Grain Refinement in Electroslag Weldments by Metal Powder Addition

The electroslag process when operated with a modified strip electrode shows promise of becoming a viable alternative to high-speed welding

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ABSTRACT. In this study, the performance of a metal powder cored strip electrode in electroslag welding was studied. The process demonstrated stable operation and produced welds with full penetration. Weld deposition rate was as high as 38 kg (84 lb) per hour. Using a combination of experimental measurements and theoretical heat flow calculations, a constitutive equation, which correlates welding parameters such as current, voltage, wire feed rate and weld travel speed, was derived. Specific heat input of the process was found to be directly proportional to the fourth power of voltage and inversely proportional to the square of current. The new consumable also minimized the deleterious effect of the long thermal cycle of slow heating and cooling rate in electroslag welding, with grain refinement in the weld metal and heat-affected zone (HAZ). By increasing the welding current from 1000 to 1500 A at 40 V, the weldment structure was modified with the total HAZ width reduced from approximately 11 to less than 8 mm (0.43 to 0.31 in.). Grain refinement in the coarse grain heat-affected zone (CGHAZ) also occurred. The average prior austenite grain size in the CGHAZ of the higher current welds was less than 300 μm. Temperature distribution along the fusion line also demonstrated the influence of the metal powder cored strip electrode on the heat flow conditions. In spite of similar peak temperatures, higher current welds showed significantly shorter thermal cycles with higher heating and cooling rates. Mechanical properties of the weldments made using this process also showed significant improvement over the conventional electroslag weldments. Additionally, chemical analysis of the welds indicated that it is possible to control the chemistry of the weld pool and final weld properties by incorporating different alloying elements in the core of the electrode. In summary, the metal powder cored strip electrode presented very promising results and can be considered as an alternative technique for electroslag welding.

Introduction

Electroslag welding is mainly used to achieve high deposition rate in thick-section joining applications. Plates from 52 to 300 mm (2 to 12 in.) in thickness can be welded at a rate up to 0.6 to 1.2 m (2 to 4 ft) per hour, with one or more electrodes. Despite the recent decrease of interest of fabricators in electroslag welding and the economic conditions for the heavy manufacturing industries, major applications of this process can still be found in shipbuilding, pressure vessel, structural and basic machinery fabrication. The advantages of electroslag welding, over the other arc welding processes, include simple joint preparation, high deposition rate, minimal amount of distortion, vertical and single-pass operation. However, there are also many disadvantages and limitations associated with the process. It can only be used for joining thick sections, usually 19.1 mm (¾ in.) and greater. The materials welded are generally limited to low-carbon steels, low-alloy steels, some stainless steels, and some nickel alloys. If the welding must be interrupted before completion, restarting is always a problem because of the difficulty of completely removing the solidified slag bath. Finally, electroslag welding can only weld in the vertical or near-vertical position.

In addition to the operational characteristics described above, it is also known that electroslag welds are significantly different from the welds made by conventional open arc processes. The cooling conditions produced by the electroslag welding process are extremely slow, resulting in excessively coarse grains in the as-solidified weld metal, constituted mainly of grain boundary ferrite and some ferrite sideplates (Ref. 1). Furthermore, the extremely large columnar grains are often segregated with impurities causing grain boundary separation to occur. The effect of cooling rate can also be noticed in the base metal next to the fusion line. The extended period of heating at high temperatures coarsens the inclusions or second phase particles, allowing the austenite grains to grow. Subsequent slow cooling will allow the formation of large volume fractions of allotriomorphic structure with carbide precipitation and ferrite sideplates, reducing the toughness of the CGHAZ of the weld (Ref. 2). Consequently, electroslag welds often present poor mechanical properties, low strength and toughness. Postweld heat treatments are often specified to restore the impact toughness of the weld metal and the HAZ such that they satisfy the design requirements. This is sometimes uneconomical, and other times, impractical.

High Productivity Electroslag Processes

More recent efforts in arc and electroslag welding focus on process developments which improve productivity as well as mechanical properties (Refs. 3-5).
Fig. 1 — Narrow groove electroslag welding with single and double strip electrode and solid flux blocks to prevent arcing (Ref. 13)

Fig. 2 — Equipment setup for square-grooved high-speed welding with inert gas metal powder delivery system. Left = Plate thickness 10–40 mm; Right = Plate thickness 40–100 mm (Ref. 18)

20). One of the two most used approaches is to decrease the overall heat input of the process by decreasing the volume of the weld deposit and the dimension of the root opening. This leads to an increase in the cooling rate to refine the weld metal and HAZ microstructure. The other method is to increase the deposition rate and welding speed such that the process heat is distributed throughout a long section of the weld, lowering the effective heat input.

Narrow Groove Approach

Avramenko, et al. (Ref. 12), suggested that the most expedient and simple way of increasing the productivity of the electroslag welding process is the reduction of groove width with a simultaneous increase of electrode wire feed rate. This procedure decreases mainly the amount of weld metal deposited in the weld joint and the time needed to complete the weld. However, the extent to which the groove opening can be reduced is limited by the stability of the process and the size of the electrode and guide tube inserted into the opening. If the groove is too narrow, arcing may occur between the electrode and the base metal.

Using solid flux blocks to avoid arcing between a solid strip electrode in a thin channel consumable guide and the base metal, Watanabe, et al. (Ref. 13), was able to weld with groove openings as small as 12 mm (0.5 in.). Figure 1 shows the electrode setup for the narrow groove process. Sound welds with good penetration were made at approximately 800 A and 34 V, with 100-mm (4-in.) thick plate and an opening of 15 mm (0.6 in.), attaining a welding speed of about 15 mm (0.6 in.) per minute. The specific heat input was 1 kJ/mm² (645 kJ/in.²). Despite the improved weld mechanical properties reported, the production rate is still not high enough, and the specific heat needs to be further lowered.

Venkataraman, et al., and Atleridge, et al. (Refs. 5, 6), investigated the effects of root opening and reported that narrow groove welds resulted in higher base metal dilution than standard groove welds. Dilution was also observed to increase linearly with decreased joint spacing. The specific heat input of these narrow groove welds was comparable to that reported by the Japanese researchers (Ref. 13).

Metal Powder Addition

In arc welding, the addition of powdered metal, which can be easily melted by the excess process heat of the arc, was introduced in the early 1960’s to increase the deposition rate in what became known as the “Arcmetal” (Ref. 14) and the “Bulkweld” process (Ref. 15). Reynolds and Kachelmeier reported increased deposition rate, decreased heat input, reduced HAZ, and lower consumption of fluxes in hardfacing and cladding with powdered metal filler. The powder-to-wire weight ratio was approximately 1:1. Campbell and Johnson (Ref. 14) used powdered filler metals to reduce the heat input of heavy butt and fillet welds in both submerged arc and gas shielded arc welding processes. Thomas (Ref. 16) reported on the use of highly alloyed powders to produce cobalt-based hardfacing deposits using unalloyed cobalt strip.

The development of electroslag remelting (ESR) as a process for refining alloy steels and other alloys was being adopted in the 1960’s at the same time that powdered filler metals were being applied in arc welding. These two concepts were combined in two ESR facilities, one in the U.S. to produce stainless steels (Refs. 8, 9) and one in Europe to produce high-quality forging steels (Refs. 10, 11). In both facilities, one or more low-carbon steel strips carried the electric current, and alloy powders were conveyed to the strips to which it adhered by the magnetic field generated by the currents carried by the strip electrodes. This led to the use of powdered filler metals in electroslag welding.

Smirnov and Efimenko (Ref. 17) reported that powdered filler metal in electroslag welding refined the weld metal and HAZ microstructure. Low-temperature impact strength of the weldments in the as-welded condition increased by a factor of two. Deposition rate was approximately 13 to 24 kg (30 to 50 lb) per hour with slight reduction in the specific heat input.

Eichhorn, et al. (Refs. 18-20), added powder metal filler and increased the deposition rate while reducing the overheating of the weld pool. The ferromagnetic metal powder was supplied to the weld by a flow of argon gas —Fig. 2. The powder-to-electrode weight ratio was 1.2 : 1. He used single and dual electrode configurations and different powder delivery locations to increase the welding speed to approximately 230 mm (9 in.) per minute. A simultaneous reduction of energy input was also observed. Notch impact testing results measured in samples taken at distances of 1 and 2 mm from the fusion line showed very good Charpy impact toughness.

Reynolds (Ref. 21) reviewed the vari-
ous methods of improving productivity in both electroslag and electrogas welding. The experiments carried out included varying the weld root opening and the metal powder addition. Figure 3 shows the window for acceptable welds as a function of metal powder ratio and heat input for root openings of 51 mm (2.0 in.).

**Filler Wire Addition**

Rather than metal powder additions to absorb the excess thermal energy in the electroslag bath, Yakushin, et al. (Ref. 22), provided a separate wire fed into the slag. This resembles the feeding of a cold wire into plasma arc or gas tungsten arc welding processes. The authors demonstrated that not only was the productivity of the process increased, but like the powder fed systems, the HAZ width was reduced by increasing the welding speed. The authors suggested that filler wires could also be used to sense the depth of the metal pool, thus assisting in the control of the weld pool geometry and reducing the hot cracking tendency.

Little, if any, production experience has been obtained on the developments reported in the preceding paragraphs. The results reported by the various authors point to a potential for increased productivity and improved mechanical properties in the as-welded condition. Both the narrow groove approach (Refs. 12, 13) and the addition of metal powders to the slag bath appear to yield a considerably lower specific heat input with improved mechanical properties. On the other hand, the operating range for successful welds is also more restricted. For example, a 12- to 15-mm (0.5- to 0.6-in.) narrow groove may require machined plate edges in thicknesses 100 mm (4 in.) and greater. Furthermore, this raises the question as to whether the average fabricator of heavy plates is equipped to control the parameters within the narrow ranges required for such improvements to be obtained.

Furrthermore, the distortion of the thin strip guides, even though restrained by fusible flux blocks and the thin strip electrode, raises questions as to the feasibility of the process in long joints under production conditions. The more conventional groove width of the metal powder approach would seem to be more feasible.

Processes which feed loose metal powders into a welding zone have presented production control problems, often militating against their use in production. But improvements in powder flow systems offer hope that the approach of Eichhorn, et al. (Refs. 18-20), may be found useful for some heavy plate fabrications. Control of the uniformity of the alloy, particularly in high-alloy systems, presents the same problems faced by the producers of metal cored wires for arc welding and by the users of loose unalloyed powders in thermal spraying applications. The requirement that the powders be ferromagnetic is a further drawback for highly alloyed powder additions.

The objective of this research is to develop a high deposition rate welding technique that will also refine the HAZ and weld metal grain structure. The present approach involves the design of a special cored strip electrode which adds metal powder to the weld pool in a more efficient way, eliminating the need of a special inert gas metal powder delivery system. It incorporates the ideas of reduced root opening, electrode geometry, chemical composition modification, and high electrode melt rate.

It is the intent of this paper to report and discuss the performance and feasibility of the metal powder cored strip electrode as an electroslag welding consumable and how it affects the metallurgical, chemical and mechanical properties of the weldments produced.

**Experimental Procedure**

ASTM A588 grade structural steel was chosen for the consumable guide welding experiments. Plates of 305 X 305 X 38 mm (12 X 12 X 11/2 in.) were used. A hollow low-carbon manganese steel "strip" electrode, which allowed for chemical composition change by adjusting the alloy additions to the core of the electrode, was devised. In this work, the cavity of the electrode was filled with ferro-silicon and ferro-manganese powder at 50% compaction and a 3 : 1 metal powder-to-electrode weight ratio. The chemical composition of the base metal and electrode used in this work are given in Table 1.

With cross-sectional dimensions of 35.4 X 4.5 mm (1.4 X 0.18 in.), the metal powder cored strip electrode was made to carry high current and achieve high melt rate. And as shown in Figure 4, the surface of the electrode is corrugated for

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**Table 1—Chemical Composition of the Electrode and Base Metal Used in the Welding Experiments (wt-%)**

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Al</th>
<th>Ti</th>
<th>Co</th>
<th>V</th>
<th>Cu</th>
<th>Nb</th>
<th>B</th>
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<tbody>
<tr>
<td>Electrode</td>
<td>0.022</td>
<td>1.05</td>
<td>0.34</td>
<td>0.028</td>
<td>0.018</td>
<td>0.08</td>
<td>0.04</td>
<td>0.01</td>
<td>0.007</td>
<td>0.002</td>
<td>0.013</td>
<td>0.002</td>
<td>0.065</td>
<td>0.005</td>
<td>0.0005</td>
</tr>
<tr>
<td>Base metal</td>
<td>0.26</td>
<td>1.05</td>
<td>0.21</td>
<td>0.022</td>
<td>0.008</td>
<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
<td>0.032</td>
<td>0.001</td>
<td>0.004</td>
<td>0.0002</td>
<td>0.012</td>
<td>0.002</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

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**Fig. 3—Acceptable electroslag welding operating window as a function of metal powder ratio for weld grooves of 51 mm (Ref. 21)**
the feeding mechanism and also the retention of powder in case the end of the electrode is cut open. The width of the electrode covers almost the entire thickness of the base plate promoting more uniform heating of the weld pool. In addition, a pair of low-carbon-steel consumable guide plates were also used. The root opening was held constant at 38.1 mm (1 1/2 in.) for all welds, with the opening at top 3.2 mm (1/8 in.) greater than the opening at the bottom. Figure 5 shows the electrode-to-joint configuration in this process. Moreover, because of the specific electrode-to-joint geometry, no lateral oscillation of the electrode was needed.

For the determination of temperature distribution and heat extraction conditions in the HAZ, thermocouples were inserted into drilled holes in the plates and monitored throughout the heating and cooling cycles. Temperature profiles of welds were obtained and compared to data available in the literature.

The welds were produced at a constant potential of 40 V with the welding current varying from 800 to 1500 A. The details of welding parameters selection have been presented previously (Refs. 3, 4, 7) and will not be discussed in this paper. Commercial starting and running fluxes were used to carry out the welding experiments. The weld to promote magnetic stirring of the weld pool. The two weldments obtained were examined using metallographic techniques.

Results and Discussion

Process Variables and Welding Behavior

It was found that voltage has strong effects on both process stability and base metal penetration. Voltage should be maintained between 36 to 46 V to produce stable operation of the process. A voltage below 36 caused short circuiting between electrode and molten weld metal with frequent arcing. Excessively high voltage also resulted in severe spatter from flux bath and arcing. However, stable operation within 36- to 46-V range did not guarantee fully penetrated welds. A minimum of 40 V was required to achieve full penetration.

Within the 800 to 1500-A range, the feed rate of the metal powder cored strip electrode varied from 5 to 20 mm/s (0.2 to 0.8 in./s), which is much slower than that of conventional solid electrodes, typically 70 to 200 mm/s (2.8 to 7.9 in./s) (Ref. 4). Of course, the cross-sectional area of the strip electrode is much larger than that of the conventional solid electrode. For the same length of both electrodes, strip electrodes can carry much more current than the conventional solid ones. Several investigators (Refs. 2, 23-26) reported a linear relation between current and electrode feed rate, while others (Refs. 27, 28) found a nonlinear behavior. From the data obtained in this study, the relation between current (I) and electrode feed rate (W) was:

\[ I = A W^{0.35} \]

where \( A \) is a proportionality constant. Figure 6 is a graphical representation of Equation 1 with the experimental data. The coefficient of correlation, \( r^2 \), is 0.942 and indicates a good fit.

The average weld deposition rate was approximately two to three times higher than the solid wire process, reaching

<table>
<thead>
<tr>
<th>Weld</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Al</th>
<th>Ti</th>
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<th>V</th>
<th>Cu</th>
<th>Nb</th>
<th>B</th>
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<tbody>
<tr>
<td>1000 A</td>
<td>0.15</td>
<td>0.89</td>
<td>0.19</td>
<td>0.016</td>
<td>0.012</td>
<td>0.05</td>
<td>0.04</td>
<td>0.01</td>
<td>0.011</td>
<td>0.001</td>
<td>0.004</td>
<td>0.001</td>
<td>0.041</td>
<td>0.002</td>
<td>0.0003</td>
</tr>
<tr>
<td>1200 A</td>
<td>0.11</td>
<td>0.87</td>
<td>0.17</td>
<td>0.014</td>
<td>0.015</td>
<td>0.07</td>
<td>0.04</td>
<td>0.01</td>
<td>0.022</td>
<td>0.002</td>
<td>0.006</td>
<td>0.001</td>
<td>0.053</td>
<td>0.003</td>
<td>0.0003</td>
</tr>
<tr>
<td>1300 A</td>
<td>0.10</td>
<td>0.79</td>
<td>0.16</td>
<td>0.010</td>
<td>0.014</td>
<td>0.07</td>
<td>0.04</td>
<td>0.01</td>
<td>0.015</td>
<td>0.001</td>
<td>0.005</td>
<td>0.005</td>
<td>0.048</td>
<td>0.003</td>
<td>0.0003</td>
</tr>
<tr>
<td>1400 A</td>
<td>0.11</td>
<td>0.90</td>
<td>0.18</td>
<td>0.012</td>
<td>0.014</td>
<td>0.07</td>
<td>0.03</td>
<td>0.01</td>
<td>0.012</td>
<td>0.001</td>
<td>0.005</td>
<td>0.001</td>
<td>0.054</td>
<td>0.002</td>
<td>0.0003</td>
</tr>
<tr>
<td>1500 A</td>
<td>0.10</td>
<td>0.88</td>
<td>0.18</td>
<td>0.011</td>
<td>0.013</td>
<td>0.06</td>
<td>0.04</td>
<td>0.01</td>
<td>0.014</td>
<td>0.001</td>
<td>0.005</td>
<td>0.001</td>
<td>0.048</td>
<td>0.002</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Table 2—Typical Chemical Composition of a Running Flux for Electroslag Welding (wt-%)

\[ \text{CaO} \] | \[ \text{MgO} \] | \[ \text{MnO} \] | \[ \text{CaF}_2 \] | \[ \text{SiO}_2 \] | \[ \text{Al}_2\text{O}_3 \] | \[ \text{TiO}_2 \] | \[ \text{K}_2\text{O} \] | \[ \text{Na}_2\text{O} \] | \[ \text{FeO} \] | \[ \text{Bl} \] 
<table>
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</tr>
</thead>
<tbody>
<tr>
<td>12.2</td>
<td>2.3</td>
<td>22.5</td>
<td>8.6</td>
<td>33.0</td>
<td>8.3</td>
<td>8.0</td>
<td>0.9</td>
<td>0.6</td>
<td>1.8</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 3—Chemical Analyses of Some Representative Weldments
above 38 kg (84 lb) per hour. Specific heat input of the welds produced was found to be lower with respect to the other electroslag welds, 0.8 kJ/mm² (520 kJ/in.²).

Constitutive Equations for Welding Current, Voltage and Travel Rate

One of the major objectives for all welding process studies is to control the power input per unit length of weld since this is the primary variable to influence the degree of melting of the base material, the amount of dilution of the weld metal, and the thermal history of the HAZ. In electroslag welding, current and travel speed are not independent variables as in other arc welding processes. Holding constant the welding potential, the current and power are both functions of the resistance of the slag pool. Hence, they are functions of the electrode feed rate, the mechanics of electrode melting, and the nature of the electrical and thermal transport at the electrode/slag interface. Using an oscillating consumable guide in electroslag welding of 102-mm (4-in.) 2½ Cr-1Mo steel plate, Frost, Edwards and Rheinlander (Ref. 29) derived functional relations between the various process variables for the selection of a voltage and current range within which the energy input is just sufficient to achieve penetration of the parent plate but without overheating the HAZ. A constitutive equation of the following form was determined:

\[ I = B' W^{0.35} V^{1.03} \quad (4) \]

\( B' \) is the proportionality constant. The coefficient of correlation, \( r^2 \), is 0.9813, indicating a fairly good statistical fit for the power function. Figure 7 plots the current as a function of wire feed and voltage.

The specific energy input of the metal powder cored strip electrode process was also found to present a different relationship than that shown by Equation 2, and that \( E \), as shown in Equation 5, was found to be proportional to \( V^4/12 \) rather than \( V^4/2 \) as in Equation 3.

\[ E = B' \frac{(L - g - 2w) t_e}{[L + (g - 2t_b)] (w_e t_e)} V^4 \quad (5) \]

That is, the process with metal powder cored strip electrode was more sensitive to current than the conventional circular wire process, and energy input can be reduced significantly by increasing the welding current. In this equation, \( w_e \) and \( t_e \) are the width and thickness of the consumable guide plates used, and \( w_e \) and \( t_e \) are the width and thickness of the strip electrode, respectively. The different degrees of specific energy input dependency on the welding current of the two processes are due to the different electrode geometry, current path, current density and thermal transport conditions. In the case of metal powder cored strip electrode welding, the area ratio, \( A_g/A_w \), in Equation 3 (Lg/2πt) is substantially greater than that shown in Equation 5 (wgl/wel), hence the considerable difference in the energy dependence on the voltage/current ratio noted. Figure 8 is a plot of specific heat input as a function of welding current.

Unlike arc welding processes where an increase in current results in greater energy input and deeper penetration, the reverse occurs in electroslag welding. An increase in current requires an increase in electrode burn-off rate. This increases the welding speed and decreases the energy input per unit area of weld. An excessive increase in the current at constant voltage can shift the process from penetration to nonpenetration of the base plate. Based on experimental welding results and theoretical heat flow calculations, the process control boundaries for successful electroslag welding can be developed (Ref. 29). It took into consideration the
power contributions required to heat and melt the electrode, guide plates, and base metal surfaces, and the various heat losses, such as flux pool radiation, weld puddle superheating and copper shoe heating. Figure 9 illustrates the boundaries determined for electroslag welding with metal powder cored strip electrodes. The boundaries for solid wire electroslag welding (Ref. 29) are also included for comparison. Boundaries A through D enclosed an operating space exhibiting good process stability and base metal fusion. Outside the indicated boundary, the process often appeared to operate well but with inadequate base metal penetration. Boundary A represents the voltage threshold for parent plate fusion at low power inputs. Boundary B represents the constitutive equation for adequate penetration at high power levels. Boundary C represents the maximum power output of the welding power supply and Boundary D represents the limit of electrode feed rate at which the wire electrode melts by ohmic heating. Compared to the conventional electroslag process, a higher current level is needed in order to obtain fully penetrated welds. This is not of concern since higher current will also decrease the specific heat input of the process. However, the much narrower operating space observed indicates that this process may require more critical process and parameters control.

From the heat balance calculations, the role played by the various factors in the consumption and transport of energy was also determined. Table 4 shows the effect of each of the heat terms for several welds prepared at different current levels. As the welding current increased, the percent of energy dissipated in the form of heat loss to base metal decreased, indicating the possibility of lowering the specific heat input and improving the HAZ properties of the welds.

### Table 4—Energy Balance of Electroslag Welding with Metal Powder Cored Strip Electrodes

<table>
<thead>
<tr>
<th>Major Power Contributions</th>
<th>1300 A</th>
<th>1100 A</th>
<th>900 A</th>
<th>700 A</th>
</tr>
</thead>
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<tr>
<td>Heat input to the base metal</td>
<td>32.9</td>
<td>35.7</td>
<td>38.5</td>
<td>41.2</td>
</tr>
<tr>
<td>Resistive heat loss to guide plates</td>
<td>27.8</td>
<td>21.7</td>
<td>15.6</td>
<td>10.1</td>
</tr>
<tr>
<td>Heat input to melt electrode</td>
<td>22.1</td>
<td>23.2</td>
<td>25.8</td>
<td>27.6</td>
</tr>
<tr>
<td>Heat loss to copper shoes</td>
<td>14.0</td>
<td>15.2</td>
<td>16.4</td>
<td>17.5</td>
</tr>
<tr>
<td>Heat loss by flux pool radiation</td>
<td>1.9</td>
<td>2.1</td>
<td>2.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Heat loss by weld pool superheating</td>
<td>1.1</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

### Solidification Structure and Refinement

In a more recent publication, Yu, et al. (Ref. 30), characterized the solidification structure of low-carbon structural steel electroslag weldments and related them with the welding current and weld pool form factor (pool width/pool depth). They observed both cellular and columnar dendrites, named previously as coarse and fine columnar grains by Paton (Ref. 24). The coarse columnar grains protrude from the fusion line toward the center of the welds. At some distance from the fusion line, fine columnar grains could be observed. The location of cellular to columnar dendrite transition and the angle of inclination that the grains
The coarse as-welded structure of electroslag weldments is a major concern to the welding engineers and several attempts were made to refine the as-solidified structure of these high heat input welds. Venkataraman, et al., and Atteridge, et al. (Refs. 5, 6), investigated the effects of mechanical vibration on electroslag weld pools. The observed movement of the slag surface as a result of plate vibration was insufficient to cause turbulence at the slag-metal pool interface for grain refinement to occur. However, refinement of the as-deposited grains resulted from the use of an externally shrouded electrode guide tube as an extended stirrer. The form factor of the weld pool decreased from 3 to 1.5. Multiple orientation and finer columnar grains were observed throughout the entire cross-section of the welds. The authors concluded that because of the quartz shielding, a sharp thermal gradient was established in the slag pool generating an intense stirring action. The turbulent convection which oscillates the hot zone in the slag and metal pool led to periodic solidification and remelting of some dendritic arms. Subsequent renucleation resulted in the multiple orientation growth of the columnar grains. Eastering (Ref. 31) also mentioned several techniques for refining welds which include magnetic stirring, ultrasonic cavitation and the use of chemical inoculants. With ultrasonic vibration at 20 kHz, the grain structure along the centerline of an electroslag weld was refined significantly.

Even though magnetic field application is quite common in the processes of arc welding and electroslag refining, the technique is not generally applied to electroslag welding. For electroslag overlays, Nakano, et al. (Ref. 32), used magnetic field to promote fluid flow and drive the molten slag layer from the hotter region to the colder region to eliminate undercutting. In this work, some preliminary tests were done to investigate the effect of electromagnetic refinement of electroslag weld metal. The weldments with magnetic field coupling showed evidence of grain refinement. The length of the columnar grains decreased significantly, while the equiaxed dendritic zone increased. This is shown in Fig. 12. The results seem to indicate that the induced convective fluid motion in the weld pool disrupted the solidification process and growth of columnar dendrites.

HAZ Microstructures

The CGHAZ and the fine-grained HAZ (FGHAZ) sizes were measured and compared with data obtained in the literature. Under similar operating conditions, the present technique with metal powder cored strip electrodes produced welds with reduced HAZ. The thickness of the heat-affected zone also varied with the current level. At 1500 A, the CGHAZ and FGHAZ were approximately 5 and 2 mm, respectively. This represented a reduction of almost 50% from the 1000-A weld. Figure 13 shows the HAZ reduction as a function of welding current. Furthermore, grain size reduction in the HAZ was also observed. Figures 14 A and B show representative HAZ micrographs. At 1000 A, the average CGHAZ grain size was approximately 550 µm. At 1500 A, the average CGHAZ grain size was reduced to approximately 230 µm. Figure 15 illustrates graphically the relationship between CGHAZ grain size and the welding current. When compared to conven-
tional electroslag welds, which generally exhibit grains of 600 to 800 μm, the present technique produced welds with much refined grain size in the CGHAZ. Grain size variation was observed to be more significant at current levels around 1200 and 1300 A.

It is recognized that an austenite grain size of 250 μm is still quite coarse, particularly when compared with the newer fine-grained steels, yet the present finding is a positive indication of the ability of HAZ grain refinement by controlling thermal history of the welding process.

Weld Metal Microstructures

Figure 16 shows representative weld metal micrographs of low- and high-current welds taken at equivalent positions. As expected, the high-current weld exhibited finer prior austenite grain size, delineated by the grain boundary ferrite network. On the other hand, the lower-current weld showed microstructure comparable to conventional welds with extremely large prior austenite grains. Figure 17 shows the variation of prior austenite grain size with the welding current. Again, a sharp decrease in austenite grain size was observed in the 1200- to 1300-A range welds. Both Paton (Ref. 24) and Yu, et al. (Ref. 30), indicated that...
coarse columnar grain zones usually contain more acicular ferrite, while fine columnar grains zone exhibit higher volume fraction of grain boundary ferrite. During cooling, cellular dendrites transform into coarse columnar austenite grains and result in an acicular ferrite dominant room-temperature microstructure. Columnar dendrites will generally transform into fine columnar austenite grains with grain boundary and sideplate ferrite as the predominant structure. This is also verified in this work. Increasing current led to an increase in volume fraction of fine columnar grains. Subsequent transformation of finer austenite grains resulted in high volume fractions of grain boundary ferrite.

Heating and Cooling Rate Effects

The temperature profiles of the lowest and highest current welds, shown in Fig. 18, were chosen to verify the effects of heating and cooling rate on the HAZ grain size control. The readings represented real-time measurements taken at 1.5 mm (0.06 in.) from the fusion line, after

**Fig. 16** — Representative weld metal microstructure of the: A — 1000-A; B 1500-A, 40 V welds

**Fig. 17** — Prior austenite grain size in the weld metal as a function of the welding current

**Fig. 18** — Temperature profiles of high- and low-current welds indicating the differences in heating and cooling rates of the two welds
steady-state welding regime was reached. The 1500-A weld temperature profile showed a steeper temperature increase with time during the heating cycle with a peak temperature of approximately 1400°C (2552°F). The lower current weld experienced a more sluggish temperature increase, and the peak temperature was slightly below 1400°C. During cooling, the higher current welds showed faster cooling rate than the lower current samples. For welds of similar chemical composition, the different thermal history experienced by the welds will promote the formation of distinct microstructures.

Excessive grain growth in the CGHAZ occurs mainly as a result of the coarsening and dissolution of nonmetallic particles such as carbides and nitrides (Ref. 33). The presence of these particles is essential to the stability of the structure, since they can interact and pin the grain boundaries. In the case of an aluminum killed fine grain steel, the grain coarsening temperature is related to the aluminum nitride dissolution temperature. The aluminum content of the base metal used in the present experiment is 0.032 wt-%, and the grain coarsening temperature was estimated to be approximately 1000°C (1832°F) (Ref. 33). However, with heating and cooling rates greater than those corresponding to the equilibrium conditions, the dissolution of these particles in the HAZ will depend on the peak temperature, the concentration of aluminum and nitrogen in the alloy, and the time duration that the base metal is subjected to the severe thermal cycles during welding. In terms of peak temperature, the low- and high-current welds had experienced quite similar temperature readings, 1340°C and 1400°C (2444°F and 2552°F), respectively. However, the two welds showed distinct heating and cooling characteristics. The lower current weld had a heating rate of approximately 10°C/s (18°F/s) and its cooling rate was 6°C/s (11°F/s). On the other hand, the high current weld showed approximately 15°C/s and 30°C/s (27°F/s and 54°F/s) in the heating and cooling cycle, respectively. This observation is particularly important in the interpretation of the grain refinement event in higher current welds. The higher heating rate does not allow for the equilibrium heating and dissolution of the aluminum nitride particles, even up to a very high temperature. During the entire thermal cycle, particle pinning of the austenite grain boundaries was never ceased. In addition, the time that the CGHAZ experienced temperatures above 1000°C for the lower and higher current welds were 90 and 50 s, respectively. Therefore, one can conclude that the higher current weld experienced a shorter thermal cycle above 1000°C with faster heating and cooling rates which limited particle coarsening or dissolution. This also explains the resulting finer CGHAZ grain size observed in the higher current welds. However, \( \Delta T_{905} \) in the low-current weld was not observed to be much longer (approximately 150 s, as compared with the higher current weld reading of 120 s). This is confirmed by the observation that the CGHAZ structure of both welds was composed of proeutectoid ferrite networks along the prior austenite grain boundaries, intragranular ferrite and pearlite matrix with carbide and bainite.

Specific Heat Input Effect

Grain refinement in weldments is a complex matter and generally cannot be achieved by changing one single parameter, even though the faster heating and cooling rate of the higher current electroslag weldments were shown to have a strong influence on the HAZ grain growth restriction. In fact, the temperature profile itself is due to a combination of other factors such as welding current, welding speed, geometry of the strip electrode, thermal properties of the materials used, and specific heat input. Specific heat input of the higher current welds produced in this work was found to be approximately 0.8 \( \text{kJ/mm}^2 \) (520 \( \text{kJ/in.}^2 \)) and lower than that of an average conventional electroslag weld. The effect of specific heat input and welding speed on CGHAZ grain size is illustrated in Fig. 19. The sharp decrease in grain size at specific heat input of approximately 1.3 \( \text{kJ/mm}^2 \) follows the trend described previously, for it corresponds to the 1200- to 1300-A range. Due to the nonlinear behavior of electrode feed rate with increasing current, a faster increase in deposition rate with current at the 1200- to 1300-A range resulted in a significantly larger amount of electrode being deposited into the weld joint and accelerating the welding process (Ref. 34). Consequently, heat input into the molten metal pool is spread out to a longer section of the weld decreasing the specific heat input. This also leads to a faster heating and cooling cycle resulting in effective control of HAZ grain growth.

Hardness Measurements and Chemical Composition Variation

Hardness measurement of the weld specimens are shown in Fig. 20. When considering the highest and lowest current welds prepared, only a slight difference in the HAZ hardness readings was observed. This is consistent with the previous observation that even though the HAZ size and the grains were refined in the higher current welds, the constituents found in the microstructures were generally the same. Therefore, the increase in HAZ hardness with increasing current was minimum. However, the average hardness of the weld metal with the refined solidification structure was approximately 10% lower than that of the coarse structure weld. Venkataraman, et al. (Ref. 5), reported similar findings that the hardness of the quartz shroud refined weld metal was lower than that of the standard electroslag weld. The decrease in hardness is related to the microstructure discussed previously. Since higher current welds showed smaller austenite grains with large amounts of grain boundary ferrite, the average hardness was observed to be lower. A weld with microstructure of coarser austenite grains and higher volume fraction of acicular ferrite results in higher hardness.

An interesting feature observed, how-
ever, is the variation of weld metal hardness with the welding current. A minimum in hardness was observed in the specimens at welding current around 1200 to 1300 A. This shows that the decrease in weld metal hardness is not due to the grain size variation alone. Process characteristics of the metal powder cored strip electrode technique may have affected the slag/metal interaction, particularly within the 1200- to 1300-A current range. Therefore, relative chemical element loss was determined for each of the major alloying elements.

Relative chemical element loss of an element \( \Delta X \) is expressed as the difference between the calculated \( X_{th} \) and measured composition \( X_{mea} \) of the element X in the weld. It was observed in Fig. 21 that at 1200- to 1300-A range, a larger loss of manganese, silicon, and phosphorus occurred. A lower carbon pickup was also observed within the same weld. Lower chemical hardenability contributed to the lower weld metal hardness. The loss observed at this particular current range is very interesting since it follows the same trend as observed in CGHAZ grain size and weld metal prior to austenite grain size decrease with welding current. This indicates that the observed behavior is originated from the thermal history of the process, which includes the heating and cooling cycle, temperature distribution and molten metal pool chemistry. Element recovery in the weld pool will also depend on current efficiency. Frost, Olson and Edwards (Ref. 35) concluded that the current efficiencies for electrochemical reactions involving chromium, manganese, silicon, molybdenum, oxygen, and aluminum increased with increasing current density. The concentration changes observed were directly proportional to the welding current and to the current efficiency for the reactions, and were inversely proportional to the melt rate. As compared to conventional electroslag welding practice, this difference arises from the significant difference in the ratio of the electrode cross-sectional area to that of the weld groove and the welding current. The area ratio, \( A_2/A_w \) in Equation 3 (Lg/2irr) is substantially greater than that shown in Equation 5 (wg/tg/wel), hence, the considerable difference in the energy dependence on the voltage/current ratio noted in an earlier section. The balance between increasing current and melt rate determines the alloying element recovery in this process.

**Mechanical Properties: Charpy Impact Toughness**

A set of 5 welds covering the 1000- to 1500-A range was chosen for the Charpy impact toughness testing and the results are summarized in Fig. 22. The effects of grain refinement in the CGHAZ is clearly shown. The upper shelf energy of the 1500-A weld is significantly higher than that shown by the 1000-A one. The lower shelf energy of the two welds, however, are quite similar. This seems to indicate that at high testing temperatures, the fine precipitate population and distribution of the higher current welds were not affected very much by the faster heating and cooling rate. More energy
was required for a crack to propagate through the specimen, moving from precipitate to precipitate. On the other hand, the coarsening of the precipitates and the decrease in number of precipitates in the lower current weld, because of longer thermal cycles, will lower the energy for crack propagation. The ductile-to-brittle transition temperature (DBTT) of the welds was also observed to decrease with increasing welding current. The 1500-A weld exhibited the lowest DBTT of approximately -40°C (-40°F) with an energy of 100 ft-lb (70 ft-lb).

Finally, when the Charpy V-notch energy absorbed at 0°C (32°F), -20°C (-4°F), and -30°C (-20°F) of the metal powder cored strip electrodes welds are compared with the generally accepted specification of 25 ft-lb at 0°C for weld acceptance, as shown in Fig. 23, it can be seen that the welds generated in this work performed satisfactorily and would be qualified for many of the so-called critical applications.

Conclusions

1) Electroslag welding with the metal powder cored strip electrode and consumable guide plates demonstrated stable operation with increased travel speed and decreased specific heat input, indicating the strong potential of the process to become an alternative for high-speed welding.

2) Expressions were developed to relate welding current, voltage, electrode feed rate, travel speed, weld, and consumable geometry, and specific heat input of the electroslag welding process using a metal powder cored strip electrode.

3) Process boundaries for obtaining sound welds with acceptable properties by this process were determined.

4) Even at high current levels and welding speed, Types I and II solidification structures containing essentially cellular and columnar dendrites were observed, with no signs of hot or cold cracking.

5) With the metal powder cored strip electrode, both CGHAZ and FGHAZ size were reduced with increasing welding current.

6) Substantial grain refinement in the CGHAZ was achieved with the metal powder cored strip electrode. Average grain size was reduced from about 600 to approximately 250 μm.

7) The faster heating and cooling rates of the metal powder cored strip electrode process provided adequate conditions for grain growth control in the CGHAZ.

8) The metal powder cored strip electrode affected the heat distribution in the molten weld pool as well as the chemistry resulting in distinct carbon, manganese, silicon, and phosphorus transfer behavior within the range of 1200 to 1300 A.

9) Charpy impact toughness data showed that it is possible to obtain welds with acceptable properties by this process.

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References

10. Descamps, J., and Etienne, M. Production of large ingots by continuous electroslag powder melting, ibid.
22. Yakushin, B. F., Basheve, L. F., Tikhonov, V. P., and Zalevskiy, 1982. Improving the capacity of electroslag welded joints for resisting hot

WRC Bulletin 338
November 1988
Interpretive Report on Electroslag, Electrogas and Related Welding Processes
By R. D. Thomas, Jr., and S. Liu

These processes are characterized with emphasis on fundamentals of heat flow conditions, metal transfer, weld pool morphology and the chemical and electrochemical aspects of the slag and weld pool reactions. A total of 146 references are included in this report.

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By A. Bazergui and L. Marchand

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