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DOE Research and Development Report

ARC - Weld Pool Interactions

S. S. Glickstein

Bettis Atomic Power Laboratory
West Mifflin, Pennsylvania 15122

August 1978

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EY-76-C-11-0014

Contract No. EY-76-C-11-0014

August 1978

Printed in the United States of America
Available from the
National Technical Information Service
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ARC-WELD POOL INTERACTIONS

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Abstract

The mechanisms involved in arc-weld pool interactions are extremely complex and no complete theory is presently available to describe much of the phenomena observed during welding. For the past several years, experimental and analytical studies have been undertaken at the Bettis Atomic Power Laboratory to increase our basic understanding of the gas tungsten arc welding process. These studies have included experimental spectral analysis of the arc in order to determine arc temperatures, and analytical modeling of the arc and weld puddle. The investigations have been directed toward determining the cause and effects of variations in the energy distribution incident upon the weldment. In addition, the effect of weld puddle distortion on weld penetration was investigated, and experimental and analytical studies of weld process variables have been undertaken to determine the effects of the variables upon weld penetration and configuration. A review of the results and analysis of these studies are presented.

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I. Introduction

Gas Tungsten Arc Welding (GTAW) is a process wherein coalescence of metal is produced by heating the metal with an arc discharge formed between a tungsten electrode and the workpiece. The resultant weld is a product of complex interactions that occur between the electrode, the arc, and the weld pool. A review of the GTAW process was made several years ago by this writer and it was concluded that efforts devoted to improving our understanding of these complex arc-weld pool interactions have found little support in the research and development laboratories in the United States. As a result, a program at the Westinghouse-Bettis Atomic Power Laboratory devoted to fundamental studies of the GTA welding process was initiated. These studies have focused on three major areas of investigation 1) arc physics, 2) weld pool distortion, and 3) heat transfer within the weldment.

While we have tried to analyze each of these areas of concern separately, the interaction between the arc, the weld pool, and the heat transfer mechanisms play a dominant role in the weld process. For example, distortion of the weld pool can affect both the size and shape of the weld. The distortion is a result of arc pressure exerted on the surface of the weldment. This pressure results from a changing arc configuration and is influenced by the thermal and electrical properties of the gas. The properties of the gas are affected by vapor emission from the surface of the weldment. The type, and rate of vapor emission is determined by the temperature of the weld pool which in turn is established by the heat transfer processes within the weldment. In addition, the shape of the electrode has a strong influence on the configuration of the arc discharge. Vapor emission can erode the electrode and thus perturb the shape of the arc.

These feedback mechanisms between the electrode, the arc, and the weldment are extremely complex and have yet to be incorporated into a complete analysis. What has been done at this stage of development is to study the arc, weld pool distortions, and the heat transfer process separately. The objective in each of these studies was to establish the important factors that influence the welding process.

The following sections of this paper briefly review and summarize the results of our investigations in these three areas of concern. Details of the studies can be found in References 1-5.

II. Arc Studies

The size and shape (width/depth) of the weld is strongly dependent upon the magnitude and distribution of the input energy³. Because the welding arc is a principle factor in determining the input energy to the weldment, calculational⁴ and experimental¹⁻³ studies have been initiated to investigate the properties of a typical welding arc.

Calculationally, a one dimensional axisymmetric model of the arc as expressed by the energy conservation equation

$$\sigma E^2 - U = - \frac{1}{r} \frac{dT}{dr} \left(r K \frac{dT}{dr} \right) \quad (1)$$

where

σ = electrical conductivity

K = thermal conductivity

E = electric field strength

U = radiated power per unit volume

r = distance from the axis of the arc

T = temperature

was used to study the radial temperature distribution as it is effected by the temperature dependent thermal and electrical properties of the gas. In particular, helium, argon, and various mixtures of these gases were investigated. The importance of the temperature distribution resides in the fact

that once the temperature distribution is known, the current density j can readily be inferred assuming knowledge of the electric field intensity E . This can be obtained from the following equation:

$$j = -\sigma(T)E \quad (2)$$

From j , the energy distribution $\epsilon(r)$ can be obtained from

$$\epsilon(r) = j(r) \left[V_a + kT + W \right] \quad (3)$$

where

V_a = anode potential drop

kT = thermal energy in plasma

W = anode work function

It should be stressed that a one-dimensional analysis represents the effect in the column region of a long arc. The actual input energy at the arc-weldment boundary is complicated by convection and electromagnetic interactions occurring within the arc. It is these interactions at the weldment boundary that have made the development of the welding arc model extremely complex, difficult, and incomplete. Typical temperature and current density distributions for helium, argon, and argon-helium gas mixtures are shown in Figure 1. Unfortunately, under practical welding conditions the arc contains metal vapors emitted from the weldment during the melting of the workpiece. These vapors interact with the "clean" gas environment. The arc analysis has been extended to include the effects of minor addition of aluminum vapor entering an argon helium discharge. The results shown in Figure 2 reveal a significant perturbation of the radial temperature and current density distributions of a helium discharge when a small addition of aluminum vapor is present. These results are a typical representation of any low range ionization potential element such as Al, Fe, Ni, or Cr, etc. in helium, whose ionization potential is 24.46 eV. For argon whose ionization potential is 15.08 eV, the effect of impurity contamination due to these lower ionization potential elements is less significant.

Also studied experimentally and analytically were shielding gases containing mixtures of argon and helium. The results show that less than 1% addition of argon gas significantly perturbs a pure helium discharge, while small additions of helium to an argon discharge have little effect on the arc configuration. Measurements of the electric field and analysis of the potential drop associated with each gas indicate that the greater energy of a helium welding arc compared to argon can be attributed to a larger anode drop potential in helium relative to argon. This accounts for the so called "hotter" arc of helium and is not due to the higher arc temperature of the helium discharge as is commonly believed.

The electric field and configuration of the arc are also influenced by the shape of the electrode tip in the GTA welding process. Vapor emission from the weldment can interact with the electrode causing erosion of the tip⁶, thus perturbing the arc discharge.

Although these arc studies have emphasized the effects of minor contaminants in the welding gas and their effect on arc configuration, minor elements in the weldment can significantly affect weld penetration through other type interactions that have been discussed elsewhere⁶.

While radiation from the welding arc contributes a negligible amount of energy to the weldment, it is an important factor in the energy conservation equation for an argon arc with temperatures greater than 10 000 K. The analytical studies clearly revealed that radiation losses for a 100 A arc cannot be considered negligible. These losses reduce the peak temperature along the arc axis and broaden the radial temperature distribution, thus influencing the energy distribution.

An important factor controlling the rate of vapor emission into the arc from the surface of the weldment is the heat transfer mechanism within the weldment. In order to understand the important factors that influence heat transfer, calculational and experimental studies were initiated. The results of these investigations are discussed in the next section.

III. Heat Transfer

Variations in the input energy distribution at the surface of the weldment can be attributed to the arc-weld pool interaction such as explained previously in the arc analysis. The consequences of such variations have been studied analytically³ using a heat transfer model and the finite element method for calculating the transient temperature, stress, and distortion resulting from the welding process.

Briefly, the energy input from the welding arc is assumed deposited on the surface of the weldment as a radially symmetric normal distribution function. Heat flow is assumed axisymmetric about the center of the heat source. A unique feature of the model is the inclusion of phase change effects such that latent heat is absorbed during melting and liberated during solidification of the weld metal.

Temperature-dependent specific heat and thermal conductivity are employed, and surface heat losses due to convection and radiation are included in the model. Temperature transients were calculated and compared to experimentally measured values at discrete points on the weldment. Typical results are shown in Figure 3. Such comparisons permit an evaluation of the strength of the heat source Q_0 , and an estimation of the weld process efficiency η given by

$$\eta = \frac{Q_0}{VI}$$

where

Q_0 = strength of heat source

V = welding arc voltage

I = welding current

The analytical and experimental investigation of the welding thermal cycle for stationary gas-tungsten arc welds led to the following conclusions:

1. The welding thermal conduction analysis produces a thermal cycle that is in very good agreement with thermocouple data at locations outside the weld metal and heat-affected zones.
2. Though calculated depth of penetration of the weld was in line with depths measured from metallographic sections, the humped, shallow weld metal configuration observed for stationary test welds could not be reproduced analytically. Introduction of anisotropy of the effective weld pool conductivity, though producing a more shallow weld bead, resulted in bead dimensions that are smaller than the measured values.
3. The nature of the weldment thermal response and the resulting weld bead penetration and shape characteristics were very much dependent on the thickness of the weldment relative to the heat input from the arc. The differentiation between "thin" and "thick" weldment types of thermal response is crucial for proper interpretation of any experimental or analytical welding analysis. When attempting to identify certain characteristics of a welded joint by performing bead-on-plate welds, the thickness of the test weld must be compatible with the actual thickness of the weldment for which the test results are to be applied.
4. The analytical model demonstrated that, for a weld whose depth of penetration is as low as 60% of the thickness, a small increase in current can produce a full-penetration weld.
5. In addition to the magnitude of the heat input from the welding arc, the area over which that heat is distributed on the weldment surface is an additional parameter that strongly influences penetration and weld bead shape characteristics.

6. The finite element welding thermal analysis method is very well suited for determining the interrelationship of heat input magnitude, heat input distribution, duration of the heat input, and weldment geometry on the thermal response. In particular, it can be used for calculating that combination of thermal and geometric parameters that will produce an optimum weld configuration for a given joint.

7. Though the means have been established to specify magnitude and distribution of the heat input from the arc so that an optimum weld metal configuration and weldment thermal response will be obtained, the problem remains as to how these parameters may be controlled by varying specific welding parameters such as current, voltage, electrode shape, arc gap, shielding gas, and insert additives. The previous discussion of the arc studies attempted to direct itself to the effects of various shielding gases and impurities in the arc on just this problem.

As a result of this study on heat transfer within the weldment, it was concluded that heat transfer exclusively by conduction is inadequate to completely characterize thermal conditions in the weld puddle. To accurately predict both depth of penetration and width of the weld metal cross-section, work on weld pool heat transfer, as well as effects of weld pool distortion need to be considered. Distortion of the weld pool is affected by the configuration of the arc. The results of an analytical study which investigated the effects of weld pool distortion on weld penetration is discussed in the next section.

IV. Weld Pool Distortion

The change in the radial current density distribution along the axis of the welding arc coupled with the electromagnetic interaction induces the so called "arc jet". This phenomenon had been discussed and explained in detail by Finkelburg and Maecker⁷ many years ago. The effect of the arc jet is to distort the surface of the weld puddle as shown for example in Figure 4.

An analytical model has been developed by Friedman⁵ using the finite element method of analysis, and considers both heat flow in the weldment and changes in pool shape due to both the arc jet and gravitational forces.

The heat supplied by the arc is conducted through the weldment in its distorted configuration. Under the action of the arc pressure and gravitational forces, the heated surface of the weld puddle in the vicinity of the weld centerline is depressed below its original elevation as shown by the distorted finite element grid in Figure 4. It is this depression that significantly affects the penetration characteristics of the weld. Calculations were carried out in increments of time, so that weld puddle distortion progressed in discrete steps, rather than continuously. The distortion of the molten surface is inhibited by the surface tension existing at the interface between the puddle and atmosphere. In the analytical model, it is simulated by a membrane with uniform isotropic tension. The pressure supplied by the arc to the surface of the weldment is taken to be distributed as a radially symmetric normal distribution function.

The effects of arc pressure and gravity forces on penetration and weld bead dimensions are illustrated by determining the growth of the weld pool with time neglecting pool distortion (i.e., neglecting arc pressure and gravity forces or assuming very large surface tension), and then comparing the results with those obtained using representative pool distortion parameters.

The results plotted in Figure 5 show that the distortion of the pool contributes significantly to the penetration characteristics of the weld - especially when the depth of penetration approaches the weldment thickness. When including the effects of puddle distortion due to arc pressure and

gravity forces, full penetration occurs after 32 s of heating; neglecting pool distortion, full penetration is not yet attained at 40 s.

The maximum arc pressure resulting from electromagnetic forces is proportional to the square of the current. It is thus of interest to determine the effects of arc pressure on the growth and penetration of the weld puddle. (Although an increase in current produces increases in both heat input and arc pressure, only the latter is considered here).

The results are presented in Figure 6, in which the growth of the pool dimensions with time is plotted for a number of values of the maximum arc pressure. Figure 6 also demonstrates that arc pressure significantly influences weld penetration when the puddle penetrates to approximately 60 percent of the weldment thickness. For these penetrations, the depression of the heated surface of the pool is of sufficient magnitude that the rate of further penetration depends strongly on the degree to which the surface is depressed. The effect on bead width (at the heated (top) surface) is less pronounced, since the influence of pool depression on the radial transfer of heat in the weldment is less than on the heat transfer through the thickness.

From this study, the following was concluded:

1. Distortion of the weld pool contributes significantly to the penetration characteristics of the weld, and the propensity of a weld bead to fully penetrate the thickness of the weldment is enhanced by weld pool depression.
2. Arc current influences weld penetration from two standpoints:
 - (a) increased current results in more heat input from the arc to the work-piece, causing more material to be melted; and
 - (b) arc pressure increases

with the square of the arc current, producing a greater degree of pool depression. Application of heat at surfaces beneath the undistorted surface of the weld further enhances penetration. Penetration becomes sensitive to small changes in current when the depth of the pool exceeds 60 percent of the weldment thickness.

3. For partial penetration welds, depression of the top surface of the weld pool varies linearly with arc pressure. When full penetration is achieved, weld bead shape changes are significantly more sensitive to changes in pressure.

4. Both pool depression and weld penetration are strongly dependent on surface tension at the puddle surfaces. The understanding and controlling of surface tension is essential to controlling weld pool shape change, as well as enhancing penetration. But surface tension can be affected by minor elements in the weldment as well as the temperature of the weld pool. Thus, the need for an accurate heat transfer model is again emphasized.

V. Summary and Conclusions

In order to improve our current understanding of the arc-weld pool interactions that occur during the GTAW process, experimental and analytical studies of the welding arc and heat transfer process have been performed. Temperature in arcs and metal vapor emission from the weld pool produced under typical welding conditions were investigated spectroscopically. This information has provided a basis for comparing experimental results with those of a simplified analysis of the arc discharge. The present analysis employs a one-dimensional model of the welding arc that considered heat generation by the Joule effect and heat losses by radiation and conduction. It has been used to study the effects of various gases and gas mixtures currently employed for welding applications. Minor

additions of low ionization potential impurities to these gases have been shown to significantly perturb the electrical properties of the parent gas causing gross changes in the radial temperature distribution of the arc discharge. Such changes are reflected in the current density distribution, input energy distribution of the weldment, and ultimately in weld penetration and configuration.

One of the more important arc-weld pool interactions is the distortions of the weld puddle due to pressure from the weld arc, and inherent changes in weldment heat transfer that accompany such distortion. An analysis of weld pool distortion which treats the effect of arc pressure and surface tension on the pool configuration has recently been completed. The results of this study has significantly contributed to our understanding of how welding parameters influence weld penetration and configuration.

Variations in input energy distribution to the weldment that may occur due to arc perturbations have been input to an analytical model developed for calculating transient temperatures, stresses, and distortions resulting from the welding process. Verification of the thermo-mechanical analysis has been achieved through experimental studies. An in-depth analytical investigation has also been performed to study the effects of varying a number of welding parameters on the thermal response of the weldment.

While each of these studies have been treated separately, it has been stressed repeatedly that the interaction between the arc, the surface of the pool, and the heat transfer mechanisms are intertwined such that each study is strongly influenced by the other. In addition, the important role of weld pool motion has been omitted at this stage of development. It too must be considered as a major parameter in establishing the

the solidification pattern of the weld pool. In the future, more effort must also be directed toward incorporating into the analysis the complex feedback mechanisms that have been discussed in this paper.

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Figure 1 - Radial Temperature and Current Density Distributions for Pure Helium and Argon Arcs. $I = 100$ amps
a) Temperature Distribution b) Current Density Distribution

Figure 2 - Radial Temperature and Current Density Distributions for Various Mixtures of Aluminum and Helium Gas.
a) Temperature Distribution b) Current Density Distribution

Figure 3 - Comparison Between Calculated and Experimental Transient Temperature Response at Four Thermocouple Positions $I = 90A$, $V_a = 7.7$, V Arc Gap = 0.76 mm
Weld Time = $10s$, $Q_o = 530 \text{ W}$, $r = 3.81 \text{ mm}$

Figure 4 - Weld Bead Distortion As Depicted By Deformed Finite Element Mesh

Figure 5 - Effect of Pool Distortion on Pool Dimensions.
Pressure = 1000 Pa.

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Figure 6 - Effect of Arc Pressure On Pool Dimensions