Dynamic Control of the GTAW Process Using a Human Welder Response Model

A model was implemented to adjust the welding current in response to the characteristic parameters of the 3D weld pool surface to maintain consistent, complete joint penetration in GTAW

BY W. J. ZHANG AND Y. M. ZHANG

ABSTRACT

In the modern welding industry where automated welding tends to be the mainstream, manual welding is still not replaceable when human experience and skills are critical to produce quality welds. Yet the mechanization and transformation of a human welder’s intelligence into robotic welding have not been explored. In our previous study to understand a human welder’s behavior, the welder’s adjustments on welding current were modeled as a response to characteristic parameters of the three-dimensional weld pool surface. In this work, the response model is implemented to feedback control the gas tungsten arc welding (GTAW) process to maintain consistent, complete joint penetration. Experiments were designed to start welding using different welding conditions (arc length, welding speed, and root opening) along with initial current. After the initial open-loop control period, the welding current is adjusted by the controller that uses the welder’s response model to determine how to adjust the welding current based on the measured weld pool surface characteristic parameters. The resultant current waveform and its backside weld bead width were recorded/measured and analyzed. It was found that the human welder response model can adjust the current appropriately to control the welding process to a desired penetration level despite the difference in the welding conditions and initial current. The desired backside width of the weld bead, 5.2 mm, was produced with a 0.4 mm variation successfully in all experiments despite their diverse welding conditions and initial current.

Introduction

Manual gas tungsten arc welding (GTAW) is thought by many as an operation that requires the highest skills, yet is commonly used in the industry, especially for applications requiring assured weld quality. A human welder can hear the sounds of the arc, sense the reactive forces from the torch, and observe the weld pool surfaces. Using such feedback information, a welder can appraise the welding process with respect to the desired state, then intelligently adjust the welding parameters (e.g., current, welding speed, arc length), and maintain appropriate torch orientation and distance in an effort to control the desired weld state. Because of their experience-based behavior in response to the information they sense, human welders may be preferred over mechanized welding control systems in certain applications.

Although welders’ experience and skills are crucial to producing quality welds, human welders have limitations. Critical welding operations require welders concentrate consistently to react rapidly and accurately. Inconsistent concentration, fatigue, and stress build up such that welders’ capabilities degrade during daily operations. Moreover, experience and skills needed for critical operations typically require years to develop while the manufacturing industry is experiencing an insufficient number of skilled welders for a long time (Ref. 1).

The mechanism of welders’ experience-based behavior, i.e., how welders respond to the information they acquire from their sensory system, should be explored and utilized to develop intelligent robotic welding systems that combine intelligence and physical capabilities for the next generation of manufacturing. Exploring the mechanism may also be utilized to understand why less skilled welders are not performing as well as skilled welders and help train welders faster to help resolve the skilled welder shortage issue the manufacturing industry is facing (Ref. 2).

However, developing a model of the welders’ experience-based behavior and adapting it as a controller in automated welding is so far a challenging task. Numerous studies have been conducted with different sensing techniques mimicking welders’ sensing capability to the weld pool. Various types of information about the weld pool have been extracted and interpreted to describe the state of the welding process (Refs. 3–9).

Although successes in monitoring the weld pool continue to be made in the academic community, the intelligent behavior of a human welder has not yet been successfully transferred to automated welding. This is because welders, in the role of human controller in the welding process, make decisions primarily based on past learned experiences, which might not involve a fundamental understanding of the laws of physics. Also, a skilled welder assesses and controls a welding process using a humanistic approach where the feedback sensory information acquired by...
the welder is imprecise and can only reflect partial truths about the instant status of the weld process. An automated welding control system requires both mechanistic methods for the welding phenomena that are physically well understood and mathematically feasible for both sensors and control algorithms.

The theory of modeling for the human controller dynamics has been extensively studied since the 1940s. Great progress was achieved in the 1960s and 1970s (Ref. 10), such as linear crossover model (Ref. 11) and the optimal control model (Ref. 12). The physical nature of a human operator indicates that the human controller is naturally dynamic, stochastic, nonlinear, and time varying. In this sense, nonlinear methods were introduced to model the human action neural networks, and neuro-fuzzy or adaptive models (Refs. 13–17).

Although nonlinear methods typically improve the prediction performance to some extent, it is still very appealing to use linear models due to their convenience for analysis and design. Instead of taking real industrial processes, most of the literature in this area took certain benchmarks as control objects, such as the pendulum, joystick, etc. Besides, those developed models tend to be too complex to understand and difficult to apply to the practical control systems.

In our first study on human welder responses (Refs. 18, 19), dynamic models of a novice human welder’s behavior were developed. The studied behavior of the welder is focused on the adjustment of welding current in response to the observed three-dimensional (3D) weld pool surface during the complete-joint-penetration process. The weld pool geometry is used as the sensory feedback information since it is believed to provide valuable insights into the welding process state.

Important information such as weld defects and penetration are contained in the surface deformation of the weld pool in the GTAW process (Refs. 20, 21). The geometry of the weld pool has been studied (Refs. 22–26) as a means of monitoring and controlling the weld joint penetration. A vision-based sensing system has been developed to simultaneously measure the 3D weld pool surface and record the responses the human welder made to the surface. A dynamic model that correlates the welder responses (model outputs) to the characteristic parameters (model inputs) of the 3D weld pool surface has been established.

This paper is the first of this kind addressing implementation of the human welder response model as a controller in the automated GTAW process. In particular, this study focuses on how this model controls the current to achieve consistent complete joint penetration under different welding parameters. The backside weld bead width is used as a measurement for the penetration state. The effectiveness and robustness of the model-based control are evaluated and verified in this paper.

Modeling of the human welder response is briefly reviewed in the next section. In the experimental system and methods section, a vision-based sensing system is detailed as well as the experiment method for implementation of the model. The results of the model-based control are presented and analyzed in the human welder response model control section. The human welder response model is further improved in the improvement of the human welder response model section. The robustness of the control using the improved model is then analyzed in the results and analysis of robustness experiments section. The conclusion is then given.

**Table 1 — Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Root opening/mm/s</td>
<td>[0, 5]</td>
</tr>
<tr>
<td>Arc length/mm</td>
<td>[2, 5]</td>
</tr>
<tr>
<td>Welding speed mm/s</td>
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</tr>
<tr>
<td>Initial welding current/A</td>
<td>[50, 62]</td>
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<tr>
<td>Argon flow rate/L/min</td>
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<tr>
<td>Project angle/deg</td>
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<td>Laser to weld pool distance/mm</td>
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<td>Imaging plane to tungsten axis distance/mm</td>
<td>101</td>
</tr>
<tr>
<td>Camera to imaging plane distance/mm</td>
<td>57.8</td>
</tr>
</tbody>
</table>

**Fig. 1 — Demonstration of a manual control system of the GTAW process. It is not a typical manual GTAW process. The human welder only adjusts the welding current based on his observation of the 3D weld pool surface. The pipe rotates during the experiment while the torch, imaging plane, laser, and camera are stationary.**
A skilled welder starts a welding process with initial welding parameters that are considered optimal based on past experiences. After observing the weld pool surface until enough feedback information is perceived, the welder assesses the process and adjusts the welding parameters accordingly to produce desirable welds. Skilled human welders are believed to make an optimal or nearly optimal control to minimize the error between the current and desired states of the welding process. Ideally, qualified/skilled welders make similar welds that meet the requirements because they all possess the ability to sense the process and make a decision using the sensed process feedback.

### Manual GTAW Experimental System

With the principle of the human welders’ behavior, an experimental system has been developed (Refs. 18, 19) as shown in Fig. 1. The pipe is rotated and butt joint welded using DCEN GTAW at 12 o’clock without a filler metal. A human welder observes the weld pool and adjusts the welding current using an amperage remote control installed on the torch. The use of the remote controller for the welding current shown in the figure is for demonstration purposes only. The actual current remote controller is a thumb turn knob on the torch. It adjusts the current setting for the power supply.

### Vision-Based Sensing Subsystem

The 3D weld pool surface being observed by the human welder is also simultaneously measured by a vision system. The system includes the low-power, 20-mW illumination laser generator at a wavelength of 685 nm with variable focus, a 19x19 dot matrix structured light pattern (Lasiris SNF-519X (0.77)-685-20) attached to the head of the laser, an imaging plane made by a piece of glass attached by a sheet of paper, and a camera (Point Grey Flea 3). The laser projects the 19 x 19 dot matrix on the melting region. Part of the dot matrix projected inside the weld pool is reflected by the specular weld pool surface. Then a reflection pattern of the dot matrix is intercepted by the imaging plane. Because of the plasma impact, the surface of the weld pool is depressed and distorted in GTAW. Therefore, no matter which shape (concave or convex) the weld pool presents, the alignment of the reflected laser dot matrix is distorted by the deformed specular weld pool surface. The distortion of the reflected dot matrix is determined by the shape of the three-dimensional weld pool surface and contains the 3D geometry information about the weld pool surface. The camera captures the images of the reflected laser dot matrix from the imaging plane. A computer connected to the camera processes the images and reconstructs the 3D weld pool surface in real time (Ref. 27).

Taking Fig. 2A, an acquired image in the imaging plane, as an example, the results of image processing and reconstruction are shown in Fig. 2B–E. The time for the image capturing, processing, and weld pool reconstruction is about 30 ms, which is fast enough for monitoring the weld pool dynamics in GTAW.
To define these parameters, the 2D parametric model of the weld pool shown in Fig. 3A is adopted (Ref. 28). This model uses $x_r = x/L$ and $y_r = y/L$. Once this model is obtained, the width of the weld pool is then calculated

$$w = w_r \times L = 2aL \left[ \frac{b}{1+b} \left( \frac{b}{1+b} \right) \right]$$

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Figure 3B shows the longitudinal intercepted area of the weld pool in oxy plane. The convexity is defined as the intercepted area divided by the length of the weld pool. Modeling the human welder response is then to correlate his adjustment $\Delta I_{k}$ as a function of the characteristic parameters in different instants around instant $k$. This can be done using the standard least squares algorithm. To obtain this optimal model, F-test (Ref. 31) has also been used to determine the instant range that needs to be included in the model for each of the characteristic parameters. As a result, the following model was obtained (Refs. 18, 19):

$$\Delta I_{k} = 0.4725 \Delta I_{k-1} + 0.1366 \Delta I_{k-2} + 0.6097 \Delta I_{k-3} - 2.2283 \Delta I_{k-4} + 1.6137 L_{k-5} - 1.2675 W_{k-3} + 1.7667 W_{k-4} + 0.0930 W_{k-5} - 0.6088 W_{k-6} + 30.3688 C_{k-3} + 19.6357 C_{k-4} - 67.6373 C_{k-5} + 18.7761 C_{k-6}$$

where $\Delta I_{k-j}$ is the current adjustment at instant $k-j$ with a 0.5-s sampling period. It can be found the human welder adjusts the current based on the previous current adjustments and weld pool surfaces.
is, the adjustment on the welding current by the human welder requires the length, width, and convexity of the weld pool surface to model adequately. In addition, the human welder makes the adjustment on the welding current based also on the previous adjustments he made 1 s ago.

**Experimental System and Methods**

In this section, the experimental setup and methods used to implement the human welder response model-based control are summarized.

**Experimental Setup**

The configuration of the experimen-
tal system is shown in Fig. 4. As mentioned in the human welder response model section on a vision-based sensing subsystem, having the laser pattern projecting the dot matrix on the weld pool surface, part of the dot matrix pattern is specularly reflected from it. Intercepted by the imaging plane, the reflection pattern is then captured by the camera. A computer connected to the camera is responsible for processing the captured image, reconstructing the weld pool surface, and extracting the characteristic parameters. Based on the obtained characteristic parameters of the weld pool surface, and extracting the characteristic parameters. Based on the obtained characteristic parameters of the weld pool surface, the adjustment needed for the welding current is calculated by the human welder response model.

According to the principle of welders' behavior briefed previously, a welder starts a welding performance with an optimal estimation of the welding parameters based on past experience. To imitate the welder’s behavior, in each experiment of the study, specific welding conditions (welding conditions and parameters that are not changed/adjusted on purpose in each particular experiment including welding speed, arc length, etc.) and an initial current are first applied for the weld pool to grow freely to complete joint penetration. Then the welding process is manually switched to control mode, i.e., the human welder response model starts to adjust the current for consistent complete joint penetration.

### Experimental Approach

In a manual welding process, a qualified welder can control the welding process to obtain a nearly uniform penetration (backside weld bead width) that he/she desires, even with different welding conditions. To this end, a number of experiments were conducted with different welding conditions and initial welding current in this study. At the beginning of each experiment, the weld pool grows freely.

### Table 5 — Welding Parameters for Root Opening Robustness Experiments

<table>
<thead>
<tr>
<th>Welding parameters</th>
<th>Experiments</th>
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<tbody>
<tr>
<td>Root opening/mm</td>
<td>0 2 [0, 5]</td>
</tr>
<tr>
<td>Arc length/mm</td>
<td>3</td>
</tr>
<tr>
<td>Initial current/A</td>
<td>54 58 54</td>
</tr>
</tbody>
</table>

**Fig. 8 — Current and voltage of the experiments. A — Initial current of 50 A; B — initial current of 54 A; C — initial current of 58 A; D — initial current of 62 A.**
With specific welding conditions and initial current, the welding process is able to reach to complete joint penetration. Yet, the dimension of the weld pool at complete joint penetration in each experiment is expected to be different. Then the experiment is manually switched to control mode, that is, to apply the human welder response model to control the process. Specifically, the model adjusts the welding current based on the geometry of the 3D weld pool surface such that the adjusted welding current controls the process to obtain a desired penetration that is evaluated by the backside weld bead width. After each experiment, the width of the obtained backside weld bead is measured to verify the effectiveness of the human welder response model-based control.

The experimental parameters used here are listed in Table 1. The pipe used in this study is 4-in. nom. stainless T-304/304L Schedule 5.

As mentioned before, a welder estimates an initial welding current to start a manual welding operation. The past experience-based estimation might vary within a reasonable range. Also, the arc length maintained by the welder might not always be the same during manual welding, as well as the root opening. The welding speed, on the other hand, does not change much when controlled by the welder, although it might vary within a small range. The welding speed is constant for the experiments in this study. The welder’s behavior under large welding speed variation is the authors’ future work and beyond the scope of the first study of this kind.

As presented in the introduction, the response model is developed based on the behavior of a human welder with limited skills. Given the physical limitation as a human, the welder might feel stress, fatigue, and lack of concentration in manual welding. Because of the possible inconsistent welding behavior, the welder’s response data used to develop the model cannot represent the prime performance of the human welder. In this sense, the model is only able to present an average performance of the human welder.

As the backside appearance of the weld bead. A — Initial current of 50 A; B — initial current of 54 A; C — initial current of 58 A; D — initial current of 62 A.

The effectiveness and robustness of the human welder response model-based control will be evaluated against those welding parameter variations in this paper.

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However, the control based on the human welder response model should be able to get rid of the inconsistency, which is a major issue with manual welding. The model is expected to either consistently produce a good weld by adjusting the current quickly and accurately to maintain uniform penetration, or produce an unqualified weld with a same failure pattern. Therefore, to verify the effectiveness of the model is to check if it is able to control the welding process to a comparatively consistent penetration, i.e., the backside width of the weld bead under different welding conditions and initial current can converge to a constant within a small variation margin.

There are several types of relevant data in this study. For the process, such data include welding current, arc length, and welding speed. Since the human welder response model under this specific study controls the welding process only by adjusting the welding current, such data are especially concerned with analyzing the performance of the control. Second, for the weld pool surface, the data include all its characteristic parameters, i.e., the length, width, and convexity. Studying the current adjustment and variation in the characteristic parameters can reveal how the model controls the welding process. At last for the weld bead, the backside width is the major data of interest. All these data, except the backside weld bead width, are acquired/recorded in real time. The backside bead width is measured with one sample/s interval offline. For example, if the welding speed in one experiment is 1 mm/s, then the bead width is measured every 1 mm while it is
measured every 1.5 mm if the welding speed is 1.5 mm/s, etc. In this sense, the bead width measurement can be matched with the time scale for other types of data.

**Human Welder Response Model Control**

In this section, the results from the experiments with initial current are presented and analyzed. As the first time to implement the human welder response model-based control, we focused on how the model controls the process to consistent complete joint penetration. Major welding parameters used in the experiments are listed in Table 2; the rest are the same as in Table 1.

Results from the two experiments, including the current, backside bead appearance, and its width, are presented in Figs. 5 and 6, respectively.

The data acquisition starts before the welding process begins. It is found that at the beginning of the two experiments, there are about 13-s (shown in Fig. 5A) and 12-s (shown in Fig. 6A) periods during which the current is 0, and the voltage is the open-circuit one at approximately 70 V.

The red vertical dash line in Fig. 5A indicates the time instant when the process is switched to the model-based control mode, i.e., the human welder response model is applied to adjust the current based on the 3D weld pool surface. From the figure, the control begins at 40 s and ends at approximately 96 s. The length of the weld bead obtained in this period can be easily calculated using the known welding speed. Since the position of the end of the welding is clearly seen in Fig. 5C, the position where the welding process begins to be controlled on the produced weld can be determined as shown by the red vertical line in the middle of Fig. 5C.

By the start position of the model control, each of the weld beads in the two experiments is divided into two zones as shown in Figs. 5C and 6C. In zone A, the backside bead width is determined by the welding conditions used and initial current. In the first experiment, the initial current is 50 A. The average width of the backside bead in this zone, shown in Fig. 5B, is about 1.7 mm. With a greater initial current (54 A) in the second experiment, the average width becomes 3.2 mm in zone A as can be seen in Fig. 6B. In zone B, the human welder response model starts to control the process for a desired and consistent penetration. Despite the fluctuation, the average width for the first experiment, shown in Fig. 5B as about 4.8 mm, and that in the second experiment, shown in Fig. 6B as about 4.7 mm, are considered...
A seasoned welder can easily overreact or underreact to the welding accurately so that he/she would frequently cannot predict the process quickly and accurately. The reason for using an unskilled welder with limited skill should be able to produce a comparatively consistent penetration is expected to be more consistent. The transitional period also should be reduced significantly. In this sense, adapting a low-pass filter to the human welder response model makes the model function like a more skilled welder.

**Results and Analysis of Robustness Experiments**

The human weld response model-based control is now improved simply by adding a low-pass filter as schematically illustrated in Fig. 7. To confirm its effectiveness in controlling the process to achieve the desired weld penetration, various experiments were designed and conducted in this section using this improved system to examine its performance/robustness under different welding conditions and initial welding currents.

In the first subsection, the experiments with different initial current amperages are conducted. The robustness of the waveforms. The fluctuation of the current adjusted after the model in the control system as shown in Fig. 7.

The low-pass filter used in this study can be written in Equation 4.

\[ \Delta I' = \alpha \Delta I_{k-1} + (1 - \alpha)\Delta I_k, \quad 0 < \alpha < 1 \]  

where \( \Delta I' \) and \( \Delta I_{k-1} \) are the filtered current adjustment at time instant \( k \) and \( k-1 \), respectively, and \( \Delta I_k \) is the current adjustment calculated by the welder response model at time instant \( k \). Coefficient \( \alpha \) controls the frequency bandwidth of the filter. A greater \( \alpha \) gives a wider bandwidth. In this study, \( \alpha \) is selected to be 0.5.

Since the filter blocks high-frequency components in the current output, its function would be pronounced during the transition period. However, when the current approaches its steady state, the high-frequency components become insignificant. The steady-state value of the current for a particular experiment is not affected by the filter. Moreover, since the current adjustment is smoothed by the filter, the current ripple is expected to be minimized. The backside weld bead width is expected to be more consistent. The transitional period also should be reduced significantly. In this sense, adapting a low-pass filter to the human welder response model makes the model function like a more skilled welder.
the human welder response model-based control with respect to the initial current is analyzed. In the next subsection, the arc length changes from 2 to 5 mm in the conducted experiments. The root opening is designed to vary from 0 to 5 mm in the last subsection.

Robustness with Respect to Initial Current

Experiments with different initial welding currents are conducted again but with the improved control system. Since the purpose is to examine the effectiveness of the improved control, more initial currents (Table 3) in a greater range are used to examine the system’s robustness against the initial current used. The results are shown in Figs. 8 to 10. Figure 8 shows the current and voltage from these four experiments; the backside weld beads obtained are demonstrated in Fig. 9; and the measurements of the backside width of the weld beads are presented in Fig. 10.

Since the initial welding current determines the backside width of weld bead in zone A, with different initial currents, the obtained weld beads have different backside widths. Specifically, the backside bead width in the experiment with the initial current 50 A is 3.2 mm; with greater initial current (54 A) in the second experiment, the backside width is 3.7 mm; the backside width obtained in the third experiment (initial current 58 A) and fourth (initial current 62 A) are 4.7 and 5 mm.

The settling time (set the error margin 5%) (Ref. 30) for the process to achieve the steady state is in the range from 3.5 to 4.5 s. For the experiment with an initial current of 62 A, the steady-state current is only about 0.5 A less than the initial current. The transition period is negligible from Fig. 8D. Besides that, the settling times of the other experiments are close to each other, only with 1 s difference, despite the difference in the initial current used. As discussed in the human welder response model section under the principle of human welder’s behavior, a welder would start to weld with an optimally estimated initial current (initial welding parameters) based on past experiences. A skilled welder might adjust the initial current close to the steady-state current that produces a desired penetration. The effect from the transition period on the result then can be minimized. An unskilled welder, on the other hand, might not be able to predict the initial current close to a current that leads to the desired penetration.

The transition period for the backside weld bead is different such that the settling time for the backside bead width differs from that of the welding current. From Fig. 8C and D, the initial current is close enough to the steady-state current. Therefore, the width of the backside bead in each of the two experiments only increases about 0.2 mm after the control is applied as shown in Fig. 10. The effect from the settling time on the welds produced for these two experiments is negligible. However, the settling time for the backside bead width observed from the experiments with an initial current of 50 and 54 A is about 13 and 10 s, respectively. The backside weld beads take a longer time than the welding current to reach the steady state.

The difference in the settling time between the welding current and backside bead width is understandable. There are two dynamic processes involved, and each of them has a settling time. First, after the current settles down reaching its steady state, the weld pool surface will take an additional transition period to reach the corresponding dimension. The first dynamic process is the transfer from the welding current (parameters) to the weld pool surface. Second, after the 3D weld pool surface (front side) is settled down and reaches its steady state, the 3D weld pool surface on the backside that determines the backside bead width will take extra time to reach its corresponding steady state. The transition period associated with the backside width of weld bead is longer than the transition time of the welding current.

Figure 8 shows the steady-state current corresponding to the penetration obtained by the human welder response model varies from 59.5 to 61.5 A. And the steady-state width of the obtained weld beads, shown in Fig. 10, converges within the range from 5.0 to 5.3 mm in zone B. A 0.3-mm deviation in the backside bead width is considered acceptable. It is known that the weld pool is dynamic and vibrat-
ing through the welding process. Even a constant welding input might cause the backside bead width varies within a small range. It is possible that the difference of the weld pool dimension generated by the current varying from 59.5 to 61.5 A is unperceivable to the human welder response model. In this sense, despite the different backside width obtained at the beginning of those experiments, because of different initial current, a consistent penetration with only a 0.3-mm width variation is achieved using the model-based control.

**Robustness with Respect to Arc Length**

Arc length is another variation whose effect on the control system needs to be examined. Hence, experiments with different arc lengths are conducted. The initial current, arc length, and welding speed are listed in Table 4; the rest are the same as in Table 1. As can be seen from Table 4, only the arc length differs in the four experiments to be conducted while other parameters are the same. The resultant current, backside weld bead, and backside width measurements are presented in Figs. 11-13, respectively.

With an increase in the arc length, the arc distribution becomes broader, and the arc energy intensity decreases. The penetration capability thus reduces. From Figs. 12 and 13, the width of the four weld beads in zone A reduces down from 3.7 to 2.5 mm. To obtain a consistent penetration, the model-based control increases the steady-state current from 61 to 64 A in the experiments with the arc length ranging from 2 to 5 mm. As mentioned in the results and analysis of robustness experiments section under robustness with respect to initial current, a 2A deviation of the steady-state current is considered a reasonable margin for the control of the human welder response model. Only a 3A deviation is obtained here because of the difference in arc lengths. Therefore, the arc length does not significantly affect the value of steady-state current during the control using the human welder response model.

It is noticed that the voltage in Fig. 13 increases from 9 to 9.8 V due to the increase in the arc length. A difference of 0.8 V in the arc voltage is observed between 5 and 2 mm arc length. As for the settling time for the current in the four experiments, it is similar to each other, which is about 5 s, as can be seen from Fig. 11. The transition period for the backside width is also similar to each other, as shown in Fig. 13. The arc length difference does not affect that transition period of the current or backside width of the weld bead.

From Fig. 13, the backside width of the weld bead in the four experiments converges to about 5.2 mm in zone B. Among the four weld beads, the one with 2 mm arc length reaches the largest steady-state width (5.4 mm), and the weld beads with 3 and 4 mm arc length have the smallest steady-state width, which is about 5.0 mm. From Figs. 13 and 10, one can find that a nearly identical backside width, which is about 5.2 mm with a 0.4-mm variation margin is obtained despite a difference in arc length and initial current. That means the human welder response model is able to control the welding process to achieve a consistent penetration under different arc length and initial current. It is reasonable because the model changes the current based on its previous current adjustments and the 3D weld pool geometry, as discussed in the human welder response model heading under the human welder response model section.

Differences in weld pool dimension caused by different initial currents or arc lengths might not be undetectable for the human welder response model. Therefore, the model is able to maintain a consistent penetration despite the different arc length and initial current.
Root Opening Robustness

Root opening is difficult to be precisely controlled in production. The effectiveness of the human welder response model-based control needs to be examined under varying/different openings. In this subsection, experiments with different root opening conditions/variations are conducted. The root opening, arc length, and welding speed are listed in Table 5; the rest are the same as in Table 1.

There are three experiments. The nominal/intentional root opening in the first experiment is 0 mm as shown in Fig. 14A. As demonstrated in Fig. 14B, a 2-mm root opening is used in the second experiment. In the third experiment, the nominal opening gradually increases from 0 to about 5 mm as shown in Fig. 14C and D. The resultant current, backside weld bead, and their widths are presented in Figs. 15–17, respectively.

The steady-state current differs in these three experiments. The root opening is close to zero in the first experiment. The welding process is close to those in the results and analysis of robustness experiments section under robustness with respect to initial current and robustness with respect to arc length. Therefore, the steady-state current (63 A) is close to the resultant steady-state current obtained in the last two subsections. However, as the root opening increases, the weld pool surface tends to be more concave, which means the convexity of the weld pool is smaller. The current adjustment controlled by the human welder response model (Equation 3) tends to be smaller accordingly. The penetration capability of the arc also increases with the opening. Therefore, less heat input is required to produce the same penetration as the opening increases. The steady-state current for the second and third experiments are reduced to 61.5 and 54 A, respectively. The obtained backside widths of the weld beads in these three experiments are about 5.2, 5.5, and 5.6 mm, which are considered consistent with a reasonably small variation margin.

It needs to be mentioned that the welding process stops at the position where the root opening is about 4 mm in the third experiment. The experimental results in experiment 3 only claim that the human welder response model-based control can control the welding process to maintain the consistent penetration for a root opening 4 mm or smaller.

Conclusion

This paper addresses implementing the human welder response model to adjust the welding current in reply to the characteristic parameters of the 3D weld pool surface for maintaining consistent, complete joint penetration in GTAW.

The effectiveness and robustness of the human welder response model-based control are verified in the experiments with different welding conditions and the initial current. The material used in the experiments is stainless steel pipe (4-in. nom. stainless T-304/304L Schedule 5). For the initial conditions, the current varies from 50 to 62 A, arc length is within [2, 5 mm], and the root opening changes from 0 to 5 mm.

Under the experimental conditions used, the following were found:
- The human welder response model can diminish the inconsistent manual welding performance. The model can control the welding process by adjusting the current to maintain consistent complete joint penetration.
- The backside width of the weld bead corresponding to the consistent complete joint penetration is about 5.2 mm with a 0.4-mm error margin.
- The maximum root opening at which the human welder response model can produce a consistent complete joint penetration is about 4 mm.

The effectiveness and robustness of the human welder response model control are verified against different welding conditions and initial current amperages.

Future studies will focus on modeling behaviors of skilled welders. The resultant models may be directly used without low-pass filters to develop control systems for improved performance. Differences and similarities with those of the novice welder will be analyzed and used to help train and improve less skilled welders.

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References


