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FUNDAMENTAL MECHANISMS OF PENETRATION
IN GTA WELDING

A general, qualitative understanding of the phenomena that determine penetration in GTA welding is developed.

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Abstract

Continued study of arc properties using emission spectroscopy coupled with computer simulation of the heat flow in welds has led to an understanding of the phenomena that control weld fusion zone shape. It was found that the liquid metal flow patterns in the weld pool are of prime importance and that arc current density characteristics and base metal properties have only indirect influence. The mode of interaction between the arc and weld pool flow is presented in qualitative terms.

Introduction

During the course of investigating a problem encountered in making deep penetration GTA welds in high manganese stainless steel (21Cr-6Ni-9Mn), it was discovered that the determinative effects occurred in the weld pool rather than the arc. The details of this work were reported previously (1) but the highlights are repeated here for completeness.

Emission spectroscopy was used to measure temperature profiles in the arc plasma immediately above the weld pool (manganese vapor dominated) for identical arc parameters and different heats of steel. These measured profiles were then simulated by a computer solution to the radiation equations using assumed radial temperature and vapor density distributions. The results of these measurements and calculations showed that the temperature distributions (current density distributions) were essentially the same even though the depth-to-width ratios (D/W) of the fusion zones in the different heats of steel varied by a factor of 1.8. Since there were no definitive variations in heat flow within the arc which related to the changes in D/W, the differences had to occur within the weld pool. In fact, different patterns of heat and material flow within the weld pools were clearly implied by the data analysis.

Two questions resulted from this work: Do weld pool effects dominate over arc character in all GTA welding? What exactly, is the mechanism by which the pool controls weld penetration?

In order to answer the first question, another fusion zone shape effect in arc welding was explored. Typically, helium is added to argon shielding gas to obtain an increased in weld penetration without the increase in weld width usually obtained with an increase in weld current. The resultant increase in fusion zone volume implies an increase in the energy of electrons striking the work piece so the change in arc anode voltage (not the same as total arc voltage) was relevant to understanding this phenomenon. The change in D/W implies a change in arc current density distribution and/or weld pool flow, making measurement of these quantities important in answering both questions.

The results of experiments and further computer modeling carried out in comparing pure argon arcs with helium-argon arcs are presented in the following. Conclusions concerning the general importance of weld pool effects and the mechanism by which they interact with the arc to control fusion zone shape are also given.

Results and Discussion

Current density distribution measurements were made, using the intensity-maximum method (2), on 100% Ar arcs and 50%He-50%Ar arcs. The values of full width at half maximum (FWHM) taken from these current density distributions are shown in Table I. In spite of the scatter inherent in such data, the current density distribution for the 50/50 mixture is clearly broader than for the pure Ar case. Further qualitative measurements

of current density distributions in arcs with 75%He-25%Ar and 100%He shielding gas showed even more drastic broadening which serves to confirm the fact that increased helium spreads the heat input to the work piece rather than concentrating it. This effect is quite logical in view of the large thermal conductivity of helium, relative to argon, which enhances heat transport transverse to the arc axis. The effect of helium on current density is contradictory to the observed weld shape changes and suggests, again, that fusion zone shape is influenced more by the weld pool than the arc. (Measurements of relative current density versus arc length and total current exhibited the trends expected from arc theory and served to confirm the dependability of the measurement technique).

To get a more comprehensive base of information on GTA welding response to parameter changes, an extended series of welds was made on rotating stainless steel bars using a representative range of arc length, current and gas mixture values (see Table II). The welds were sectioned (90° , 180° , 270° after the start) and photomicrographs made to simplify measurement of fusion zone area and width. These data together with the arc current density data yielded a general, qualitative picture of the effects of weld parameters on weld geometry. However, the variety of distinct quantitative parameter-effect relationships derived from the data suggested that a general understanding of the GTA welding process was not yet in hand.

As an aid to unraveling the complexities of this purely experimental effort, a computer simulation was employed. A finite element solution to the heat

flow equations was programmed to duplicate the fusion zone areas and widths of the various experimental welds. The parameters adjusted to obtain the various area-width combinations were: total input energy per unit length of weld and width (transverse to the weld path) over which energy was supplied to the surface of the simulated rotating bar. The calculated input energy for each weld was divided by the total arc current to yield an "effective" anode voltage and the widths were compared on a relative basis to the FWHM of the corresponding arc current density distributions.

Compilation of these data revealed that the heat input widths determined from the calculations do not correlate with the experimental values of current density FWHM. Furthermore, the larger values of D/W cannot be accounted for by diffusive heat conduction alone and the anode voltage varies with shielding gas mixture only (independent of arc length and current). The first point is seen from Table III by noting that the Energy Input Widths vary irregularly with increasing current while the Current Density FWHM increases linearly with current. The second point is evident from Table III as well, in that an Energy Input Width of zero or less would be required to get the largest experimental value of D/W . The third point is illustrated in Figure 1 by the fact that the voltages do not show any consistent trend with respect to arc length or current (to within the scatter of the data and the influence of secondary heat sources such as radiation and heat conduction in the gas). Further, Figure 2 illustrates a statistically significant change in voltage versus gas mixture when the values for all currents and arc lengths are pooled

for each gas mixture.

While the third point is important to the general understanding of arc behavior, the first two points make it clear that weld pool effects are of primary importance in determining fusion zone shape and the arc current density distribution has, at most, a secondary effect.

Having confirmed that the behavior of the weld pool has primary influence on weld shape in the case of varying arc parameters as well as the case of varying material properties (ref. 1), the details of the mechanism and its interaction with the arc were sought. The mechanism which fit all of the welding results obtained to date was "inverted convection" driven by the flow of weld current through the liquid metal. Current flowing into the weld pool exerts a (Lorentz) force distribution on liquid metal which is the analog of the force exerted by the acceleration of gravity acting on a thermally induced density gradient in a fluid (normal convection). Under proper conditions, this force on the weld pool will induce a circulation of metal downward at the center and radially inward at the surface with outward flow at the bottom completing a stable convection cell (Figure 3). The flow of metal carries heat to the perimeter of the pool and produces a relatively broad, shallow weld.

With such a convection analogy in mind, the effects of the arc current density distribution can be understood. If the distribution is narrow (argon arc) rather than broad (helium-argon arc), convection is more

likely; just as in heating a beaker of water with a constricted (Figure 4) rather than broad (Figure 5) heat source. In the case of a welding arc, another phenomenon enters which explains the exceptionally deep, narrow fusion zones. Instead of a strong transverse flow developing as above, a predominantly front-to-back flow can occur in which heat is carried down by the metal flow at the arc center but is held near the weld centerline as the metal flows backward and then to the surface at the rear of the weld pool (Figure 6). This flow will develop if the transverse flow is suppressed by a broad current density distribution or surface forces which restrain spreading of the liquid metal.

Flow patterns such as these have been suggested, simulated and (in the second case) observed by others (3-7) but a clear, direct observation of the vertical, convective cell in a weld pool seems usually to be masked by single or double swirling flows in the horizontal plane. During the course of this present research, indirect evidence of vertical convective flow, possibly superimposed on the swirling flow, and the front-to-back flow has been obtained in the case of the high manganese stainless steels dealt with earlier. The surfaces of weld pools were observed with a video camera (and recorder) through a narrow band optical filter which singles out manganese characteristic emission light whose intensity depends on plasma temperature and manganese vapor density. The physical set up of camera, torch and rotating bar is shown in Figure 7. For welds of intermediate to poor D/W, a ring of light concentric with the arc center appeared (Figure 8). For welds of high D/W, a plume of light was

emitted behind the arc center and there was no ring (Figure 9). These areas of enhanced light emission result from local increases in manganese vapor density (1) caused by the surfacing of manganese-rich metal. The ring of light suggests the strong convective flow which spreads heat transversely and gives a weld of low D/W; the plume behind the arc center corresponds to the front-to-back flow that increases the D/W over that expected on the basis of thermal diffusion alone.

Summary and Conclusions

The measurements of current density distributions and fusion zone geometries with the aid of computer modeling, have shown that:

1. An increase in arc current causes an increase in the half-width of the current density distribution such that current density remains very nearly constant with no change in anode voltage drop.
2. An increase in arc length causes very little if any change in current density distribution or anode voltage drop but there are changes in second order heating effects which can affect D/W in certain cases.
3. An increase of helium in the argon shielding gas causes an increase in anode voltage drop and an increase in the half-width of the current density distribution such that current density is reduced. (Increasing the electrode tip angle has a similar but weaker effect on current density).

Computer modeling of the weld process to duplicate experimental fusion zone geometries and experimental data have shown that:

4. Fusion zone shape is primarily dependent on flow patterns of the liquid metal in the weld pool.

5. The current density distribution in the arc has a secondary effect in that a decrease in current density (increase in distribution width without a compensating increase in total current) reduces the tendency toward transverse metal flow in the weld pool.
6. Two key patterns of metal flow have been identified; one reduced D/W and the other (front-to-back) increases D/W.

It is concluded that a general, qualitative understanding of the arc welding process is now in hand. The question of whether arc or weld pool effects are most important in determining fusion zone shape is resolved in favor of the latter. However, data in the welding literature indicating that fusion zone shape is affected by arc or material differences are accounted for by the fact that these differences determine which metal flow patterns develop in the weld pools. This understanding does not explain the details of the delicate balance between competing effects in every GTA weld but serves as a basis for dealing with penetration problems in specific GTA welding processes without having to study the whole arc welding problem whenever a new situation arises.

References:

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TABLE I
 FULL WIDTH AT HALF MAXIMUM
 OF
 CURRENT DENSITY DISTRIBUTION
 100 amp Arcs on Cooled Copper Anode

Shielding Gas:	100% Ar	50%Ar-50%He
	10.1	11.9
	10.9	12.7
	9.8	11.6
	10.0	12.3
		13.3
		11.8
Average:	10.2	12.3
Standard Deviation:	0.5	0.6

TABLE II

ARC PARAMETERS

FOR

EXTENDED WELD SERIES*

Current (Amps)	Arc Length (mm)	Gas Mixture (20cfh total)
100	1.5	100%Ar
125	2.0	50%Ar-50%He
150	2.5	25%Ar-75%He
175		

*Thirty-seven welds using most of the possible combinations were made, including some repetitions.

TABLE III

TYPICAL RESULTS OF WELD SIMULATION

AND

COMPARISON WITH EXPERIMENTAL DATA

1.5mm Arc Length, 100% Argon Shielding Gas

Current (amps)	Current Density FWHM	Fusion Zone Area (cm ²)	Depth/Width (exp.)	Depth/Width (calculated)	Energy Input (Watts)	Energy Input Width (cm)
100	72	0.28	0.62	0.62	230	0.27
125	80	0.49	0.65	0.65	288	0.33
150	88	0.64	0.55	0.56	339	0.50

1.5mm Arc Length, 50%Ar-50%He Shielding Gas

100	80	0.40	0.60	0.60	266	0.35
125	88	0.64	0.68	0.70	332	0.30
150	96	0.82	0.68	0.68	380	0.37

1.5mm Arc Length, 25%Ar-75%He Shielding Gas

100	100	0.46	0.62	0.62	285	0.35
125	108	0.71	0.79	0.79	336	<0.10
150	117	0.92	0.85	0.80	394	≈ 0

Figure Captions

Figure 1 - Anode voltage drop versus arc current for three different shielding gas mixtures (20cfh total) and three different arc lengths: Solid line - 1.5mm, Dashed line - 2.0mm, Dotted line - 2.5mm.

Figure 2 - Anode voltage drop versus percent of argon (mixed with He for a total of 20cfh) for all currents and arc lengths used with each mixture. The error bars include the standard deviation plus the scatter for each mixture shown in Figure 1.

Figure 3 - Schematic of the current flow (solid lines) and liquid metal flow (dashed lines) as seen in a transverse (perpendicular to the welding direction) section of a convecting weld pool. Reduces weld penetration.

Figure 4 - Illustration of the convective flow which results from a constricted heat input to a beaker of water and the analogous welding situation. Note that the ink rises above the heat source in a well defined column and sinks outside the diameter of the copper heat conductor.

Figure 5 - Illustration of the absence of convection in the case of a broad heat source and the analogous welding situation. Note that there is only random stirring of the ink and no overall circulation.

Figure 6 - Schematic of the current flow (solid lines) and liquid metal flow (dashed lines) as seen in a longitudinal section of a weld pool exhibiting front-to-back flow. Enhances weld penetration.

Figure 7 - Schematic of the video camera and weld setup used to make the manganese characteristic emission light images shown in Figures 8 and 9.

Figure 8 - Photograph of a single video frame from a recording of manganese characteristic light emission above the weld pool of a 100 amp arc on low D/W stainless steel. The electrode tip is visible at the top and the leading edge of the weld pool is visible at the bottom. The black dot is a reference mark on the vidicon face used in obtaining quantitative data.

Figure 9 - Photographs of two video frames from a recording of manganese characteristic light emission above the weld pool of a 100 amp arc on high D/W stainless steel. The two views indicate the extent of random oscillation from side to side of the plume as it trails out horizontally over the back of the weld pool.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9