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On line sensing of weld penetration using infrared thermography

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Abstract

The objective of this research is to apply new sensing techniques, artificial intelligence, and robotics to improve the welding process through control of penetration depth and width parameters. By producing a constant depth and width of penetration through on line control, the quality and strength of welds may be improved to a new level of reliability previously unobtainable.

Experimental data presented in this paper indicate that depth and width of penetration can be monitored by infrared thermography and hence controlled dynamically during the weld process. Infrared thermography is used to monitor surface temperature distributions in the vicinity of the molten metal pool. Characteristics of temperature distributions perpendicular to the direction of arc travel are analyzed and correlated with weld bead width and depth as measured by destructive examination after the weld production. The results show that there is a linear relationship between peak weld plate surface temperature and depth of penetration. Additionally, surface puddle width is found to be directly correlated to measured distance separating solidus temperatures of the molten metal as measured by infrared thermography.

Introduction

Automatic welding is commonplace in industry today. However, most, if not all commercial systems rely entirely on preprogramming for performance of repetitive tasks. A reasonable automatic welding control system should be able to detect variations in the welding process which lead to impending defects. Once detected, variations could be corrected by proper controlled responses previously programmed into the system.¹ However, the large number and varied nature of the parameters affecting the welding process have thwarted previous attempts at closed loop control.

One of the main inadequacies leading to difficulties in developing an adaptive welding system is the lack of suitable sensors for dynamically monitoring the welding process. These sensors must be able to identify and discriminate between perturbations that might affect the quality of the weld. Such perturbations might result from fixturing and part tolerance fluctuations such as deviation of the seam from the preprogrammed path, gaps in the seam, and misalignment of the parts being welded. Secondly it would be ideal for the sensor to be able to locate and identify contaminants both in the molten pool and ahead of it. Thirdly the welding process would be greatly improved if the sensors were able to monitor what is happening in the plate thickness dimension as required for weld penetration and heat affected zone control.

Previously reported results²⁻⁶ have demonstrated that infrared sensors may provide the needed information to control the first two types of weld process perturbations listed above. This paper presents research into the third and most difficult type of information that is desirable, control of penetration depth and width. Experimental results indicate that this control may be achieved through monitoring characteristics of front side plate temperature distributions as measured by infrared thermography.

Experimental procedures

Two series of experiments were conducted using Gas Metal Arc (GMA) and Gas Tungsten Arc (GTA) welding processes. All experiments were conducted using 153 x 153 mm (6 x 6 in) plain carbon steel plates (AISI 1040) ranging in thickness from 5 to 8 mm (3/16 to 5/16 in). All welds were butt welds produced in the flat position under carefully controlled and monitored conditions. Plate edges were milled for a precise fit and standard procedures were used to prepare the plate surfaces near the region of the weld.

A model ESAB LAH 315P and a model Miller Syncrowave 500 AC/DC power source were used with a water-cooled torch. The torch was mounted to a Heath Engineering Co. ESAB X-Y positioning table (Model ICD/600-MODFD) which is controlled by a Hewlett Packard 9836 computer with associated acquisition and control interfaces. The current was measured using a Columbia Electric Mfg. Co. tong test (Model AX) clamp on ammeter with a scale 0-200 amperes.

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For gas metal arc butt welds, the electrodes were 0.9 and 1.2 mm (0.035 and 0.045 in) diameter - ER7053 filler metal wire. These welds were produced using direct current, reverse polarity (DCRP). Shielding gas was argon 2% oxygen with a 1.4 liters/min (30 cfh) flow rate.

The gas tungsten arc butt welds were made using 2% thoriated tungsten electrodes. The electrodes were 10 mm (3/8 in) in diameter and the welds were produced using direct current, straight polarity (DCSP). Shielding gas was argon at a flow rate of 0.94 liters/min (20 cfh).

An Inframetrics Model 525 infrared scanning camera was used in all experiments. The camera unit converts the invisible, infrared radiation given off by a hot object into equivalent voltage signals which represent the surface temperature distribution. The signals are then amplified and transferred via interconnecting cables to the display unit.

The infrared sensitive detector consists of a mercury, cadmium, telluride (HgCdTe) photovoltaic cell, sensitive in the spectral range of 8 to 12 μm . Signals from the camera unit are used to modulate the intensity of the electron beam of the TV-monitor. Synchronism of the camera scanning optics and TV-monitor is controlled by trigger pulses arriving from the camera unit. Colors or a graduated grey scale are produced on the display screen by assigning different colors or greys to different voltages. In this manner a thermal picture of the object being scanned, consisting of a matrix of 100 x 100 discrete temperature points, is obtained.

Fig. 1. Schematic of thermal line profile generated by infrared camera showing height and width parameters.

Fig. 2. Schematic of weld cross-section showing depth of penetration and bead width measurements.

The thermal picture can be represented by a series of line scans or thermal profiles, Figure 1, in which the height of each scan line (y axis) is directly related to the temperature and the x axis to distance. Any one of these line scans can be chosen corresponding to a region of weld puddle. As the heat input increases, the depth of penetration will increase and the height of the line scan will increase due to an increase in peak surface temperature. From this information it appears that surface thermograms can be used to monitor and control the penetration through the use of appropriate control algorithms.

For both GMA and GTA experiments, the infrared scanner was positioned in a fixed location in front of the welding torch. All thermal images were recorded and stored on a Panasonic Video Cassette Recorder for further analysis. The thermograms were then photographed using a 35 mm camera after welding was completed.

Measurements of penetration depth and width were made by destructive examination of welds. Standard metallographic sectioning and polishing techniques were employed. Molten puddle-solid metal interfaces and heat affected zone interfaces were revealed using a 5%

Nital etch for 10 seconds. All depth and width of penetration and heat affected zone values in this report are the average of six measurements. Figure 2 shows a schematic of weld crosssection showing penetration depth and width measurements.

Fig. 3a. Two dimensional thermal image of plate surfaces showing a symmetrical temperature distribution. Arc placed directly on the seam.

Fig. 3b. Temperature versus distance scan through the center of the thermogram image shown in Figure 3a. Inflections point the weld puddle boundary.

Experimental results

The two dimensional plate surface temperature distribution that is produced during GMA welding is shown in Figure 3. Figure 3a is the corresponding two dimensional temperature scan through a region of the weld undergoing dynamic spray transfer. The color bar at the bottom of the photograph shows the color assignment to regions of temperature ranging from blue (coolest temperature) to white (hottest temperature). Photograph 3b is a thermal profile in which temperature distribution is plotted versus distance across the center of the thermal image of Figure 3a. The distribution is symmetrical, indicating positioning of the arc over the seam center. From this profile, one can also determine the peak temperature and average diameter of the molten metal pool. The inflections around the peak represent the isothermal band of the molten metal-solid metal interface (and/or the emissivity variations associated with the phase transformation). A tabular summary of the experimental results obtained in both the GMA and GTA experiments are given in Tables 1 and 2, respectively.

Table 1. Summary of GMA Welding Experimental Results

No.	Welding Parameter		Penetration (mm)		IR Thermovision (mm)		Heat Input	
	Current(A)	Voltage(V)	Width	Depth	Width	Height	KJ/mm	KJ/in
M.01	130	22	8.6	1.27	7.5	38.1	0.843	21.4
M.02	150	24	11.2	1.52	10.2	40.6	1.061	27.0
M.03	170	25	13.3	2.0	11.4	45.7	1.253	31.8
M.04	180	26	14.2	2.2	12.3	47.0	1.380	35.1
M.05	200	28	18.0	2.4	17.0	49.5	1.651	42.0
M.06	220	30	19.4	2.9	18.5	54.6	1.946	49.5

Material: Plain Carbon Steel

Plate thickness: 6 mm

Wire diameter: 1.2 mm

Stick out: 15 mm

Welding speed: 3.39 mm/S; 203.2 mm/min

Wire speed: 7620 mm/min

Gas flow: 30 cfm

M.01-M.04: Dip transfer

M.05-M.06: Spray transfer

Table 2. Summary of GTA Welding Experimental Results

No.	Parameter		Penetration (mm)		IR Thermovision (mm)		HAZ (mm)		Heat Input	
	Current(A)	Voltage(V)	Width	Depth	Width	Height	Width	Depth	KJ/mm	KJ/in
T.01	80	11	4.7	1.37	8.9	44.2	7.6	2.8	0.415	10.5
T.02	110	12	5.8	2.0	9.7	44.7	9.6	4.1	0.623	15.8
T.03	140	12.5	6.6	2.8	10.0	45.2	11.2	6.4	0.825	21.0
T.04	170	12.5	7.6	4.1	10.4	45.7	12.1	6.6	1.002	25.5
T.05	210	13	11.1	5.1	16.0	47.0	17.8	8.0	1.288	32.7
T.06	240	16	11.6	7.6	18.6	47.5	19.9	8.0	1.811	46.0

Material: Plain Carbon Steel

Plate thickness: 8 mm

Electrode diameter: 10 mm

Stick out: 10 mm

Welding speed: 2.12 mm/S

Gas flow: 20 cfh

Fig. 4a. Penetration depth and bead width as a function of heat input. Heat input: 0.843 kJ/mm.

Fig. 4b. Penetration depth and bead width as a function of heat input. Heat input: 1.061 kJ/mm.

Fig. 4c. Penetration depth and bead width as a function of heat input. Heat input: 1.253 kJ/mm.

Fig. 4d. Penetration depth and bead width as a function of heat input. Heat input: 1.380 kJ/mm.

Fig. 4e. Penetration depth and bead width as a function of heat input. Heat input: 1.651 kJ/mm.

Fig. 4f. Penetration depth and bead width as a function of heat input. Heat input: 1.946 kJ/mm.

Figure 4 is a set of thermal line scans produced during GMA experiments. These photographs show that with increasing heat input, the peak plate temperature increases (height increases) and width of the thermal profile increases too. Figure 5 graphically displays data taken from the line scans of Figure 4. In this figure, the relationship between peak temperature (heights of infrared line scan) and heat input is shown. A linear relationship exists in which the measured peak temperatures on the surface increases as the heat input is increased. This data was taken over a range of welding parameters in which the metal transfer process transcended both the dip and spray transfer modes and covered welding penetration depth ranging from 20 to 50%.

Figure 6 graphically displays measured peak surface temperature and depth of penetration. As shown, a linear relationship exists over the range of experimental data. This indicates infrared thermography may be ideal for penetration control in GMA welding applications.

Fig. 5. Height of IR line scan versus heat input: GMA welding.

Fig. 6. Height of IR line scan versus penetration depth: GMA welding.

As indicated in the description of Figure 3 above, the infrared line scan can also be used to provide information on weld bead width. Figure 7 is a plot of infrared line scan width versus measured GMA surface bead width and heat affected zone width. Measured width of the infrared image was taken at the inflection position of each line scan photograph of Figure 3. Again, over the range of experimental data, a linear relationship exists.

The results displayed in Figure 6 and 7 demonstrates that infrared thermography can be used to control both weld penetration and width over the range of parameters investigated in GMA experiments. Similar experiments were conducted using GTA equipment. Figures 8 and 9 are the corresponding peak surface temperature versus penetration depth and infrared image width versus weld bead width for GTA produced welds. The results are very similar to those obtained in GMA, showing a linear relationship between infrared image parameters and penetration depth and width over the range of the experimental data.

One difference was noted between GTA and GMA results. The change in measured peak surface temperature in GTA experiments for corresponding changes in penetration depth was much less, i.e., the slope of the peak temperature versus penetration depth curve is smaller. This indicates that infrared sensing techniques may be more applicable to controlling GMA penetration than GTA weld penetration.

Fig. 7. Width of IR line scan versus bead width: GMA welding.

Fig. 8. Penetration and HAZ depth versus IR height: GTA welding.

Fig. 9. Bead and HAZ width versus IR width: GTA welding.

Discussion

As should be noted in the tables relative height and width of the thermal line scan taken perpendicular to the welding direction was used to produce the correlation between penetration depth and peak surface temperatures. This method avoids calibration of the infrared sensors to absolute temperatures by using relative differences (between room temperature and peak surface temperature) to monitor the depth of penetration. In actual algorithms being developed to control penetration, the peak infrared temperature would be measured in terms of voltage rather than in terms of distance. Similarly width control would be completed by measurement of a voltage difference between two temperatures which would correspond to a distance on the welded plates.

Although the research which has been presented in this paper indicates that infrared thermography may be very useful in monitoring the penetration parameters of the welding process, there are many experiments that are yet to be completed. Experiments which extend the data to penetration depths of 100% are in progress for both GTA and GMA welding processes. Experiments have also been initiated to change the depth of penetration while keeping the bead width constant. This is being accomplished by altering the gas composition to promote a greater depth of heat transfer.

Conclusions

Infrared thermography can be used to monitor plate surface temperature distributions during both dip and spray metal transfer of the GMA welding process. GMA temperature distributions are similar to those previously reported in GTA welding experiments.

A linear relationship exists between measured peak surface temperature and depth of penetration during GMA and GTA welding.

A linear relationship exists between measured infrared image width and weld bead width during GMA and GTA welding.

The change in peak surface temperature and infrared image width for corresponding depth and width of penetration changes is much greater for GMA than GTA welding. This indicates a greater sensitivity of penetration control of the GMA welding process is possible using infrared thermography.

The above conclusions suggest that infrared thermography may be an ideal sensor for penetration control in adaptive welding systems.

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