

# Electrochemical Oxygen Transfer during Direct Current Arc Welding

*An investigation was conducted on the influence of process parameters on oxygen transfer in submerged arc, shielded metal arc and gas tungsten arc welding*

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**ABSTRACT.** The electrochemical transfer of oxygen was investigated for electrode negative and electrode positive polarities in the submerged arc, shielded metal arc and gas tungsten arc welding processes. Analysis of the welds showed that electrochemical reactions as well as thermochemical reactions are significant in altering the oxygen content of the weld metal. The oxygen transfer in the submerged and shielded metal arc welding processes is strongly influenced by electrochemical reactions at the slag/metal interface, and oxygen transfer in gas tungsten arc welding is strongly influenced by electrochemical reactions at the plasma/metal interface. The electrochemical oxygen reactions at the slag/metal interface include oxygen pickup at the anode and oxygen refining at the cathode. Electrochemical oxygen reactions at the plasma/metal interface include the refining of oxygen at the anode and pickup at the cathode. Electrochemical reactions have the greatest influence on weld metal chemistry at high welding currents and at slow weld travel speeds.

## Introduction

Oxygen control during arc welding has an important influence on weld metal transformations and on the resulting notch toughness (Refs. 1-4). Both slags and/or shielding gases can alter the weld pool oxygen content during welding. Therefore, the mechanisms that control oxygen content during welding should be understood to ensure high-quality welds.

Two types of mechanisms are responsible for the transfer of oxygen during welding (Refs. 5-17). Thermochemical

reactions occur in the molten electrode tip, the separated droplet and the weld pool. They are significant because of the high temperature kinetics and the large thermodynamic driving forces (Refs. 18-20), and they move the composition in the direction of thermochemical equilibrium. Electrochemical reactions occur at the electrode and weld pool surfaces because of the high current densities and ionic conduction of the welding current through the plasma/metal or slag-metal interfaces. These reactions may move the compositions away from thermochemical equilibrium.

The purposes of this investigation are to evaluate the influence of welding process parameters on oxygen transfer in submerged arc, shielded metal arc and gas tungsten arc welding, and to investigate the relative importance of plasma/metal and slag/metal interfaces on weld metal oxygen control.

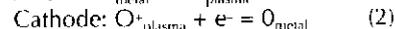
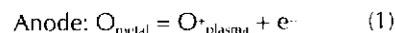
## Electrochemical Reactions

Charge transfer across the slag/metal or plasma/metal interfaces in arc welding processes can be electronic by transfer of electrons or by the electrochemical movement of ions. Electronic conduction is similar for various welding processes. Electrochemical conduction is different

at slag/metal and plasma/metal interfaces because of the differences in the ionization states and in the possible electrochemical reactions.

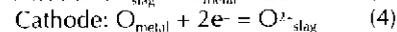
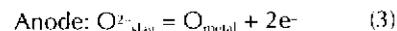
Both positive and negative ions are possible in slags, so electrochemical charge transfer at the slag/metal interface can involve either positive or negative ions. Negatively charged ions have difficulty forming in a welding arc plasma because of the high temperatures. Therefore, singly charged positive ions are the predominant species (Ref. 21). Doubly charged positive ions are possible, but are much less probable than are singly charged ions. The low-negative ion concentrations in the plasma limit electrochemical reactions at the plasma/metal interface to reactions involving positive ions in the plasma (Ref. 21).

The primary electrochemical oxygen reactions at the plasma/metal interface involve  $O^+$  cations in the plasma:



These reactions are expected to result in the removal of oxygen at the anode and the pickup of oxygen at the cathode.

In submerged and shielded metal arc welding, the slag/metal interface should be considered as well as the plasma/metal interface because a portion of the welding current passes through the molten slag layer. Reactions at the slag/metal interface can include both positive and negative ions because both ions are present in the flux. The electrochemical oxygen reactions at the slag/metal interface include the following:



As a result, the anode is expected to show oxygen pickup, and the cathode is expected to show oxygen removal.

## KEY WORDS

DCEN

DCEP

Gas Tungsten Arc Welding

Oxygen Transfer

Shielded Metal Arc Welding

Submerged Arc Welding

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**Table 1 — Ionization Energies of Representative Elements of Interest in Arc Welding**

Element	Ionization Energy (ev)
Al	5.986
Ar	15.759
C	11.260
Ca	6.113
Cr	6.776
Fe	7.87
H	13.598
He	24.587
Mo	7.099
N	14.534
Ni	7.635
O	13.618
Si	8.151

reactions, but most likely at the slag/metal interface. The responsible slag/metal interface reactions are given by Equations 3 and 4.

The electrochemical reactions cease after the molten droplet separates and electrical contact with the electrode tip is lost. Thermochemical reactions, however, continue while the droplet is falling toward the weld pool. Thus, the detached droplets show higher oxygen content than the molten electrode tips. Even though electrochemical reactions do not occur in the detached droplets, the difference in oxygen contents between the anodic and cathodic droplets shows the effect of the prior electrochemical reactions at the electrode tip.

Weld pool reactions can be thought of as happening in two stages: Molten metal reactions occur in the hot weld pool and weld pool reactions occur during cooling and solidification. Both electrochemical and thermochemical reactions occur in the weld pool immediately below the electrode. Electrochemical reactions stop in the portion of the weld pool behind the arc, but thermochemical reactions continue as the weld pool cools and starts to solidify. The thermochemical reactions are characterized by deoxidation reactions and the precipitation on non-metallic inclusions (Ref. 34).

The delta quantity calculations for weld metal analysis utilize the droplet compositions rather than the wire electrode composition as the nominal. This treatment prevents the weld pool reactions from being clouded by reactions at the molten electrode tip or in the detached droplet. The delta quantity, therefore, represents the chemical change caused only by weld pool reactions.

Figure 3 shows the variation of delta oxygen ( $\Delta^{oxy}_{weld}$ ) as a function of travel speed for both DCEN and DCEP polarities. Both the anode and cathode show oxygen losses caused by thermochemi-

cal deoxidation reactions. As the travel speed decreases, the oxygen concentration in the weld metal approaches the thermochemical equilibrium level because of increased reaction time and a larger slag/metal interface contact area for thermochemical reactions.

Based on the variations of oxygen content at the anode and cathode, the relative importance of thermochemical vs. electrochemical reactions on the oxygen transfer can be expected to change as a function of travel speed. At low travel speeds the reaction time and the interfacial contact area between the molten metal and the slag are large, more current is conducted through ionic reactions, and the extent of electrochemical reactions is greater. Oxygen removal at the cathode and oxygen discharge and pickup at the anode produce higher oxygen content (reduced oxygen losses) at the anode than at the cathode. At higher weld travel speeds, the reaction time and the slag metal interfacial contact area are reduced, and thermochemical reactions are more important for chemical modification of the weld metal. The heat input and the extent of thermochemical deoxidation are greater at the anode than at the cathode; thus, the anode shows greater thermochemical oxygen losses than the cathode.

#### Shielded Metal Arc Welding

The shielded metal arc welding experiments investigated reactions at the molten electrode tip and in the weld pool. The experimental results show different trends in oxygen transfer at the anode and cathode as a function of the current and weld travel speed. These differences are the result of electrochemical reactions. The results suggest that the slag/metal interface is as important for electrochemical oxygen transfer in shielded metal arc welding as it is in submerged arc welding.

Figure 4 shows a schematic of the shielded metal arc welding process for DCEP and DCEN polarities. Reactions occur at the electrode tip, in the droplet and in the weld pool. Figure 5 shows the oxygen concentrations as a function of welding current for droplets from anodic and cathodic electrodes. The oxygen contents for droplets of both polarities are shifted above those for the electrodes so that droplets of either polarity show a net oxygen gain. This gain is probably the result of thermochemical oxygen pickup from the atmosphere. Oxygen levels between 500 and 1000 ppm would be found in a partially deoxidized steel heat. Both the anodic and cathodic droplets show the decrease in oxygen concentra-

tion as a function of welding current. This behavior can be explained based on work by Potapov and Lyubavski (Ref. 28) that showed the frequency of droplet transfers increased with increasing welding current. Thus, a decrease in current reduces the droplet transfer frequency and allows more time for the thermochemical pickup of oxygen from the slag and the atmosphere.

The influence of electrochemical reactions at the electrode tip on the oxygen concentration is demonstrated by two experimental observations. First, the oxygen concentrations in anodic droplets are higher than those of the cathodic droplets. This difference is caused by oxygen removal reactions at the cathode and the discharge and pickup of oxygen at the anode. Second, the extent of electrochemical oxygen removal at the cathode and pickup at the anode increases with increasing welding current.

Composition changes in the weld pool were studied using welds produced on copper plates. The use of a copper substrate simplified calculation of the concentration changes (delta quantities) by eliminating dilution by the base metal. The influence of reactions at the electrode were separated from those reactions at the weld pool by using droplet compositions as the starting point for the calculation of chemical changes at the weld pool.

Figure 6 shows the variation in the delta oxygen for anodic and cathodic weld pools as functions of the welding current. Thus, both anodic and cathodic weld pools showed larger decreases in oxygen concentration at higher welding currents. The oxygen decrease for both polarities is the result of thermochemical deoxidation reactions. Higher welding currents increase the heat input, the weld pool temperature and the time for thermochemical reactions before weld solidification. Figure 7 shows the delta composition changes as a function of the weld travel speed. Both anodic and cathodic weld pools showed increased oxygen concentrations with increasing weld travel speed. Thus, the extent of thermochemical oxygen reactions increases with increasing reaction time and heat input.

Figures 6 and 7 illustrate the importance of thermochemical reactions by the fact that both electrodes show the same direction of oxygen change with increasing welding current and weld travel speed. These figures illustrate the influence of electrochemical reactions by the consistent higher oxygen content for the anodes compared to that for the cathodes, even though the oxygen for both electrodes decreases with increasing



