

Identification of Reaction Mechanism to Produce High Quality Weld During Submerged Arc Welding

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ABSTRACTS

The interpretation of the reaction mechanism is significant to produce the high quality welds and understand the welding processes. This investigation is important for the design of welding consumables and the selection of welding process parameters to develop the high quality welds.

The objective of this study is to investigate the effect of electrochemical reactions on the transfer of alloy elements between slag and weld metal during submerged arc welding. During submerged arc welding weld metal composition is shown to be controlled by two reaction mechanisms in four reaction zones. The responsible reaction mechanisms are thermochemical and electrochemical reactions. The possible reaction sites are the melted electrode tip, the detached droplet, the hot weld pool immediately below the moving electrode, and the cooling and solidifying weld pool behind the moving electrode. The possible reactions in submerged arc welding at different zones of the process is schematically shown in Figure 1.

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1. Introduction

During submerged arc welding, chemical reactions take place between molten flux and metal. This interaction between slag and metal results in compositional changes affecting the structure and properties of the weldment. Thus, in order to control the mechanical properties of the weld metal and match them with those of the work piece, it is necessary to estimate the extent of interaction between slag and metal.

The submerged arc welding process consists of a consumable electrode, an electrically

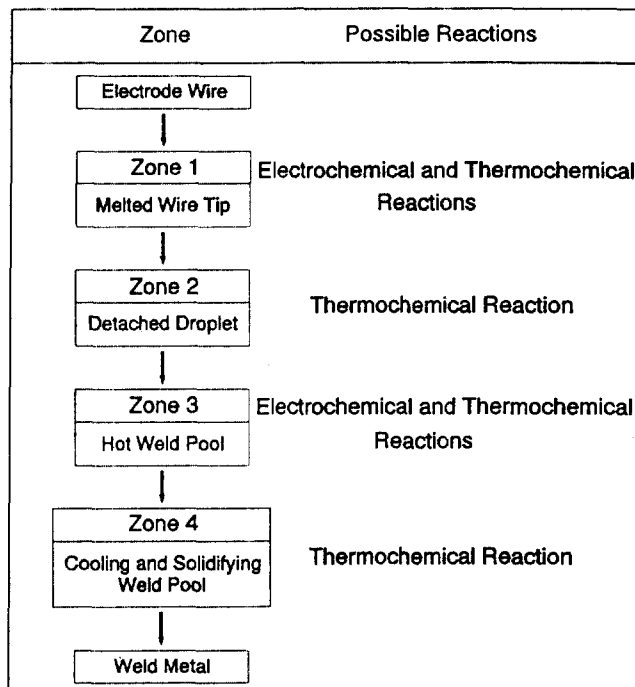


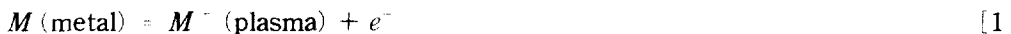
Figure 1 : Possible Reaction Sites and Reactions in Submerged Arc Welding

conducting slag and plasma, and a work piece. The welding current is carried largely by the submerged arc and to some extent by the conduction in the molten slag layer. The overall composition of the weld is controlled by the composition of the metal droplets which enter the weld pool, by the amount of dilution, and by the electrochemical and thermochemical reactions at the slag/metal and plasma/metal interfaces. The electrochemical reactions, which occur at the melted electrode tip and the hot weld pool, would result from ionic conduction of a portion of the welding current through the molten slag layer and plasma. Only thermochemical reactions are expected to occur at the surface of the detached droplets

and the cooling and solidifying weld pool since these zones are no longer carrying current. A number of investigations have been made concerning the nature of chemical reactions during submerged arc welding. These include work by Palm (1963), Davis and Bailey (1980), Chai and Eagar (1981, 1982), North (1977), Mitra and Eagar (1984), and Indacochea et al. (1985). However, a few investigators have considered the electrochemical reactions that occur when direct current is used in welding. Frost et al. (1983) considered the different chemical effects at the anode and cathode in electroslog welding. Blander and Olson (1986) postulated an electrochemical mechanism for the alteration of weld metal chemistry in submerged arc welding. This postulation has recently been verified experimentally by Kim et al. (1987, 1990) and done later by Indacochea et al. (1989, 1990).

During submerged arc welding the electricity is transferred across the slag/metal and plasma/metal interfaces, and the possible electrochemical reactions at the plasma/metal interface is different from those at the slag/metal interface due to difference in conduction mechanism of electricity. Figure 2 shows the schematic drawing of the cross-sections of submerged arc welding processes for both polarities. The potential charge transfers which may occur are included in this figure.

The possible anodic electrochemical reactions are the oxidations of metallic elements at the plasma/metal and slag/metal interfaces :



where M is iron or alloy elements and n is the valance of M . The possible cathodic electrochemical reactions are the reductions of metallic cations from the plasma and the slag :



Equations [1] and [3] are the reactions at the plasma/metal interface, and equations [2] and [4] are the reactions at the slag/metal interface. In the temperature range of welding arc plasma, only first ionization is possible due to very high second ionization energy. Therefore, the electrochemical reactions at the plasma/metal interface is controlled by the singly ionized atoms in the plasma.

The thermochemical reactions include oxidation reactions, such as those encountered in steelmaking, which lead to a closer approach to equilibrium between the flux and metal phase. Examples of such reactions would be silicon pickup from a high silica flux or the oxidation loss of transition elements through a deoxidation reaction :

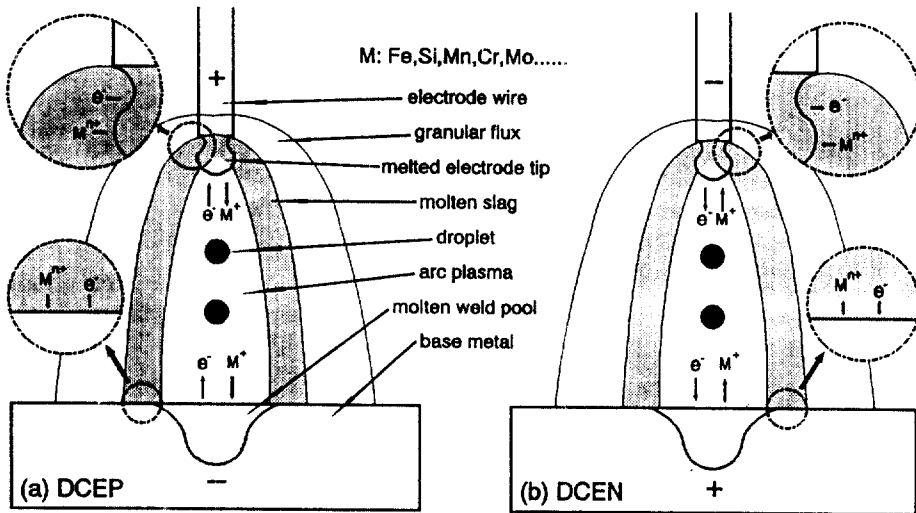
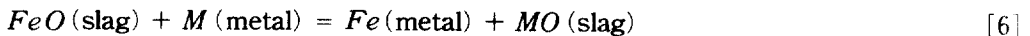
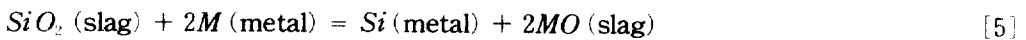


Figure 2 : Schematic of the Cross-Section of Submerged Arc Welding Process Including Potential Charge Transfers for Both Electrode Negative and Electrode-Positive Polarities



where M can be aluminum or calcium in reactions [5] and [6] and manganese in reaction [6] for the flux system used in this research.

2. Experimental Procedure

Straight (direct current electrode negative) and reverse (direct current electrode positive) polarity submerged arc welds were made with a commercial low carbon steel welding wire (2.38mm) on ASTM A36 steel plates and a water cooled pure copper plate. The compositions of the welding wire, the steel plate, and the commercial flux are given in Table 1.

The welding process parameters employed are listed in Table 2 for the collections of detached droplets and weld deposits. The detached droplets were collected by magnetic separation after running the weld at a high velocity over a water cooled copper plate. Single pass, bead-on-plate welds were made on the steel plates at several welding speeds with constant voltage and current.

A Baird-Atomic emission spectrometer was used to determine the alloy elements in weld

Table 1. Compositions of Welding Consumables (wt. %)

Element	Steel Plate	Welding Wire	Substance	Welding Flux
<i>C</i>	0.18	0.059	<i>SiO₂</i>	11.22
<i>Mn</i>	1.25	1.38	<i>Al₂O₃</i>	18.14
<i>Si</i>	0.05	0.05	<i>MgO</i>	33.23
<i>Mo</i>	0.03	0.33	<i>CaF₂</i>	25.26
<i>Cr</i>	0.077	0.073	<i>CaO</i>	6.29
<i>Ni</i>	0.06	0.11	<i>MnO</i>	1.15
<i>Al</i>	0.004	0.018	<i>TiO₂</i>	0.90
<i>Cu</i>	0.036	0.77	<i>Na₂O</i>	0.82
<i>Ti</i>	0.001	0.033	<i>Fe₂O₃</i>	1.99
<i>P</i>	0.018	0.012	<i>C</i>	0.37
<i>S</i>	0.031	0.015		
<i>O</i>	0.002	0.002		
<i>N</i>	0.004	0.004		
<i>B</i>	0.002	0.007		

Table 2. Welding Conditions for the Collections of Detached Droplets and Weld Deposits

	Polarity	Current (A)	Voltage (V)	Travel Speed (mm/sec)
Weld	DCEP	580	28.5	15.5 - 34.67
	DCEN	580	28.5	15.5 - 34.67
Droplet	DCEP	580	28.5	
	DCEN	580	28.5	

metal. The detached droplets were analyzed using the wavelength dispersive analyzer on JEOL scanning electron microscope.

A metallurgical model by Thier (1980) is adopted to show the extent of element transfer between the weld metal and flux. Its application gives quantitative data for the gain or loss of elements. The transfer efficiency into the weld can be expressed in terms of the difference between analytical and nominal compositions (Δ Quantity : Δ).

$$\Delta = (\text{Analytical Composition}) - (\text{Nominal Composition}) \quad [7]$$

The analytical composition is obtained by chemical analysis methods and the nominal

composition can be obtained by calculations based on the wire and plate compositions and dilution. The nominal composition is given by the following formula :

$$X_w = (1 - D) X_u + DX_p \quad [8]$$

where X_w = nominal composition

X_u = concentration of element in the electrode wire

X_p = concentration of element in the base plate

D = dilution

The dilution indicates the contribution of the parent metal to the composition of the weld metal, and can be determined by metallographic observation

$$D = A_p / (A_w + A_p) = A_p / A_t \quad [9]$$

where A_p = area of the fused base plate

A_w = area of the reinforcement

$A_t = A_p + A_w$

A positive concentration change ($\Delta > 0$) indicates a gain of a particular element, and a negative change ($\Delta < 0$) indicates a loss.

3. Results and Discussion

3. 1 Reactions at the Melted Electrode Tip and Detached Droplet

The thermochemical and electrochemical reactions are expected at the melted electrode tip. However, the electrochemical reaction ceases after the molten droplet separates from the wire because the detached droplets do not carry the current. Even though the electrochemical reactions do not occur in detached droplet, the results of the chemical analysis still show the electrochemical reaction effect at the melted electrode tip, as indicated by the difference in alloy compositions between anode and cathode droplets.

Figure 3 shows the delta quantities of the detached droplet for the various alloy elements. The detached droplet shows the increases in silicon concentration and the decrease in manganese concentration for both polarities. The initial welding wire has low silicon and high manganese concentrations while the flux has high silicon oxide and low manganese oxide concentrations. Therefore, these concentration changes are due to the thermochemical pickup of silicon from the flux and the thermochemical loss of manganese to

the flux. Therefore, manganese oxidation and silicon reduction reactions are major thermochemical reactions in this system. The effect of electrochemical reactions on the transfer of silicon and manganese can be shown by the fact that the anode shows less increase in silicon content and greater decrease in manganese content. These behaviors are the results of the electrochemical oxidation losses at the anode and the electrochemical reduction at the cathode during the reaction at the melted electrode tip.

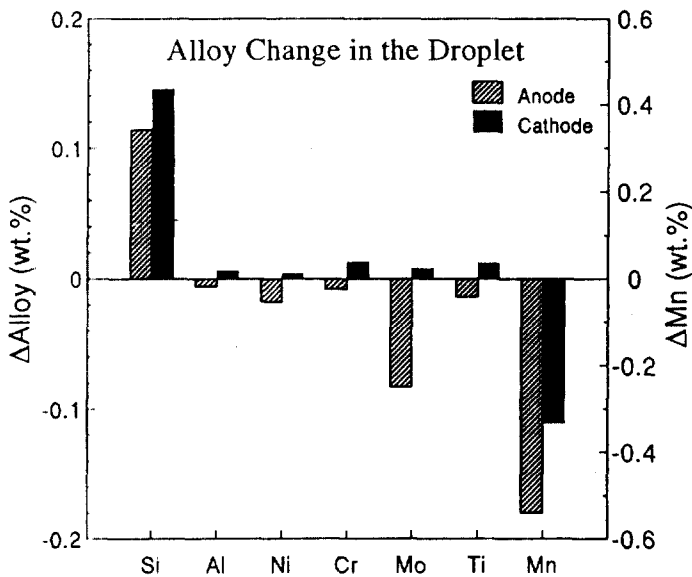


Figure 3 : Gain or Loss of Alloy Elements at the Detached Droplets for Electrode-Negative and Electrode-Positive Polarity Submerged Arc Welding

The evidence of the electrochemical reaction can be also arise from the chemical analysis of other alloy elements. Aluminum, nickel, titanium and chromium show the pickup at the cathode and the loss at the anode due to the oxidation reaction at the anode and the reduction reaction at the cathode. However, molybdenum shows the opposite trend. That is, the anode shows the pickup and the cathode shows the loss of molybdenum. This behavior is difficult to explain in terms of the molybdenum reaction alone, but if the iron reaction is also taken into account, it can be explained easily. Iron is the major electrode constituent, and it is more easily oxidized than molybdenum. Therefore, the loss of iron at the anode and the gain of iron at the cathode are relatively greater than those of molybdenum, and these cause an increase in the molybdenum concentration at the anode and a decrease at the cathode. Thus, this behavior of molybdenum is also the result of electrochemical reactions.

3. 2 Reactions at the Weld Pool

Weld pool reactions can be divided into two parts: molten metal reactions in the hot weld pool and weld pool reaction during cooling and solidification. At the molten weld pool immediately below the electrode, both electrochemical and thermochemical reactions occur. The part of the molten weld pool behind the electrode starts to cool and solidify after the arc has passed, and electrochemical reactions stop as the electrode moves away. Thermochemical reactions continue, however, and are characterized by deoxidation reactions, i. e., by precipitation of nonmetallic inclusions in the weld pool followed by more or less complete separation of the dispersed particles in the form of a slag phase.

Figures 4 through 7 show the results of the chemical analyses of the anode and cathode weld metal for silicon, manganese, molybdenum and chromium as a function of welding speed. The results for the anode and cathode of each element are plotted together. In this work, the droplet compositions were used to calculate the nominal composition, instead of wire composition, in order to prevent the weld pool reactions from being clouded by reactions at the melted electrode tip and the detached droplet. These results show that electrochemical reactions cause substantial changes in weld metal chemistry and that the travel speed is the important factor which controls the extent of the electrochemical reactions. As the travel speed decreases, the weld metal has more time for electrochemical reactions. Therefore, the difference in compositions between the anode and cathode increases as the travel speed decreases.

Figure 4 illustrates the variations in delta silicon due to polarity. High transient concentration of oxygen may exist in the liquid metal at the hot weld pool as a result of high solubility at elevated temperature. On slow cooling down to the solidification temperature, this will lead to spontaneous reaction and loss of dissolved silicon. The silicon loss must be due to the formation of some deoxidation reaction product. It is generally accepted that the formation of silicon dioxide (SiO_2) takes place when sufficient oxygen is available. But silicon loss is recovered by electrochemical reduction reaction at the cathode and increased at the anode by electrochemical oxidation reaction. Therefore, silicon shows greater loss at the anode, and a little gain or almost no change at the cathode.

Figure 5 shows the variations in delta manganese due to polarity. Similar to silicon, the oxidation of manganese is favored by the lower temperature prevailing in the cooler part of the weld pool. Here, manganese will react with dissolved oxygen to form slags that exhibit a large loss of manganese in both anode and cathode weld metal. The reason why manganese shows extensive losses in both cases is because the flux has a little manganese oxide (MnO) and the base plate has a high manganese content. Therefore, manganese can be oxidized easily. Another reason for manganese loss can be a result of the evaporation, because the vapor pressure of manganese increases strongly with temperature. But the

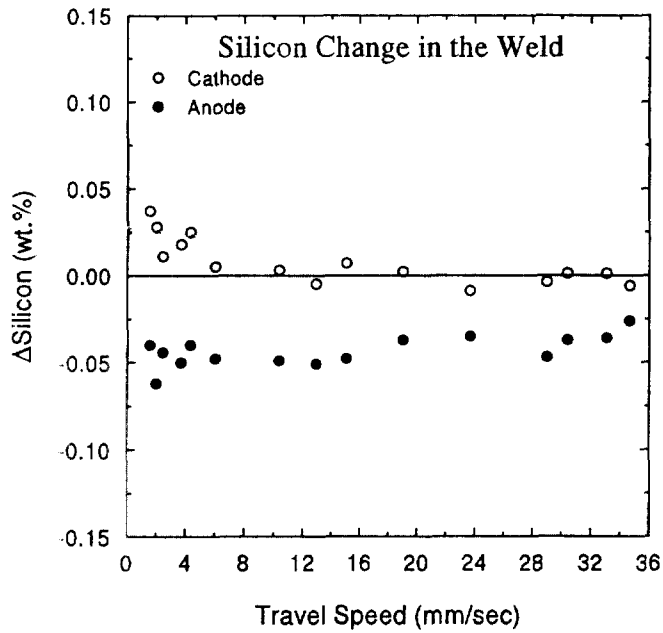


Figure 4 : Changes in Delta Silicon in the Weld Deposits for Electrode-Negative and Electro-Positive Polarity Submerged Arc Welding as a Function of Welding Speed

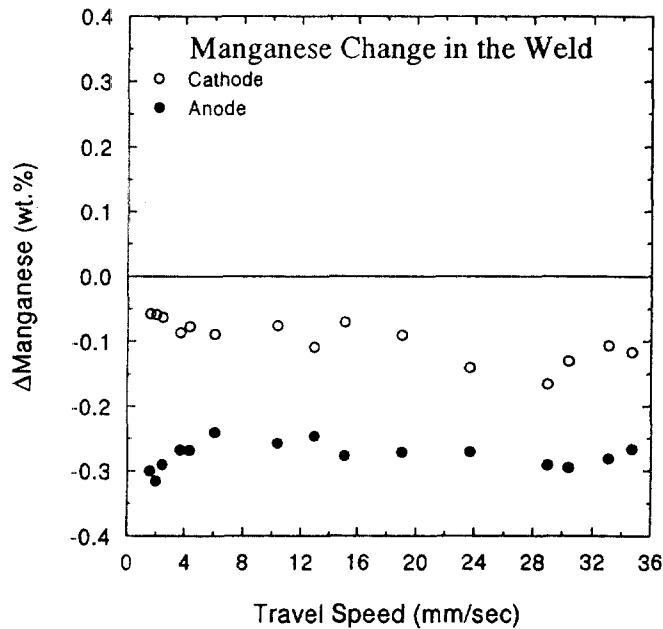


Figure 5 : Changes in Delta Manganese in the Weld Deposits for Electrode-Negative and Electro-Positive Polarity Submerged Arc Welding as a Function of Welding Speed

difference in delta manganese due to polarity shows the effect of electrochemical reactions. That is, the cathode shows a smaller loss than the anode because of the electrochemical reduction reaction at the cathode, and the electrochemical oxidation reaction at the anode.

Figure 6 shows the variations in delta molybdenum due to polarity. Molybdenum changes show the opposite trend as in the melted electrode tip. This behavior of molybdenum is the result of iron losses at the anode and pickup at the cathode as discussed previously. Figure 7 shows the variation in delta chromium and also shows a little electrochemical effect.

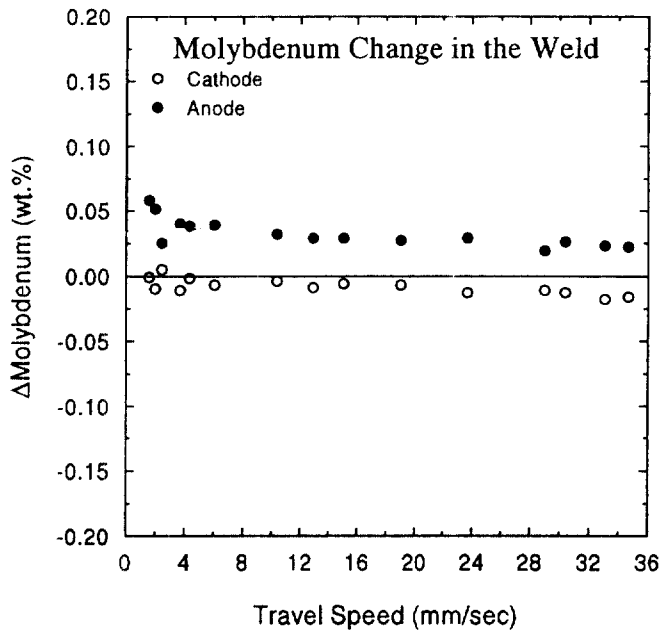


Figure 6 : Changes in Delta Molybdenum in the Weld Deposits for Electrode-Negative and Electrode-Positive Polarity Submerged Arc Welding as a Function of Welding Speed

4. Conclusions

- 1) Electrochemical reactions are significant in direct current submerged arc welding.
- 2) The electrochemical reactions are the oxidation losses of metallic elements at the anode and the reduction of metal ions at the cathode.
- 3) Welding travel speed is the important factor controlling the extent of electrochemical reactions. The extent of both anodic and cathodic electrochemical reactions increases as the welding travel speed decreases, because electrochemical reactions are enhanced by higher total current flow per unit volume of weld metal.

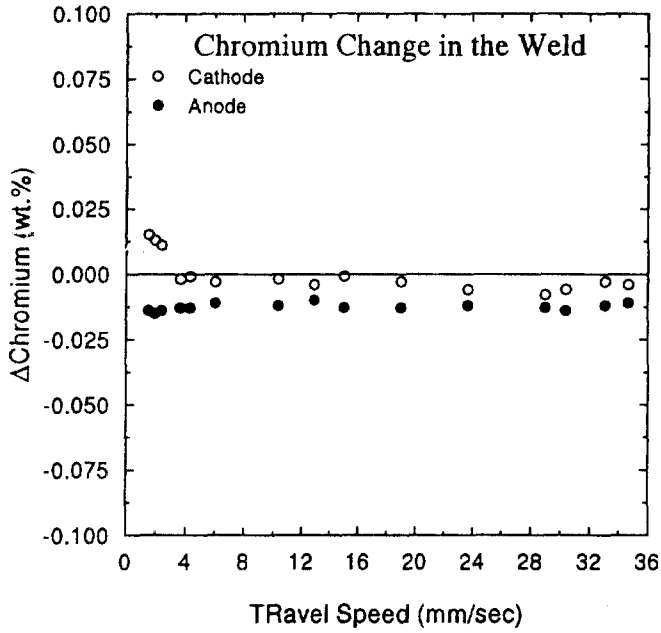


Figure 7 : Changes in Delta Chromium in the Weld Deposits for Electrode-Negative and Electrode-Positive Polarity Submerged Arc Welding as a Function of Welding Speed

- 4) The proper selection of welding consumables and welding process parameters can minimize the adverse effects of electrochemical reactions on the chemistry of the weld metal.

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