} \right] \left[ \frac{I}{L^{1.22}} \right] \quad (1)
\]

where \( I \) = welding current (A)
\( D \) = wire diameter (mm)
\( L \) = electrode extension (mm)

Such a relationship is very useful as it enables the preselection of welding variables for a particular melting rate. However, it has some drawbacks, as it does not take into account the effect of voltage, polarity, the type of power source and flux basicity.

Robinson (Ref. 10) observed that Equation 1 was not valid for alternating current (AC) or direct current electrode negative (DCEN), so he modified it to take the effect of electrode polarity into consideration. His modified equations, originally in Imperial units, are converted to SI units as follows:

\[
\text{MR (for DCEN) = } \frac{1}{1000} \left[ 9.45 + \frac{0.042 D^2 + 2.906 	imes 10^{-4}}{I^2} \right] \left[ \frac{I}{L^{1.22}} \right] \quad (3)
\]

\[
0.042d^2 + 2.906 \times 10^{-4} \left[ \frac{I}{d^2} \right]^{1.22}
\]

\[
\text{MR (for AC) = } \frac{1}{1000} \left[ 9.45 + \frac{0.042 D^2 + 2.906 \times 10^{-4}}{I^2} \right] \left[ \frac{I}{L^{1.22}} \right] + \left[ \frac{3.485 \times 10^{-8}}{2.5721 + 3.565} \right] \quad (4)
\]

where \( MR \) = melting rate (kg/h) \( I \) = welding current (A) \( d \) = electrode diameter (mm) \( L \) = electrode extension (mm)

Martin (Ref. 11) and Jackson (Ref. 12) had observed that arc voltage also has an influence on the melting rate. Robinson (Ref. 10) reported that for direct current electrode negative, an increase in arc voltage resulted in a decrease in melting rate. However, neither Wilson’s nor Robinson’s equations reflect this. Mantal (Ref. 13) reported that for arc welding the melting rate for AC is the geometric mean of the melting rates for DCEN and DCEP. Lesniewich (Ref. 14) also compared the melting rates for AC, DCEN and DCEP and observed that the melting rate during AC is the arithmetic mean of melting rates during DCEN and DCEP. Robinson’s experimental results and theoretical calculations show that for welding currents of up to 750 A, direct current electrode positive (DCEP) gives higher melting rates than DCEN. Thus, in the light of this controversy, the validity of Robinson’s (Ref. 10) equations becomes questionable.

There have been a few other attempts to formulate mathematical relationships between welding variables and melting rates (Refs. 15-18). However, most of these models are useful only for particu-
Table 1—Welding Variables and Melting Rates for DC Welds

<table>
<thead>
<tr>
<th>Wire dia. (mm)</th>
<th>E.E. (a) (mm)</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Flux A</th>
<th>Flux B</th>
</tr>
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<tr>
<td></td>
<td></td>
<td>Constant voltage</td>
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<td></td>
<td></td>
<td>DCEP</td>
<td>DCEN</td>
<td>DCEP</td>
<td>DCEN</td>
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<td>4.00</td>
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<td></td>
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<td>400</td>
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<td>4.9</td>
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<td>400</td>
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<td>4.9</td>
<td>6.30</td>
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<td>550</td>
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<td>13.74</td>
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<tr>
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<td>32</td>
<td>13.74</td>
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(a) Electrode extension

lar situations and are thus not applicable to shop floor welding. Therefore, the aim of this work was twofold: 1) to study the effect of welding current, arc voltage, electrode diameter, electrode extension, electrode polarity, type of power source, and flux classification on the melting rate for submerged arc welding, and 2) to develop mathematical models to correlate the melting rates with the welding variables.

Experimental Work

The base material used for the experimental work was a 19-mm (0.75-in.) thick ASTM A36 steel plate. This plate was cut into 600- X 150-mm (24- X 6-in.) pieces, and both surfaces were cleaned (sand blasted) to remove dirt and oxides. AWS EL12 electrodes of 2.4-, 3.2- and 4-mm (%2-, %2- and %2-in.) diameter were used, along with Fluxes A and B. Flux A was a fused acid flux with a basicity index of 1, while Flux B was an agglomerated basic flux with a basicity index of 3.

DC 1500 and AC square wave 1000 power sources were used. The DC 1500 can be operated on both constant current and constant voltage modes, while the AC square wave 1000 is designed for the constant voltage mode only. The experimental work was designed to study the effect of welding current, voltage, electrode extension, electrode diameter, polarity, type of power source, and flux classification on melting rate. The welding current and arc voltage were recorded on a chart recorder for each deposit, while the corresponding wire feed speed (which was converted into melting rate) was read from a digital wire feed tachometer. A total of 336 welds were made, and their welding variables and corresponding melting rates are given in Table 1.

Results

The results of the investigation are given in Figs. 1-4 and Tables 1 and 2. Figure 1 shows the effect of welding current and wire diameter on the melting rate. It can be seen that for a given wire diameter, melting rate increases with welding current. However, for a given welding current, the melting rate is higher when a smaller diameter electrode is used. Varying the voltage between 30 and 38 V did not have any effect on the melting rate.

The effects of polarity and electrode extension on the melting rate are shown in Fig. 2. For the same welding variables, DCEN results in a higher melting rate than DCEP. When AC is used, the melting rates are slightly higher than those of DCEP and significantly lower than DCEN when a 25.4-mm (1-in.) electrode extension is used. However, when a 76.2-mm (3.0-in.) electrode extension is used, the melting rates with AC become similar to those of DCEP.

The effects of power source type (constant voltage and constant current) and flux classification on the melting rate
The results indicate that power source type and flux classification did not have any significant effect on melting rates.

Mathematical Model

The above results have shown that the melting rate during submerged arc welding is affected by welding current, electrode diameter, electrode extension and electrode polarity. To present the above results in a meaningful mathematical expression, some fundamental concepts of melting during arc welding have to be considered. It is well understood that the total melting is composed of melting due to arc energy and melting due to resistance heating (Joule heating effect) (Refs. 9, 10 and 15–18). Arc heat is proportional to welding current, while the Joule heating effect is proportional to the (current)² and electrode extension, and inversely proportional to (electrode diameter)². An equation to correlate melting rate and welding variables and incorporating arc
**Fig. 1 — Effect of welding current and wire diameter on the melting rate (Flux A, 25.4-mm electrode extension)**

**Fig. 2 — Effect of electrode polarity and electrode extension on the melting rate (Flux A)**

**Fig. 3 — Effect of power source type on the melting rate (Flux A, 25.4-mm electrode extension)**

**Fig. 4 — Effect of flux type on the melting rate (25.4-mm electrode extension)**
energy and Joule heating effect was conceived in the following form:

\[
\text{MR} = A + B \frac{PL}{d^2} + C
\]

where \( A, B \) and \( C \) are constants which depend upon the polarity and electrode material and \( I, L \) and \( d \) are welding current, electrode extension and electrode diameter, respectively.

In order to compute the values of \( A, B \) and \( C \), multiple regression analyses of the experimental data were carried out and the following equations were obtained:

- **MR (for AC):**
  \[
  0.01523I + 1.6882 \times 10^{-6} \frac{PL}{d^2} - 2.396 \\
  (R = 0.991, \text{SE} = 0.435)
  \]

- **MR (for DCEN):**
  \[
  0.016178I + 2.087 \times 10^{-6} \frac{PL}{d^2} - 0.643 \\
  (R = 0.996, \text{SE} = 0.5)
  \]

- **MR for (DCEP):**
  \[
  0.01037I + 2.2426 \times 10^{-6} \frac{PL}{d^2} - 0.462 \\
  (R = 0.993, \text{SE} = 0.56)
  \]

where \( R \) is the coefficient of multiple correlation and SE is the standard error.

The validity of the above equations can be judged from their high coefficients of correlation (>0.99) and Fig. 5, which shows the relationship between measured and computed melting rates. Compared with other equations referred to earlier (Refs. 9,10), these equations are simpler, maintain mathematical uniformity and show a better relationship between measured and calculated melting rates—Fig. 6. The important feature of the above equations is that the coefficients for the second term, \( \frac{PL}{d^2} \), are similar for electrode negative and electrode positive, which agrees with the findings of Demyantsevich (Ref. 18) and Chandel and Malik (Ref. 19). This implies that resistance heating is not influenced by the polarity during direct current arc welding. However, this coefficient is smaller for AC, which indicates that melting due to resistance heating is smaller during AC welding. This discrepancy in the resistance heating during AC and DC welding is difficult to explain at this stage, and it is recommended that further work be carried out. The regression coefficient for the first term, i.e., arc heat, is highest when the electrode is negative and lowest when the electrode is positive, because during arc welding, more heat is liberated at the cathode, which for electrode negative is the electrode tip. The value of this coefficient for AC is higher than when the electrode is positive, but smaller than when the electrode is negative.

The effect of current, wire diameter, electrode extension and polarity on the melting rates can be explained by the equations above. As explained earlier, the total melting is composed of melting due to arc heat and resistance heat. Thus,
with an increase in welding current, there is a linear increase in arc heat, while the resistance heat increases exponentially. The rate of increase in arc heat and resistance heat with current also depends upon the coefficients. Thus, for the same increase in welding current, there is a larger increase in melting from arc heat when DCEN is used.

Conclusions

1. Submerged arc welding variables such as current, polarity, wire diameter and electrode extension have an influence on the melting rate.

2. For a given wire diameter, electrode polarity and electrode extension, there is an increase in melting rate with an increase in welding current.

3. For a given welding current, higher melting rates are obtained when longer electrode extension and electrode negative and smaller wire diameter electrodes are used. For the same welding variables, melting rate for AC is slightly higher than that for DC electrode positive.

4. Arc voltage and power source type do not show any significant effect on melting rate.

References


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Sensitization of Austenitic Stainless Steels: Effect of Welding Variables on HAZ Sensitization of AISI 304 and HAZ Behavior of BWR Alternative Alloys 316NG and 347
By C. D. Lundin, C. H. Lee, R. Menon and E. E. Stansbury

The research described in this report was undertaken to derive a better understanding of the HAZ sensitization response of 304, 304LN, 316NG and 347 austenitic stainless steels. The results are directly applicable to both the as-welded and long-time service behavior of these austenitic stainless steels. Publication of this report was sponsored by the Subcommittee on Welding Stainless Steel of the High Alloys Committee of the Welding Research Council. The price of WRC Bulletin 319 is $24.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.

WRC Bulletin 320
December 1986

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By S. Kou

A literature survey was conducted to gather the information available on the welding metallurgy of high strength aluminum alloys, and its effect on their weldability. Both conventional high strength aluminum alloys and newer products, e.g., powder metallurgy aluminum alloys, Al-Li alloys and Al-matrix composites, are included in this report. Publication of this report was sponsored by the Aluminum Alloys Committee of the Welding Research Council. The price of WRC Bulletin 320 is $12.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.