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Effects of Electrode Extension on Deposit Characteristics and Metal Transfer of E70T-4 Electrodes

The mode of metal transfer is influenced by electrode extension, with a change in mode occurring with increasing current at short extensions.

BY I. E. FRENCH

ABSTRACT. In order to gain a better understanding of the ways in which electrode extension influences the behavior of self-shielded flux cored electrodes, a study has been made of typical E70T-4 electrodes operating at electrode extensions of 25, 65 and 95 mm (1, 2.5 and 3.75 in.). The variations of deposition rate, deposition efficiency and root penetration with welding current were measured at each extension, while high speed photography was used to assess metal transfer behavior. A globular repelled mode of metal transfer was observed under all conditions except for short extensions and currents above 450 A. In these circumstances, a change to a non-axial projected spray mode of transfer was observed and the deposition rate-current relationship showed a change in gradient.

To investigate the effects of electrode extension on the partition of power dissipated in the process, measurements were made of the voltage level at various positions in the welding circuit and an approximate analysis was formulated. Analysis results suggested that the temperature rise in the electrode due to electrode extension is considerably higher at long extensions, reaching over 1000°C (1850°F) with 95 mm (3.75 in.) extension; also, for a given deposition rate the power loss due to all causes is approximately constant and independent of electrode extension.

Introduction

The use of a long electrode extension to increase weld metal deposition rate has been known for some time, particularly with regard to submerged arc welding (SAW) (Ref. 1). The open-arc process, which can most readily take advantage of this effect, is self-shielded flux cored arc welding (FCAW). A description of the advantages of using long electrode extension with self-shielded electrodes was given by Hinkel (Ref. 2), who also acknowledged that penetration decreased with increasing electrode extension and estimated that the potential drop associated with electrode extension could be as high as 3 volts (V). An example of a 40% reduction in welding current, while maintaining constant deposition rate, by increasing electrode extension from 25 to 95 mm (1 to 3.75 in.) was given by Smith (Ref. 3).

This effect is specifically utilized by using E70T-4 electrodes (Ref. 4) to produce very high deposition rates when welding in the flat and horizontal positions. However, the mechanism by which electrode extension influences features of the behavior of these self-shielded electrodes such as metal transfer and

Table 1—Variation of Deposition Efficiency with Welding Conditions

<table>
<thead>
<tr>
<th>Electrode extension, mm</th>
<th>Welding current, A</th>
<th>Voltage Vp, V</th>
<th>Deposition efficiency, %</th>
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<tbody>
<tr>
<td>25</td>
<td>250</td>
<td>26</td>
<td>88</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>380</td>
<td>36</td>
<td>86</td>
</tr>
</tbody>
</table>


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partition of power dissipated is not well documented.

Accordingly, a study has been made of the behavior of commercial E70T-4 electrodes operating at electrode extensions of 25, 65 and 95 mm (1, 2.5, and 3.75 in.) and welding currents between 200 and 550 A. These extension values were chosen because 65 mm (2.5 in.) represents normal usage for such electrodes, while 95 mm (3.75 in.) is abnormally long and 25 mm (1 in.) particularly short. Measurements were made of the deposition rate, deposition efficiency and penetration with welding current; high speed photography was used to observe metal transfer. In addition, voltage levels were measured at a number of positions in the welding circuit, and an approximate analysis of power dissipation was formulated.

**Experimental Procedure**

Initially, several 2.4 mm (3/32 in.) diameter E70T-4 electrodes from different manufacturers were assessed but, since they all exhibited similar behavior, one continuous length was chosen as typical and used for this study. The sample electrode consisted of a butt-seamed steel sheath approximately 0.47 mm (0.02 in.) thick that made up 63% of the sectional area. The core comprised 15% of total electrode weight with calcium fluoride, iron powder, aluminum and magnesium being the major constituents.

Welding trials were conducted under flat position, bead-on-plate conditions with mechanized translation of the workpiece at 400 mm/min (16 ipm) and an electrode drag angle of 10 deg using a 600 ampere DC constant voltage power supply and welding wire feed unit. Trials were made at electrode feed rates of between 2 and 8 m/min (80 to 300 ipm) using electrode extensions of 25, 65 and 95 mm (1, 2.5 and 3.75 in.), with the power supply voltages being within the range recommended by the electrode manufacturer for the current and electrode extension.

Measurements were made of deposition rate and efficiency by weighing the workpiece (less run-on and run-off portions) before and after welding, with the slag and spatter removed. Cross sections were taken through the beads to assess bead dimensions and penetration depth.

High speed motion picture films were made at 500 to 1000 frames/second. They showed metal transfer at a representative range of conditions, although a higher speed of traverse (900 mm/min or 36 ipm) was used to prevent details of the metal transfer such as average molten drop size and detachment frequency from being obscured.

The voltage normally referred to as welding voltage is that between the terminals of the power supply (V_s). The other voltages measured relative to the workpiece were: at the current contact tip in the arc welding gun (V_c) and at a point on the electrode 13 to 15 mm (0.51 to 0.59 in.) above the workpiece. This last mentioned voltage was measured by placing a thin sliding contact at this position on the electrode.

The sliding contact had to be replaced after each trial because it normally became fused to the electrode on cessation of welding. Voltage was thereby sensed as close as practicable to the arc, and this value will be referred to as arc voltage (V_a) although, in reality, it is an over-estimate. The difference between V_c and V_a is taken to be the voltage drop associated with electrode extension (V_e).

**Results**

Table 1 lists the deposition efficiency values for a range of welding voltage and current for the three electrode extensions. Deposition efficiency is not markedly affected by welding conditions or electrode extension, and the average value was 87% with a standard error of 1%. However, at 180 A and 95 mm (3.75 in.) electrode extension, a particularly low value of efficiency was measured, mainly because of the increased spatter under such conditions.

The variations of deposition rate with welding current for the three electrode extension values are plotted in Fig. 1. Here it can be seen that, except perhaps at low current, deposition rate increases with extension for given current with the increase between 25 and 65 mm (1 and 2.5 in.) extension being proportionally larger than that between 65 and 95 mm (2.5 and 3.75 in.) extension. The deposition rate increases approximately linearly with current and with similar gradient for 65 and 95 mm (2.5 and 3.75 in.) electrode extensions but, for 25 mm (1 in.) extension, this gradient is initially low, then becomes steeper at currents above 450 A. Penetration depth varies with welding current and electrode extension as shown in Fig. 2. Despite significant variations, penetration was generally higher at 25 mm (1 in.) extension but was approximately the same for extensions of 65 and 95 mm (2.5 and 3.75 in.). The increase in penetration with current is approximately linear in all cases, but the gradient is higher at short extensions. Although the results for only one electrode are presented, the other electrodes showed similar variations in both deposition rate and weld penetration with welding current.

The high speed motion picture films revealed that the size of the transferring weld metal drops decreased with increase in current, and that two distinct modes of metal transfer occurred. The globular—or in IIW terminology (Ref. 5), globular repelled mode of transfer—was most common, and a typical situation just before detachment in this mode is shown...
in Fig. 3A. Characteristic features are:

1. The drops are larger than the electrode diameter.
2. The drops are situated on the trailing edge of the electrode, largely above the arc zone.
3. The arc is rooted on the end of the electrode and bottom of the drop.

The typical appearance of the other mode of metal transfer observed is shown in Fig. 3B. In this case, the drop diameter is smaller than that of the electrode, the drops detach from the trailing edge of the electrode but are largely contained within the arc zone, and the electrode forms an acute angle at the trailing edge. This mode of transfer is not classified by the International Institute of Welding (Ref. 5) but will be referred to as nonaxial projected spray.

Average values of droplet diameter and detachment frequency for the three electrode extension values as functions of welding current are given in Table 2, with the final column indicating mode of transfer. At 25 mm (1 in) extension, globular repelled transfer was seen for currents of 250 and 360 A, while nonaxial projected spray was associated with high current (i.e., 490 A). In contrast, globular repelled transfer occurred over the whole current range for electrode extensions of 65 and 95 mm (2.5 and 3.75 in.), although drop size decreased and detachment frequency increased with increasing current.

Two further observations relevant to metal transfer were made from both the high speed films and the appearance of the electrode when welding had ceased:

1. Droplets of molten metal were observed to come from the seam of the electrode at the higher deposition rates and electrode extensions of 65 and 95 mm (2.5 and 3.75 in.); these droplets originated from the core and were an alloy of Al and Mg, implying that the electrode had been heated to at least 600°C (1100°F).
2. Metal drops present on the electrode end after welding were partly covered by slag with bare metal visible at the lower-most portion of the weld root where the arc had most likely penetrated; this suggests that the molten drops, at least in the globular repelled mode, are protected by slag both while accumulating and during transfer.

The average values of I, V₁, V₂, and V₃ for deposition rates of 3, 6 and 8 kg/h (6.6, 13 and 17.6 lb/h) and electrode extensions of 25, 65 and 95 mm (1, 2.5, and 3.75 in.) are listed in Table 3. The difference between power supply and contact tip voltages (V₁-V₃) depends on current level and can be as high as 4V. The most interesting feature of Table 3, however, is that V₁ increases markedly with electrode extension at a given deposition rate and also, for a given extension, increases with deposition rate. These variations are plotted in Fig. 4 to demonstrate that the gradient of the approximately linear increase in V₁ is independent of electrode extension.

**Discussion**

The voltage values in Table 3, together with a knowledge of the other welding variables, can be used to examine the partitioning of input power as a function of...
of electrode extension. The input power is given by:

\[ E_w = V_a I \]  

(1)

and can be partitioned into two primary components. First, the electrode extension component is given by:

\[ E_e = V_e I \]  

(2)

Once \( E_e \) is known, an estimate of the temperature rise of the electrode due to electrode extension can be obtained. Ignoring heat losses:

\[ E_e = \int_{T_1}^{T_2} m_e (C(T) + L) \, dT \]

(3)

where \( m_e \) is mass of electrode entering per unit time, \( C(T) \) is the specific heat of the electrode at temperature \( T \), \( L \) is latent heat of electrode, \( T_1 \) is initial temperature and \( T_2 \) is the maximum temperature due to resistance heating.

The term \( m_e \) can be expressed as the product of electrode mass per unit length and velocity. The value of \( C(T) \) adopted for the cored electrode was that given for steel (Ref. 6), since some 85% of electrode mass was in the steel sheath and some of the core was iron powder. The resulting variation of \( E_e \) with temperature (\( T_1 = 30°C \) or \( 86°F \), \( T_2 = 100°C \) or \( 212°F \)) for temperatures up to \( 1600°C \) (\( 2912°F \)) is shown in Fig. 5 for the three electrode feed rates used. The vertical steps in these curves reflect the influence of the latent heats of phase transition and melting.

The other primary component is the power dissipated in the arc given by:

\[ E_a = \frac{T_3}{T_2} \approx \sum m_w (C(T) + L) \, dT \]

(5)

where \( T_3 \) is the molten drop temperature, a lower limit of \( E_a \) can be obtained by assuming a drop temperature equal to the melting temperature of steel.

The \( E_w \) term can be written:

\[ E_w = \Delta H m_w \]

(6)

where \( \Delta H \) is the energy to raise 1 gram (g) of steel from room temperature to its final temperature and \( m_w \) is mass of workpiece melted per unit time. The \( m_w \) term can be written:

\[ m_w = \frac{1}{2} \rho V_w w p \]

(7)

where \( \rho \) is workpiece density, \( V_w \) is welding speed, and \( A_w \) is the cross-sectional area of melted zone. As shown in Fig. 6, a reasonable assumption is that the melted zone is triangular in section so that equation (7) becomes:

\[ m_w = \frac{1}{2} \rho V_w w p \]

(8)

where \( w \) is width of weld bead and \( p \) is penetration.

Again, a lower limit of \( E_w \) can be obtained by assuming a melted zone temperature equal to the melting point of steel. \( \Delta H \) in this case has been found previously (Ref. 7) to equal 1311 J/g.

An equation describing the partition of power consumption can now be written as:

\[ E_{in} = E_e + E_a + E_w + E_i \]

(9)

Equations (1), (2), (5) and (6) give expressions for all terms in (9) except \( E_i \). Accordingly, equation (9) can be rearranged to yield a value for \( E_i \).

The above developed technique was used to analyze the effects of electrode extension on the components of power dissipation at a range of deposition rates. Table 4 lists the calculated \( E_{in}, E_e, E_a, E_w, \) and \( E_i \) values, together with the approximate \( T_2 \) values found using Fig. 5.

![Fig. 5—Variations of power dissipated in electrode extension (E_e) with electrode temperature rise due to extension (T_2 - T_1) for the three deposition rates](image)

![Fig. 6—Etched section through a bead-on-plate deposit showing that the weld pool is essentially triangular in section](image)
The variation of $T_2$ values with deposition rate is shown in Fig. 7. At 95 mm (3.75 in.) electrode extension, $T_2$ is of the order of 1000°C (1832°F), while at 65 mm (2.5 in.) it is in the range 600–800°C (1112–1472°F); for 25 mm (1 in.) electrode extension $T_2$ increases from 300° to about 600°C (572 to 1112°F) with increase in deposition rate. $T_2$ is fairly constant at deposition rates above 6 kg/h for the two longer electrode extensions but increases over the whole range for short extensions.

The relative magnitude of the power components and their variation with deposition rate and electrode extension are shown graphically in Fig. 8. For given deposition rate the sum of $E_s$ and $E_e$ is constant in this analysis, since this is the minimum power to melt the electrode. A feature suggested by Fig. 8 is that, at given deposition rate, the $E_1$ terms are approximately constant — independent of electrode extension. Using the values in Table 4, at a 3 kg/h (6.6 lb/h) deposition rate, $E_1$ is 4.8 ± 0.4 kW while at 6 kg/h it is 6.6 ± 0.5 kW; at 8 kg/h it is 6.2 ± 0.8 kW, although the $E_1$ values at very long electrode extension appear to be generally slightly higher. The approximate constancy of $E_1$ could be used to make predictions of, for example, the joint penetration expected under particular welding conditions.

The efficiency of the process as given by $(E_s + E_e + E_w)/E_{in}$ was found, using the values in Table 4, to increase with deposition rate from about 25% at 3 kg/h (6.6 lb/h) to about 50% at 8 kg kg/h (17.6 lb/h); however, it is not strongly dependent on electrode extension.

Although the self-shielded FCAW process does not appear to have been subjected to this type of analysis previously, the processes using solid wire have been the subject of many studies. SAW, GMAW and plasma-GMAW have been analyzed with regard to the distribution of heat and temperature between the current contact tip and the molten weld metal drop (Refs. 1, 8–12). These analyses normally require a knowledge of the variations of specific heat, resistivity and density of electrode material with temperature. Such analyses have been developed to the stage that they give good agreement with observation, particularly for GMAW.

A recent study of GMAW which considers electrode extension as a primary variable is that of Waszink and van den Heuvel (Ref. 12). They obtained the expression for the resistance ($R$) associated with electrode extension:

$$R = \frac{\alpha L}{S} - \frac{\beta m}{I^2}$$

where $\alpha$ and $\beta$ are material constants, $L$ is electrode extension length, $S$ is sectional area of conductor, $m$ is melting rate and $I$ is current.

Equation (10) was applied to the present results. The $\alpha$ and $\beta$ values quoted (Ref. 11) for mild steel were used, and the resulting $V_s$ values are listed in Table 5. A comparison of the calculated $V_s$ values with the measured ones indicates that the calculated values are 2 to 3 times too high, except possibly at low melting rate and electrode extension. In fact, the calculated $V_s$ values suggest that melting of the electrode would occur within the extension length at long extension. Since the analysis by Waszink and van de Heuvel (Ref. 12) was formulated for solid wires rather than cored electrodes, such a discrepancy is not unexpected.

### Conclusion

The decreases in welding current and penetration associated with increasing electrode extension for constant deposition rate (welding wire feed rate) are a result of changes in the distribution of the input power. At a given deposition rate as electrode extension is increased, the power dissipated in the extension ($E_e$) increases relative to that needed to melt the electrode end ($E_s$). This power ($E_e$) is used to preheat the electrode so that its temperature, before reaching the arc zone, ranges from about 300°C (572°F) at low deposition rate and extension to over 1000°C (1832°F) at high extension.

The analysis developed suggests that, at a given deposition rate, the power loss due to all sources ($E_s$) is approximately constant and is independent of electrode extension. As a result, there is generally less power available for melting the workpiece at higher extension; this is in line with the lower penetrations observed.

The observations of metal transfer showed that, while the globular repelled mode operated over the whole current range at longer electrode extensions, a change to the nonaxial projected spray mode occurred between currents of 360 and 490 A at 25 mm (1 in.) electrode extension. Similarly, at longer electrode extensions, deposition rates increased linearly with current over the whole range. On the other hand, at 25 mm electrode extension, a change in gradient of deposition rate-current variation occurred at
about 450 A due to the change in metal transfer mode.

References


Appendix: List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A_w</td>
<td>Cross-sectional area of melted zone.</td>
</tr>
<tr>
<td>C(T)</td>
<td>Specific heat of electrode at temperature T.</td>
</tr>
<tr>
<td>E_a</td>
<td>Power dissipated by arc.</td>
</tr>
<tr>
<td>E_e</td>
<td>Power used to melt electrode.</td>
</tr>
<tr>
<td>E_i</td>
<td>Input power.</td>
</tr>
<tr>
<td>D_l</td>
<td>Power loss term.</td>
</tr>
<tr>
<td>E_{w}</td>
<td>Power dissipated over electrode extension length.</td>
</tr>
<tr>
<td>E_w</td>
<td>Power used to melt workpiece.</td>
</tr>
<tr>
<td>E_v</td>
<td>Potential drop across the arc.</td>
</tr>
<tr>
<td>V_a</td>
<td>Potential difference between current contact tip and workpiece.</td>
</tr>
<tr>
<td>V_p</td>
<td>Potential difference between power supply terminals.</td>
</tr>
<tr>
<td>V_s</td>
<td>Potential drop due to electrode extension.</td>
</tr>
<tr>
<td>v_w</td>
<td>Welding speed.</td>
</tr>
<tr>
<td>w</td>
<td>Width of weld pool zone or weld bead.</td>
</tr>
<tr>
<td>Delta_H</td>
<td>Energy to raise 1 gram (g) of steel from room to melting temperature.</td>
</tr>
<tr>
<td>rho</td>
<td>Workpiece density.</td>
</tr>
</tbody>
</table>

WRC Bulletin 286
August, 1983

Fatigue Behavior of Aluminum Alloy Weldments

by W. W. Sanders, Jr. and R. H. Day

This report provides a summary and overview of the fatigue behavior of aluminum alloy weldments. In 1972, a first state-of-the-art report, WRC Bulletin 171, was prepared and a computerized data bank was initiated. This report has emphasized the knowledge gained since the publication of that first summary and indicates the extent of the data added to the bank.

Publication of this report was sponsored by the Aluminum Alloys Committee of the Welding Research Council. The price of WRC Bulletin 286 is $12.75 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Room 1301, 345 E. 47th Street, New York, NY 10017.

WRC Bulletin 288
October, 1983

Fracture of Pipelines and Cylinders Containing Circumferential Crack

by F. Erdogan and H. Ezzat

This study is concerned with the problem of a pipe containing a part-through or a through circumferential crack. The main objective is to give the necessary theoretical information for the treatment of the subcritical crack growth process. The problem of a through crack in the presence of large scale plastic deformations is also considered. The crack opening displacement (COD) is used as the main parameter to analyze the fracture instability problem and to correlate the experimental results.

Publication of this report was sponsored by the Weldability Committee of the Welding Research Council. The price of WRC Bulletin 288 is $12.75 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Room 1301, 345 E. 47th Street, New York, NY 10017.