Monitoring of Weld Joint Penetration Based on Weld Pool Geometrical Appearance

The geometrical appearance of the weld pool contains sufficient information to determine full joint penetration in GTAW

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ABSTRACT. Weld joint penetration monitoring and control are fundamental issues in automated welding. A skilled human operator can determine the weld penetration from the geometrical appearance of the weld pool. To emulate this using machine vision, a high-shutter-speed camera assisted with pulsed laser illumination is used to capture the clear image of the weld pool. The pool boundary is extracted by the developed real-time image processing algorithm. In order to emphasize the emulation of the human operator, general terms, i.e., size, shape and geometrical appearance, are used for the conceptual discussion, whereas more specific terms such as length, width, and rear angles are used in the detailed analysis. In particular, the size will be specified by the pool width and length, and the shape will be defined using the proposed rear angle of the weld pool. The geometrical appearance is described by a combination of the size and shape parameters. To investigate the relationships, which could be complicated, between the weld penetration and different parameters, neural networks are used because of their capability for modeling complicated nonlinear functions. Extensive experiments have been developed to measure the weld penetration from the captured image in 200 ms using the neural network and real-time image processing.

Introduction

The sensing of weld joint penetration is a fundamental issue in automated welding. The concern is the measurement of the root surface (backside) bead width and depth of penetration in the full and partial penetration modes, respectively. In principle, these parameters can be monitored by embedding thermocouples into the weldment or by acoustic emission sensing (Refs. 1, 2). However, their practical applications are limited because of the contact between the sensors and the workpiece. In the case of full joint penetration, the root face width can be detected by measuring the light intensity from the backside (Refs. 3-5). However, it is difficult or impossible to conveniently locate backside sensors for many configurations, for instance, during the welding of pressure containers. Also, the motion match between the torch and sensor could be difficult if the torch moves. Hence, the sensor should be attached to and move with the torch to conduct the so-called topside sensing of the weld joint penetration. In this study, topside sensing is addressed.

Among the many proposed topside sensing techniques, pool oscillation methods have been extensively studied. The pioneering work was done by Richardson (Ref. 6), Hardt (Ref. 7), and their coworkers. Wang et al., found that for full penetration, the width of the stationary weld pool can be determined by the resonance frequency (Ref. 8). An interesting discovery was the distinction between the partial joint penetration and full joint penetration frequencies. Xiao and Oudén (Refs. 9, 10) found that a drop in the oscillation frequency occurs as the penetration state changes from partially penetrated to sufficiently penetrated. This frequency drop has also been observed by Richardson and Yoo (Ref. 11). For the measurement of the pool oscillation, both arc voltage and arc light fluctuations have been used (Refs. 6, 12).

Ultrasonic testing has become a standard technique for locating cracks, incomplete fusion, porosity and other discontinuities in fusion welds (Ref. 13). For a single point range measurement, the problem is to measure the transit time for a single ultrasound pulse to travel to and from the reflector, which is a discontinuity in material property. Theoretically, if the dimension of the reflector (for instance, crack, porosity, etc.) is larger than the wavelength of the incident ultrasound pulse, the reflected pulse contains information concerning the size and shape of whatever caused the reflection. Since the weld pool constitutes a change in phase and in material properties rela-
tive to the unmolten weldment, its shape and size may be measured through its re-

ected ultrasound. Hardt and Katz (Ref. 13) utilized reflection ultrasound meth-

do's to measure the size of the stationary weld pool. In their investigation, a sim-

ified weldment geometry (a cylindrical rod) combined with a ray optics wave

alysis was used. The propagation of the ultrasound in this cylindrical rod was

studied. The results showed good agreement between the measurements per-

formed on the cylindrical rods and the geometric optics prediction. Ultrasonic

measurements of the weld pool were extensively studied at the Idaho National

Engineering Laboratory (Refs. 14, 15). Different geometries of welds were dis-

tinguished (Ref. 15). Contact transducers were used. When the ultrasound was

generated by a pulsed Nd:YAG laser, the contact transducer could be eliminated

(Ref. 16). However, several new problems, including the surface damage, were

casted (Ref. 17). For the post measure-

ment of the depth of the weld pool, excellent results have been acquired by

using laser phased array technology (Ref. 17).

Modern infrared thermog-

raph equipment provides a feasible

means to measure the temperature field. At Auburn University, the in-

frared sensing of arc welding processes has been extensively inves-

tigated by Chin and cowork-

ers (Refs. 18-20). The temperature
distribution is measured in gas metal

arc welding (Ref. 20). It was found that

the depth of joint penetration can be de-

termined using the characteristics of the
temperature profiles. Beardsley, et al.,

found that the root surface bead width of

the full joint penetration welds can be de-
termined in gas tungsten arc welding

using the pool area and a ratio between

a surrounding area (600°C isotherm area)
of the weld pool and the weld pool area

(Ref. 21).

Despite the above achievements in

the topside sensing of weld joint pene-

tration, more accurate information can

still be expected from the weld pool it-

self. It is known that the weld pool con-

tains abundant information on the weld-

ing process. By viewing the weld pool, a

skilled operator can estimate the weld

joint penetration. However, detailed

studies should be done to verify that the

weld pool does contain sufficient infor-

mation on the weld penetration. If this is

ture, an approach may be developed to

measure the weld penetration using the

parameters of the weld pool.

The weld pool has been coaxially

viewed by Richardson, et al. (Ref. 22).

The principle behind this technology is

that the reflection of the arc light from the

mirror-like pool surface is primarily spec-

ular. The diffuse reflection of the arc light

is weaker from the weld pool than it is

from the surrounding area. The weld

pool is therefore expected to produce a
dark area in the image, whereas the solid
area should appear bright. This does in

fact occur, however, the intensity con-

trast between the pool and the surround-

ing area is not very pronounced, due to

the radiation from the pool.

In this study, a high shutter speed

camera assisted with a pulsed laser (Ref.

23) is used. Clear images of the weld pool

are captured. The pool boundary is ex-

tracted in real-time using the developed

image processing algorithm. The rear

angle is proposed to describe the shape of

the weld pool. The geometrical appear-

ance of the weld pool is characterized by

the rear angles and length of the weld

pool. To emulate the human operator in

extracting the weld penetration, artificial

neural networks are utilized. The feature

parameters of the weld pool are input into

the network and the weld penetration is

calculated as the output. It is shown that

the geometrical appearance of the weld

pool contains sufficient information on

the weld penetration. A real-time system

has been developed to monitor the weld

penetration using the geometrical ap-

pearance of the weld pool.

It should be pointed out that the efforts

in this study have been limited to using

the two-dimensional geometrical infor-

mation from the weld pool. The three-di-

mensional topography of the weld pool

surface may also be used to determine

the weld penetration. Previous investiga-

tors have shown that the pool sag or the

pool depression is correlated to the weld

penetration (Refs. 24, 25). However, sen-

soring the three-dimensional pool sur-

face was difficult. It was found that the

sag of the weld behind the pool rear has

Fig. 1 — Experimental setup.

Fig. 2 — Weld pools for different currents. Arc length = 3 mm, travel speed = 1.9 mm/s, bead on plate, rate of argon flow = 30 ft³/h, 304 stainless
steel, 3 mm thickness. A — current = 90 A, full penetration, backside bead width 1.8 mm; B — current = 95 A, full penetration, backside bead
width 3 mm; C — current = 105 A, full penetration, backside bead width 4 mm; D — current = 110 A, full penetration, backside bead width 4.5
mm; E — current = 115 A, full penetration, backside bead width 5 mm.
a good relationship with the root face bead width (Ref. 26). Thus, as an alternative, a vision-based adaptive system was developed to monitor and control the sag geometry for achieving the desired root face bead width (Refs. 27, 28). Recently, the authors have developed a specular reflection-based vision system to directly monitor the three-dimensional topography of the weld pool surface (Refs. 29–31). Although the pool depression may be directly controlled to achieve the desired weld penetration using this novel technology, the image processing algorithm for detecting the three-dimensional weld pool surface is much more complicated than the algorithm for the two-dimensional boundary of the weld pool. Hence, as the first step, this work will focus on the two-dimensional domain.

**Experimental Procedure**

**Experimental Set Up**

The experimental system is shown in Fig. 1. The welds are made using direct current electrode negative (DCEN) gas tungsten arc welding. The welding current is controlled by the computer (Pentium 90) through a D/A board output to the power supply ranged from 10 A to 200 A. The torch and camera are attached to a three-axial manipulator. The motion of the manipulator is controlled by the three-axis motion control board, which receives the commands from the computer. The motion can be preprogrammed and modified on-line by the computer to achieve the required torch speed and trajectory, including the arc length.

The camera is positioned directly behind the weld pool with its axis at a 45-deg angle from the horizontal. The laser is projected from the front of the weld pool with an incident angle of 50 deg, thus avoiding the bright specular reflection in the image. The frame grabber digitizes the video signal into 512 x 512 8-bit digital image matrix. To acquire a quality image for extracting the pool boundary, a high-shutter-speed camera assisted with a pulsed laser is used. The pulse of the laser lasts only 3 ns. The shutter of the camera is synchronized with the laser pulse. Although the average power of the laser is as low as 7 mW, its peak power reaches 70 kW. During the pulse duration, the intensity of the laser illumination is much stronger than those of the arc and hot metal. Thus, the area illuminated by the laser will be bright in the image. However, the weld pool will be dark since the projected laser is specularly reflected from the mirror-like weld pool surface. Consequently, clear images as shown in Fig. 2 can be acquired.

**Experimental Conditions**

Variation in weld joint penetration could be generated by changing welding parameters, such as the welding current, arc length, and travel speed, and welding conditions such as the root opening or geometry of the groove, material, thickness, workpiece size, heat transfer condition, electrode angle, and rate of the shielding gas flow. In order to form a valid method to monitor the weld penetration, the major parameters that may vary during welding should be considered in the experiments. Three-millimeter-thick stainless steel (304) plates are used without any specific surface preparation. The shielding gas is pure argon. The electrode is 3 mm in diameter with a 60-deg tip angle. Bead-on-plate welds are made. The objective is to monitor the full penetration state which is described by the root face bead (backside) width. Varied current, arc length, and travel speed are selected to make the root face bead width vary in the range of interest. The detailed experimental conditions can be seen in Table 1 and Fig. 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Current (A)</th>
<th>Arc Length (mm)</th>
<th>Speed (mm/s)</th>
<th>Duration (seconds)</th>
<th>Ar Flow Rate (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>see Fig. 3A</td>
<td>1.9</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>see Fig. 3B</td>
<td>1.9</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>see Fig. 3C</td>
<td>3</td>
<td>1.9</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>3</td>
<td>1.9</td>
<td>100</td>
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<td>100</td>
<td>3</td>
<td>2.41</td>
<td>80</td>
<td>35</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>3</td>
<td>1.43</td>
<td>130</td>
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</tr>
<tr>
<td>8</td>
<td>100</td>
<td>3</td>
<td>1.95</td>
<td>100</td>
<td>30</td>
</tr>
</tbody>
</table>

**Observation and Rear Angle**

It is known that when the current or arc length increases, the pool width increases. However, the resultant changes in weld penetration are opposite. This implies that the pool width alone may not be sufficient for representing the weld penetration in some specific cases. To describe the weld penetration, additional parameters must be considered. Figure 2 shows the weld pools made with different currents. With the increase of the current, the root face bead width increases. It is seen that the length of the weld pool keeps increasing with the current, whereas the variation in the pool width is less significant. Also, as the weld penetration increases, the tail of the weld pool becomes sharply pointed. Thus, the length and sharpness of the weld pool could be used to represent the weld penetration.

To describe the sharpness of the weld

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**Fig. 3** Some experimental parameters. A — Arc length variation in Experiment 1; B — arc length variation in Experiment 2. C — current variation in Experiment 3.
In a previous work, a real-time image processing algorithm was developed to extract the boundary of the weld pool (Ref. 32). To reduce the computation, dynamic search procedures were conducted. Although this algorithm can successfully extract the boundary of the weld pool in real-time, its programming is complicated. For convenience in implementation and application, a modified algorithm is proposed. Using this algorithm, the robustness and speed can also be improved. The boundary of the weld pool can be extracted in 60 ms from the acquired image despite the variations in surface and welding conditions.

The proposed algorithm consists of four steps: 1) image binarization, compression, and windowing, 2) edge detection, 3) boundary identification, and 4) fine search. In the first three steps, a rough boundary is acquired in order to improve the robustness and processing speed. Based on the rough boundary, a fine search can be done to find the accurate boundary of the weld pool with slight additional computation.

Assume that the axis of the electrode is \( x_i = x_i(0) \), which can be determined before welding — Fig. 5A. The weld pool lies under \( y_j = y_j(0) \) — Fig. 5A. In the first step, the captured image is scanned from \( x_i(0) \) at \((x_i(0)+iy)\)'s \((i = 0, 1, 2,...)\) along the \( x_i \) direction and at \((x_i(0)+iy')\)'s \((i = -1, -2,...)\) along the negative \( x_i \) direction, respectively — Fig. 5A. The positive integer \( y \) is the image compression factor which is taken as 4 in this study. During the scanning at \( x_i = x_i(0) + iy \), the image points at \((x_i(0)+iy, y_j(0)+iy')\)'s \((j = 0, 1, 2,...)\) are binarized. The number of dark pixels are accounted as \( N(i) \). It is evident that \( N(i) \) should be very small when \( x_i = x_i(0) + iy \) exceeds the pool range. Thus, the range of the weld pool along the horizontal direction, i.e., \((-N_2 \leq i \leq N_2)\), can be roughly acquired without excessive computation, in addition to the binarization — Fig. 5B. Using the compressed binary image within \((-N_2 \leq i \leq N_2)\), a rough estimate of the range along the vertical direction can also be obtained — Fig. 5C. The resultant window can be described by the range \((-N_3 \leq j \leq N_3, M_1 \leq j \leq M_2)\) where \(N_1, N_2, M_1, \) and \(M_2\) are all positive integers. The compressed binary image and resultant window are shown in Fig. 5C.

In the second step, the left and right edge points of the weld pool are searched from \( i = -N_1 \) and \( i = N_2 \), respectively, with increasing and decreasing \( i \) for a given \( j \), respectively. It is known that both the left and right edge points should be located at transitions from the bright to dark areas during the searches. To exclude possible small dark areas caused by the severe oxidation in the solidified region due to the possible imperfection of shielding, the search is continued for a few more pixels once the transition is encountered. If the succeeding pixels are
The boundary extracted by the image processing is described using the image coordinate. To acquire the actual geometrical appearance of the weld pool, the boundary should be described in the weld pool coordinate system. The xy plane of the work coordinate system is the work surface and the z-axis is the electrode — Fig. 6. A transformation from the image coordinates to the work coordinates must be done.

Assume that (x(i),y(i))’s are the image coordinates of the boundary of the weld pool. The pool boundary (x(j), y(j),z(j))’s must be calculated from the (x(i),y(i))’s since the work surface has been selected.

![Edge detection for the image with severe oxidation](image)

**Coordinate Transformation**

The boundary extracted by the image processing is described using the image coordinate. To acquire the actual geometrical appearance of the weld pool, the boundary should be described in the work coordinate system. The xy plane of the work coordinate system is the work surface and the z-axis is the electrode — Fig. 6. A transformation from the image coordinates to the work coordinates must be done.

Assume that (x(i),y(i))’s are the image coordinates of the boundary of the weld pool.

![Edge detection for the image with severe oxidation](image)

where \( p \) is the order which is selected to be 4 based on modeling experimentation. The least squares algorithm (Ref. 33) has been used to identify the parameters. The fitted edges are illustrated in Fig. 6E.

It can be seen that despite the poor condition, correct estimates of the weld pool edges have been acquired from the compressed image.

The rough edge acquired in the compressed image can be restored to the original image — Fig. 7A. In the fourth step, the final pool edge is searched around the rough edge. Thus, the final pool boundary as shown in Fig. 7B can always be obtained. Based on this edge, the required parameters of the weld pool can be calculated.

The above four steps can be completed by our equipment in 30 to 60 ms. To sample the image, 33 ms is required. Thus, the weld pool boundary can be acquired at 10 Hz.

![Edge detection for the image with severe oxidation](image)
to be the xy plane, the z(j)'s can be considered as zero. It can be shown that:

\[
y(j) = y_p - z_p / d_2 \\
45^\circ - \tan^{-1}(y(j) / d_2) \\
x(j) = -x_p(j) \\
y(j) + \sqrt{2d_2} / \sqrt{2d_2}
\]  

(3)

where (0, y_p, z_p) are the pinhole of the camera coordinate system to the pinhole, and d_1 is the distance from the origin of the work coordinate system to the pinhole, and d_2 is the distance from the origin of the camera coordinate system to the pinhole. The optical axis of the camera lies on the yz plane and the angle between the optical axis and the y axis is 45 deg. Thus, using the image processing results, i.e., (x(j), y(j), z(j))'s, the boundary of the weld pool (x(j), y(j), z(j))'s can be acquired.

Modeling

In order to achieve accurate predictions of the weld penetration, nonlinear models, rather than linear models, are used to correlate the weld pool parameters with the weld penetration. However, the structure of the nonlinear relationships is very difficult to determine. Neural networks provide a uniform model frame for almost all types of nonlinear relationships. Thus, a neural network can be used to relate the pool parameters to the weld penetration.

For most applications, one hidden layer is sufficient (Ref. 34). In order to guarantee the validity of the resultant model, the number of elements in the hidden layer, denoted as n_2, is selected by the following equation (Ref. 34):

\[
n_2 = N/10(n_1 + n_3) - N/5(n_1 + n_3)
\]  

(4)

where N is the number of samples, and n_1 and n_3 are the number of elements in the input and output layer, respectively.

The number of samples for each network is 7350. Different pool parameters will be used as the inputs of the network to calculate the backside bead width, which is the output of the neural network. Thus, the number of elements in the hidden layer will depend on the number of pool parameters used in the network. The general architecture of the result network is shown in Fig. 9A. The sigmoidal function (Ref. 35) is selected as the nonlinear function of the neuron which is shown in Fig. 9B. It is known as the following (Ref. 35):

\[
y_{i,k} = 1 / \left(1 + e^{-y_i}ight) \\
y_i = w_{i,k} + \sum_{j=0}^{n_i-1} w_{i,k} y_{j-1,i} 
\]  

(5)

where y_{i,k} is the output of the kth neuron (element) in layer i, n_i is the number of neurons in layer i, and w_{i,k} and w_{i,k} are the weights of the neuron which must be determined by the training process.

The training was performed using the commercial neural network software, Professional II (Ref. 34). The algorithm is the extended delta-bar-delta (EDD), which can overcome the slow convergence associated with the conventional back-propagation algorithm (Ref. 34). The learning ratio is automatically determined by the algorithm. The training cycle is selected to be 50,000.

Modeling Results

The pool feature parameters, including the length, width, and rear angles of the weld pool, are measured on-line during the experiments (Table 1) at the speed of 10 Hz. The backside width is measured off-line using a structured light vision system developed in a previous study (Ref. 36). The data in the first three seconds and last two seconds are deleted for each experiment. The resultant data is plotted in Fig. 10. It can be seen that the backside bead widths vary in a wide range, from 1 to 7 mm. The variation is caused by the different welding parameters or conditions. To monitor the weld penetration, this variation must be calculated with sufficient accuracy using the measurements of the pool feature parameters. For the thickness of the material used in this study, the required backside bead width may be selected between 2 and 5 mm so that the allowed error in determining the backside bead width should be less than 1 mm. For the convenience of the discussion, 1 mm is referred to as the critical measurement for the efficiency of the modeling accuracy in this study.

All the pool parameters have been used as the inputs of the network for modeling the backside bead width. The number of elements in the hidden layer is selected to be 45 based on Equation 4. Using the trained network, the backside bead width can be calculated from the pool feature parameters. Figure 11A illustrates the calculated values, compared with the original measurements. It is found that the backside bead width can be traced with sufficient accuracy for different welding conditions, judged by the 1-mm critical measurement. This demonstrates that enough information on the full penetration state is contained in the selected pool parameters.

The weld pool could be characterized using three types of parameters, i.e., size, shape, and geometrical appearance, from different points of view. The corresponding parameters are categorized as size, shape, and geometrical appearance parameters. The geometrical appearance
The data are arranged according to their serial number in the experiments (Table 1). The ranges of the sample number for each experiment are: No. 1 from 1 to 950; No. 2 from 951 to 1900; No. 3 from 1901 to 2850; No. 4 from 2851 to 3800; No. 5 from 3801 to 4400; No. 6 from 4401 to 5150; No. 7 from 5151 to 6400; No. 8 from 6401 to 7350. A — Backside bead width; B — length of weld pool; C — width of weld pool; D — rear angle $\theta_1$; E — rear angle $\theta_2$; F — rear angle $\theta_3$; G — rear angle $\theta_4$; H — rear angle $\theta_5$; I — rear angle $\theta_6$; J — rear angle $\theta_7$; K — rear angle $\theta_8$; L — rear angle $\theta_9$.

Fig. 10 — Experimental measurements. The data are arranged according to their serial number in the experiments (Table 1). The ranges of the sample number for each experiment are: No. 1 from 1 to 950; No. 2 from 951 to 1900; No. 3 from 1901 to 2850; No. 4 from 2851 to 3800; No. 5 from 3801 to 4400; No. 6 from 4401 to 5150; No. 7 from 5151 to 6400; No. 8 from 6401 to 7350. A — Backside bead width; B — length of weld pool; C — width of weld pool; D — rear angle $\theta_1$; E — rear angle $\theta_2$; F — rear angle $\theta_3$; G — rear angle $\theta_4$; H — rear angle $\theta_5$; I — rear angle $\theta_6$; J — rear angle $\theta_7$; K — rear angle $\theta_8$; L — rear angle $\theta_9$. 
Fig. 11 — Experiments of neural network modeling of weld penetration using different weld pool parameters. A — Length, width and rear angles; B — length; C — width; D — length to width ratio; E — rear angles; F — length and width.

represents the visual geometrical characteristics of the pool. Thus, both size and shape information should be contained in the geometrical appearance parameters. Geometrical appearance parameters could consist of the shape and size parameters.

Size Parameters

The width and length are the size parameters of the weld pool. To examine the possibility of using the length or width of the weld pool to represent the weld penetration, two networks have been trained using the length and width as the input, respectively. The numbers of elements in the hidden layer in both cases are 500 because of Equation 4. The modeling results are illustrated in Fig. 11B and Fig. 11C, respectively. It can be seen that both the length and the width can provide rough estimates for the full penetration states. However, the modeling errors often exceed the 1-mm critical measurement.

Shape Parameters

It seems that the shape of the weld pool can be roughly characterized by using multiple size parameters. The ratio between the length and width of the pool provides pure information on the shape.

Using the length-to-width ratio as the input, a network has been trained. The modeling results are plotted in Fig. 11D. It is apparent that the ratio cannot provide any useful weld penetration information. In order to explore the relationship between the pool shape and weld penetration, a more accurate description of the shape of the weld pool must be used.

The proposed rear angles can be used to characterize the shape of the weld pool. Nine rear angles can provide more accurate shape information than the ratio. If the shape of the weld pool really contains sufficient information on the full penetration, an adequate estimation of the backside bead width should

Fig. 12 — Neural network modeling of full penetration. The length and rear angles of the weld are used as the inputs of the neural network. The small difference between the measured and network estimated backside bead width, as observed in the figure, shows that the accuracy of the proposed monitoring approach for the full penetration is sufficient despite the variations in the welding conditions.

Fig. 13 — The arc appearance and the weld pool. The image shows that the arc covers the transverse span of the weld pool. The image is captured by using a slower shutter speed than was used for Fig. 2 images.
Fig. 14 — Dissimilar trends in top and backside bead widths. The top and backside appearances of a weld show that the backside bead width does not correlate with the top weld width. A — Top weld appearance; B — backside weld appearance.

Fig. 15 — Weld with arc length variation. Current = 100 A, travel speed = 1.9 mm/s, bead-on-plate, rate of argon flow 30 ft³/h. The arc length variation is shown in Fig. 3A. A — Top weld appearance. B — backside weld appearance.

Geometrical Appearance Parameters

The geometrical appearance parameters may be acquired by incorporating multiple size parameters, or by incorporating the size and shape parameters. The width and length of the weld pool characterize the geometrical appearance of the weld pool. However, the description is rough. An accurate description of the geometrical appearance can be generated by combining the rear angles with a size parameter.

Using the width and length of the weld pool as the inputs, a network has been trained. The modeling results can be seen in Fig. 11E. A noticeable improvement in the modeling accuracy, in comparison with cases using the size or shape parameters, has been obtained. In Fig. 12, the modeling results using the rear angles and length of the weld pool are illustrated. The improvement of the accuracy is significant. This improvement is achieved by the more accurate description of the geometrical appearance of the weld pool.

Current

It is known that the weld penetration is nearly proportional to the welding current. In fact, the Lorentz force is proportional to the current. Thus, the stirring of the liquid metal in the weld pool will be increased with an increase in the welding current (Ref. 25).

Also, the impact of the plasma jets on the weld pool is increased with the current (Ref. 40). As a result, an increase in the current will generate an increase in the weld penetration. In order to determine the weld penetration from the geometrical appearance of the weld pool, the corresponding change in the shape and size of the weld pool must be found.

The images in Fig. 2 illustrate the appearance of weld pools made using different welding currents. It can be seen that the length of the weld pool is significantly increased with the current. However, the increase in the width of the weld pool is much less significant. It is known that the welding current is one of the critical welding parameters that determines the geometrical appearance of the weld pool. An increase in welding current produces an increase in power density (Ref. 41). The size of the weld pool, for example, the pool width and length, increases with the current. It was shown that the magnitude of the heat flux is dominated by the current (Ref. 42).
Thus, a larger weld pool can be expected for a larger current. The image in Fig. 13 shows that the span of the weld pool along the traverse direction is covered by the arc. This implies that the surface of the weld pool is directly made molten by the arc. The width of the weld pool is primarily determined by the arc distribution. When the current increases, the radial dimensional distribution parameter slightly increases (Ref. 42). Thus, the width of the weld pool slightly increases with the current. On the other hand, the heat intensity significantly increases with the current (Ref. 42). The temperature on the surface of the weld pool is therefore expected to increase with an increased current. Hence, the length of the weld pool significantly increases when the current increases, whereas the width of the weld pool only slightly increases.

In addition to the relatively low sensitivity to the current, the width of the weld pool is also less sensitive to the variations in other welding parameters or conditions which can change the weld penetration as shown in Ref. 43 — Fig. 10B and 10C. Thus, as shown in Fig. 11C, the pool width alone may not be able to represent the weld penetration with sufficient accuracy under possible variations in welding parameters and conditions, as was expected previously. To further illustrate this, the top and bottom appearances, acquired from an experiment, shown in Fig. 14 are given. It is apparent that in this case, no correlation between the backside bead width and the pool width can be observed. Thus, the length of the weld pool, which is more sensitive to the current and other welding parameters and conditions (Fig. 11B and 11C) should be a useful parameter for determining the weld penetration.

**Arc Length**

An increase in the arc length will generate an increase in the arc voltage. It is known that the magnitude of the heat flux is proportional to the arc voltage (Ref. 44). However, the distribution parameter increases nearly linearly with the arc length (Ref. 42). Also, the arc efficiency \( \eta \) substantially decreases when the arc length increases (Ref. 44). Thus, the relationship between the weld penetration and the arc length is more sensitive to the current than to the arc length, which is why the pool width alone may not be able to represent the weld penetration with sufficient accuracy under possible variations in welding parameters and conditions, as was expected previously.
The topside and backside weld appearances of Experiment 1 are shown in Fig. 15A and B, respectively. The arc length increases from 2 to 4.5 mm during the experiment as shown in Fig. 3A. Because of the step change of the arc length, the irregularity of the weld can be observed. This irregularity can be more easily seen from the backside (Fig. 15B) than from the topside — Fig. 15A.

In the first 20 seconds, the arc length is 2 mm — Fig. 3A. The backside bead width is about 3.5 mm (Fig. 10A, B). At the transition from 2 mm to 2.5 mm, i.e., around t = 20s, there is a peak in the backside bead width — Fig. 15B. Then the backside width roughly remains as it was during the first 20 seconds — Fig. 10A. After the transition from 2.5 to 3.5 mm, the backside bead width is about 4 mm. When the arc length is increased by 4 mm, the backside bead width slowly decreases to 3.3 mm. When the arc length becomes 4.5 mm, the backside bead width increases to about 4.5 mm. It can be seen that except for the peak at the transition zone caused by the step change of arc length, the weld penetration slowly increases with the arc length before the arc length reaches 3.5 mm. After 3.5 mm, the weld penetration starts to slowly decrease with the incremental arc length. However, when the arc length becomes 4.5 mm, the weld penetration increases again. The above observations are obtained based on Fig. 10A and Fig. 3A and the backside appearance of the workpiece.

It is expected that the pool width increases with the arc length. However, in this experiment, the pool width remains almost unchanged before the arc length reaches 3.5 mm at t = 40s — Figs. 15A and 10C. After the arc length reaches 3.5 mm, although the width of the heat-affected zone still increases with the incremental arc length (Fig. 15A), the pool width begins to decrease slowly. The pool width does not increase with increasing arc length. To explain this phenomenon, the arc distribution was observed for different arc lengths — Fig. 16. It was found that the arc distribution does not keep increasing with the arc length. Before the arc length reaches a critical value, the arc spread keeps increasing. Once the arc length exceeds the critical value, the arc spread begins to concentrate. In the experiment for Fig. 16, the critical value is 3.5 mm. Thus, despite the increase in the arc length beyond 3.5 mm, the pool width decreases. Also, because of the concentration of the arc, the backside bead width becomes large when the arc length is 4.5 mm, i.e., from t = 80 to 100s — Fig. 15B.

Although the variations of the weld penetration in Experiment 1 cannot be predicted by the pool width, the weld pool geometrical appearance (Fig. 17) can be used to explain it. At t = 85s, the backside bead width is 3.5 mm. The pool is blunt and short (Fig. 17A). At t = 55s, the pool becomes longer and sharper — Fig. 17B. The backside bead width is 4 mm. When the time reaches 95s, the pool is very long — Fig. 17C. Thus, the backside bead width becomes 4.5 mm.

Travel Speed

The weld penetration increases with decreasing travel speed. As it is known, at constant current and arc length, a slower travel speed arc will supply more heat input to the weldment and provide a higher peak temperature on the surface, whereas a faster one will cause less heat input and a lower peak temperature (Ref. 45). That is, a lower speed arc can be regarded as having a higher power density, since the distribution of the arc is not expected to be significantly affected by the travel speed. In order to link the geometrical appearance of the weld pool with the weld penetration, the influence of the travel speed on the size and shape of the weld pool should be studied.

The geometrical appearances of the weld pool corresponding to different travel speeds are shown in Fig. 18. When the arc travel speed is 2.92 mm/s, the size of the weld pool is small. By decreasing the travel speed to 2.41 mm/s, the weld pool is enlarged. However, the shape of the weld pool does not significantly change. This implies that the size of the weld pool is an important parameter to determine the weld penetration. When the travel speed decreases to 1.95 mm/s, the rear of the pool becomes sharper and the pool length is significantly increased. When the speed decreases to 1.43 mm/s, a very large increase in the length is observed. The rear of the weld pool becomes very sharp. Although the length of the weld pool may indicate the change in the travel speed, the accuracy in completely determining the weld penetration is still not sufficient. It can be seen that large modeling errors occur in the data corresponding to high travel speeds (see the range from 3800 to 4400 in Fig. 11B) if only the pool length is used because of...
the complexity of the relationship between the weld pool and weld penetration. Thus, by adding the rear angles, significant improvement in the modeling accuracy has been achieved. This improvement can be observed by comparing Fig. 11B with Fig. 12.

**Trends**

Figure 19A is generated from the measurements of the backside bead width given in Fig. 10A by rearranging the data incrementally. The length, width, and a few rear angles of the weld pool plotted in Fig. 19B-F are the corresponding rearrangement from the original data. Although no exact relationship between the weld penetration and each individual parameter of the weld pool can be observed because the variations in the weld penetration are caused by changing different welding parameters, some rough trends can be observed.

In the small full penetration range, where the serial number is less than 600 in Fig. 19, the pool width and length almost do not change with the penetration. However, the rear angles do decrease when increasing the penetration. This may imply that the weld pool size cannot be used to predict the penetration variation when the full penetration is just established from the partial state. For example, the backside bead width varies from 1 to 2 mm in Experiment 5 (the sample number is from 3800 to 4400 in Fig. 10). The prediction given by the length or width of the weld pool are almost constant (Fig. 11B, C). Thus, it seems that the rear angles play important roles in determining the small full penetration.

When the degree of full penetration further increases, the pool length and the width begins to increase with the backside width. Roughly speaking, the length of the weld pool almost linearly increases with the backside bead width in the moderate full penetration range, i.e., from 2 to 4.9 mm where the serial number in Fig. 19 is from 800 to 5000. The pool width also increases with the penetration in this range. However, the increase is step-like. In the serial number range from 800 to 2200, the pool width varies around 5 mm. In the serial number range from 2200 to 6000, the pool width fluctuates around 6 mm. The full penetration is very pronounced, a linear relationship between the backside bead width and pool width is observed. This can be seen when the serial number is larger than 6000 — Fig. 19A, C. In this range, the relationship between the pool length and weld penetration becomes complicated — Fig. 19A, B. Thus, the variation of the weld penetration in Experiment 7 can be much better tracked by the pool width than by the pool length — Fig. 11C, D. However, by incorporating the rear angles with the pool length, the weld penetration has been well tracked in this full penetration range.

The relationship between the rear angle \( \theta_j (j = 1, 2, ..., 9) \) and weld penetration tends to become stronger as \( j \) decreases. For example, in the small serial number range, less than 600, \( \theta_6 \) does not significantly change with the weld penetration (Fig. 19D), whereas \( \theta_2 \) and \( \theta_3 \) do decrease with weld penetration — Fig. 19E, F. This is understandable because the sharpness of the rear portion of the weld pool plays a more important role.

Before the backside bead width reaches 4 mm, i.e., when the serial number is less than 3000, the rear angles decrease when the backside bead width increases. When the full penetration becomes more significant, the relationship tends to be complicated. However, this complexity does not mean that the correlation between the weld penetration and pool geometrical appearance becomes poorer. The weld penetration can still be determined with sufficient accuracy as it is in the small full penetration state — Fig. 12. This complexity is an inherent characteristic of the welding process. Because of this complexity, the neural network played an important role in correlating the weld penetration to the pool geometrical appearance.

Although the irregularity in the relationship between the full penetration state and individual pool parameter, a rough trend can still be observed. That is, no matter how the variation in the weld penetration is caused, the sharpness and size, including the length and width, of the weld pool tend to increase with the weld penetration.

**Real-Time Monitoring**

The full penetration has been monitored in real-time using the developed real-time image processing algorithm and trained neural network. The monitoring system is shown in Fig. 19. The inputs of the neural network are the length and rear angles of the weld pool. Since Professional II can provide the executive codes of the trained network as a sub-routine which can be called by C program, the trained network can be loaded into the main program without additional programming.

The image processing for extracting the boundary of the weld pool can be completed in 100 ms. The network computation lasts less than 50 ms. Thus, with the consideration of the other possible computation, the weld penetration has been monitored at 5 Hz. This speed can be considered to be real-time for welding process control.

An example is given in Fig. 21. The current and travel speed are 100 A and 1.53 mm/s, respectively. The arc length is 3 mm. The on-line prediction of the backside bead width is plotted in Fig. 21A to examine the accuracy of the on-line prediction. In Figs. 21B and C, the appearances of the welds are illustrated. In this case, the variation in the weld penetration is caused by naturally occurring process variations, for example, the unavoidable variation in heat transfer condition along the weld. It can be seen that the variation of the backside bead width which specifies the full penetration has been monitored with sufficient accuracy.

**Conclusions**

The stainless steel 304 has been used to make bead-on-plate welds using direct current electrode negative (DCEN) gas tungsten arc welding (GTAW). The thickness of the material was 3 mm. Under these experimental conditions, it can be concluded that the geometrical appearance of the weld pool, specified by the length and rear angles, contains sufficient information on the weld penetration, judged by the 1-mm critical measurement of the modeling error. However, pure size or pure shape parameters only contain rough information on the weld penetration.

In addition, a real-time monitoring system has been developed to monitor the full penetration state, i.e., the backside bead width. The high-shutter-speed camera assisted with the pulsating laser, the proposed real-time image processing algorithm, the relationship between the weld penetration and the geometrical appearance of the weld pool, and the neural network modeling capability play crucial roles in this achievement.

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References


