Research article

Research on weld pool control of welding robot with computer vision

H.Y. Shen, H.B. Ma, T. Lin and S.B. Chen
Shanghai Jiao Tong University, Shanghai, People's Republic of China

Abstract
Purpose – The control of weld penetration in gas tungsten arc welding (GTAW) is required for a "teach and playback" robot to overcome the gap variation in the welding process. This paper aims to investigate this subject.
Design/methodology/approach – This paper presents a robotic system based on the real-time vision measurement. The primary objective has been to demonstrate the feasibility of using vision-based image processing to measure the seam gap in real-time and adjust welding current and wire-feed rate to realize the penetration control during the robot-welding process.
Findings – The paper finds that vision-based measurement of the seam gap can be used in the welding robot, in real-time, to control weld penetration. It helps the "teach and playback" robot to adjust the welding procedures according to the gap variation.
Research limitations/implications – The system requires that the seam edges can be accurately identified using a correlation method.
Practical implications – The system is applicable to storage tank welding of a rocket.
Originality/value – The control algorithm based on the knowledge base has been set up for continuous GTAW. A novel visual image analysis method has been developed in the study for a welding robot.

Keywords Welding, Control equipment, Seam welding, Robotics, Computer-aided manufacturing

Paper type Research paper

1. Introduction

At present, more and more welding robots and automatic welding machines have been applied in automatic-manufacturing process. Compared with the automatic machines, flexibility is the biggest advantage of the robots. However, most of welding robots primarily work in "teach and playback" mode, which limits their flexibility. Generally, welding encounters many variables, such as the errors of pre-machining, fitting of work-piece and in-process thermal distortions, which will result in changes of the gap size. In welding process, such subtle changes will seriously affect the quality of the welding joint. The "teach and playback" robots cannot meet the requirement of quality and diversification. Therefore, there are many issues need to be addressed to develop an autonomous welding robot. It is obvious that real-time weld pool control is important issues in this field.

The visual sensing has become the focus in the region of studying on sensing technology of the welding robot. Since, the visual sensing has many advantages, for example, it does not contact to the weld pool, and the information is very abundant. Most welding-related applications are used in seam tracking and checking the weld pool (Yu and Na, 1997; Yu and Na, 1998; Bauchspiess *et al.*, 2001; Smith and Balfour, 2005; Zhou *et al.*, 2006; Lee *et al.*, 2007; Lee and Na, 2002, web sites: www.scout-sensor.com/; http://lca.kaist.ac.kr/Researches/; www.roboticsonline.com/public/articles/archive-details.cfm?id = 605; www.bara.org.uk/pressreleases/meta2.htm; www.manufacturingtalk.com/indexes/categorybrowseei.html). Meta is a leading manufacturer of laser vision system for welding applications worldwide (www.meta-mvs.com). Meta vision systems based on the active vision principle have been extensively applied in the manufacture. Compared with the active vision sensor, the passive vision sensor has quite low cost and can obtain more information from the weld pool. But the captured image based on the passive vision is not better than that based on the active vision. Therefore, with the development of the machine vision, there should be more techniques to be studied on the passive vision. In this paper, the technology of the passive vision is studied.

A number of significant achievements have been made in the research field of autonomous welding robot by means of visual sensing (Kim *et al.*, 1996; Kuo and Wu, 2000; Bae *et al.*, 2002; Ge *et al.*, 2005). In some studies, the camera was directly used to view the weld pool and its vicinity to obtain control information such as the size, the position of the weld

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pool and the width of the gap (Yamane *et al.*, 1993; Zhao *et al.*, 2001).

Seam gap is the most direct influencing factor for continuous gas tungsten arc welding (GTAW). In many studies on weld penetration, some geometrical properties of the weld pool have been regarded as the measurement information, such as the topface and underside width of the pool, the length of the pool. Smith (Smith and Balfour, 2005) presented a system based on the real-time vision measurement and control of the upper surface weld pool size. Zhao (Zhao *et al.*, 2001) and Wang (Wang *et al.*, 2005) viewed the topface and underside geometrical properties of the weld pool to construct a prediction model to control the underside width of the pool at next step. Then, Zhang (Zhang *et al.*, 2005) and Fan (Chongjian *et al.*, 2007) added the measurement of the seam gap to improve the prediction model. Chen (Chen *et al.*, 2000) proposed an intelligent technique for fulfilling quality control of bead-on-plate welding. In fact, except for the welding of pipes, most of the work-pieces are fixed into a welding jig during welding process, and the underside of weld pool is not visible. So, the research on the underside width of the pool as measurement signal is difficult put into practice. Moreover, most of the welding control techniques using visual sensing are all based on pulsed GTAW, because a clear image can be captured in the base time when the welding current value is constant and low. However, continuous GTAW is widely applied in manufacture, instead of pulsed GTAW. During continuous GTAW, nothing but the topface width of the pool and the seam gap can be measured (Shen *et al.*, 2007), and the topface change in width is with time lag. Therefore, the welding current and the wire-feed rate should be adjusted according to the change in the seam gap.

In this paper, the research background is the aeronautic manufacturing. The products, parts of a rocket, are welded using Motoman robot in Shanghai Spaceflight Precision Machinery Research Institute, China. The length of weld of the work-piece made of LD10 aluminum alloys is 1,300 mm and the welding procedure is continuous GTAW with BJ380A wire filler. The work-pieces are too large to assure that there is zero gap joint and this gap is randomly variable. So, weld pool control, based on computer vision for the welding robot, was proposed for this study.

In our research, the visual sensor viewed the weld pool through the optical filters. An image-processing algorithms was developed to extract the seam gap. Depending on the experiential welding procedures, a controller was built for adjusting the welding current and wire-feed rate using the seam gap as the input parameter. The image-processing program and the weld pool control program ran on a PC with the multithread programming technology in C + + computer language.

2. System description

The welding robot system developed in this study consists of a "teach and playback" robot, a visual sensor composed of a charge couple device (CCD) camera and the optical filters, a welding power source, a control computer and an interface box. According to the spectral character of the aluminium-alloy welding, a wideband filter and two-dimmer glasses are used for the sensor. The transmission and of the wideband is 590-710 nm. The attenuation of the two-dimmer glasses is 99 and 70 percent, respectively. Figure 1 shows a schematic diagram of the real-time weld pool control system of welding robot with computer vision. The photo of the welding robot is shown in Figure 2. The robot is a six-axis industrial robot, made of Motoman Robot Co. Ltd The visual sensor is fixed on the end joint of the robot and moves with the robot. The CCD camera receives the weld pool image through double-layer filter system after twice reflection. Then the computer captures the images by the image capturing board, extracts the seam gap in real time using the image-processing algorithms and calculates the adjustment of the welding current and wire-feed rate. Finally, the calculated analogue control voltages are sent to the power source and the wire feeder.

3. Image processing

The visual sensor captures the images of the weld pool in the topface front direction. Figure 3 shows the weld pool image of GTAW for the flat butt weld with groove.

The image-processing technique that has been implemented is based upon eight-bit grey-level image. This has been combined with a simple calibration procedure that has been used to calculate the relation between the real gap (in the absolute coordinate system) and the image gap (in the image plane coordinate system). Figure 4 shows the seam gap in the image plane coordinate system. As the arc light is too intense to clearly view the seam gap near the weld pool, so the current seam gap is defined as the gap at the weld center which is calculated by fitting the seam edges. In Figure 4, point a is the center of the weld pool, d is the projection offset caused by the existing angle between axis of the CCD and torch, and $f_{\mathrm{gup}}(x)$ and $f_{\mathrm{gdown}}(x)$ are the both fitted edges functions, respectively. Figure 4 can be understood better combined with Figure 5. Usually, the distance between the tip of the tungsten electrode and the work-piece is 5 mm, which is appropriate to GTAW. When keep this distance and the torch is normal to the work-piece, the relation between the real value and each image pixel is calibrated. During the welding process, a tracking board in the robot controller adjusts the distance and the offset in real time, which is another research field and will be represented in other paper.

Since, the size of the captured image is 768 × 576 pixels, most of which is useless and will cost plenty of CPU time, we selected two areas for image processing, called window 1 and window 2 (shown in Figure 3), respectively.

The seam edges and the center of the weld pool have been exacted accurately by a series of digital image processing procedures in the image plane coordinate system. In window 1, the image processing sequence is median filter, Robert operator edge detection, thresholding, removing small area, thinning, extracting the seam edges and fitting edges with least square method. Compared with window 1, the image processing of window 2 is not too hard. The sequence is median filter, thresholding, Robert operator edge detection, thinning and extracting the outline of the arc and center of the weld pool. The detailed algorithm has been represented in literature (Shen *et al.*, 2007). Figure 5(a) shows the result of seam edges fitted with least square method. $f_{\mathrm{gup}}(x)$ and $f_{\mathrm{gdown}}(x)$ are the both edges functions, respectively. In Figure 5(b), point a is defined as the center of the weld pool. It is on the line $\overrightarrow{tv}$ that is the orientation of tungsten electrode, also on the line $\overrightarrow{pw}$ that is the link of the widest

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Figure 1 The schematic diagram of the real-time weld pool control system of welding robot with computer vision

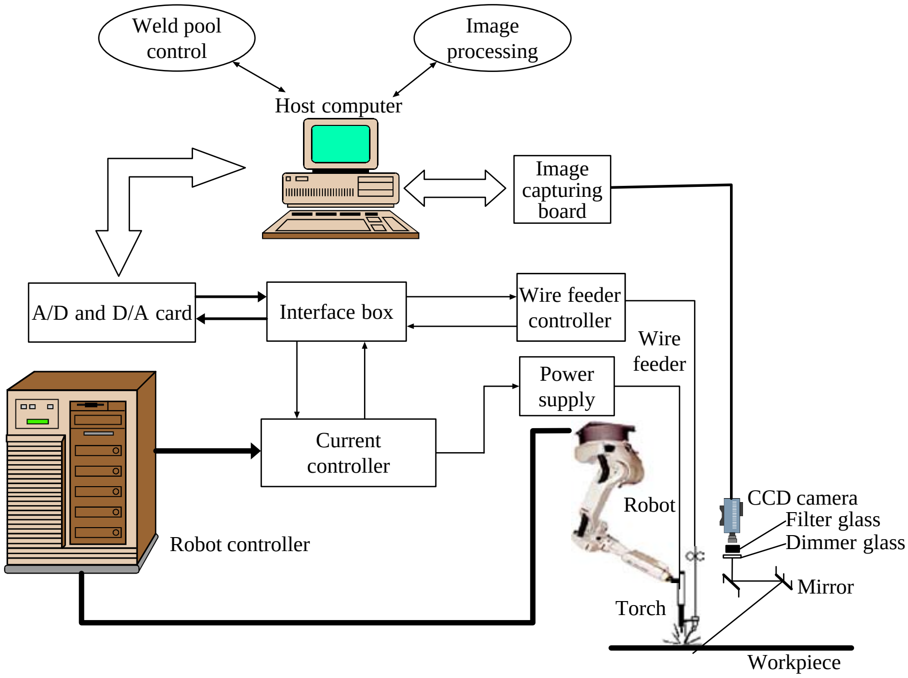
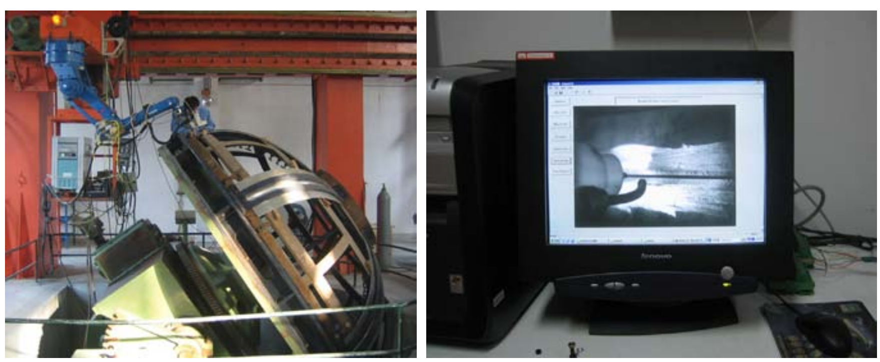
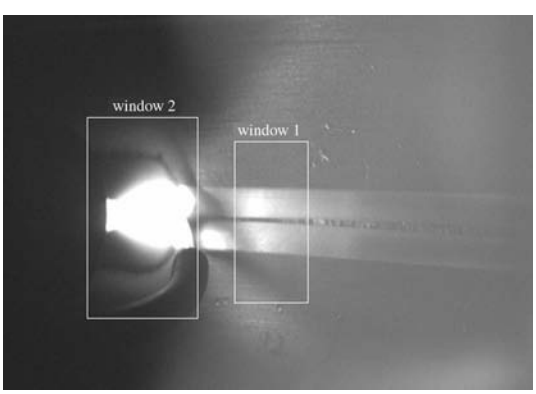


Figure 2 The photo of the welding robot system: (a) the robot and products; (b) the seam gap viewed by CCD after to be fixed



(a) **(b)**

Figure 3 The weld-pool image of GTAW



points of the arc. It is well known that the arc light is very intense and aluminum alloy has a good reflectivity, and the seam is obscure in the reflecting region in front of the weld pool. So the current seam gap ($g(t)$) is defined as the gap where point $a(a_x,a_y)$ lies according to the fitted seam edges. That is:

$$g(t) = f_{\text{gup}}(a_x) - f_{\text{gdown}}(a_x) \tag{1}$$

This image processing algorithm has been validated and demonstrated that it can cope with images when welding with the different current (in the range of 200A ~ 320A), which is usually used for making welds in medium plate aluminum alloy weld (in the range of 3 ~ 8 mm). The accuracy of the measurement is in the range of ±0.1 mm.

Figure 4 The seam gap in the image plane coordinate system

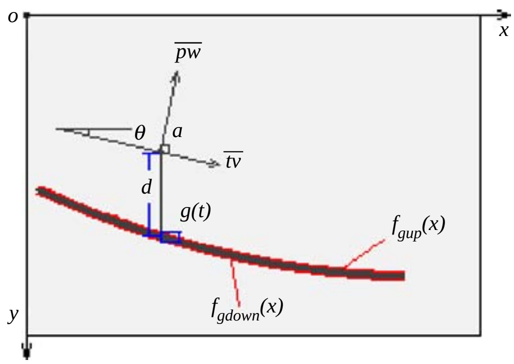
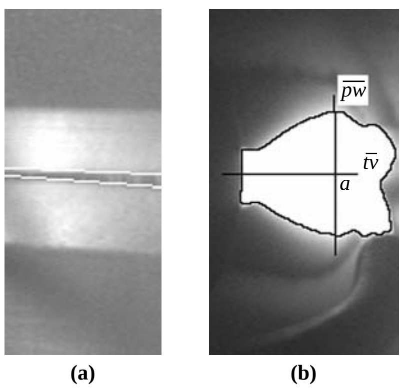


Figure 5 The results after image processing: (a) window1; (b) window2



4. Process control

Actually, to maintain the stability of the welding process, the parameters are adjusted as little as possible. When the gap is small, a good welding joint can be attained by only adjusting the wire-feed rate. But, when the gap is too great, the heat input at constant current prove to be far larger than that required and the work-piece would be often burnt through.

As a result, the control rules for different gap have been designed, as shown in Table I. The gap in the range of $0 \sim 0.3$ mm is so small that it is not necessary to adjust the welding procedures. On the other hand, when the gap exceeds 2 mm it is too large to be welded by the automatic machine, including the sensor controlled industrial robot. When the gap is in the range of $0.3 \sim 2$ mm, control of welding can be achieved. Within this range, 1.2 mm was found to be a demarcation point. If the gap is less than or equal to 1.2 mm, wire-feed rate is adjusted as the only control quantity. If the gap is greater than 1.2 mm, both wire-feed rate and welding current are adjusted.

Table I The control rules for different gaps

Gap/(mm)	Controlled quantity	Controller
$0 \sim 0.3$	-	Without control
$0.3 \sim 1.2$	v_f	PID for v_f
$1.2 \sim 2$	v_f and I	PID for v_f and Fuzzy for I
>2	-	Without control

The process controller involves two independent controllers has been designed after plenty of welding experience. One is a classical proportional, integral and derivative (PID) controller, the other is Fuzzy controller. A simplified diagram of the approach used is shown in Figure 6.

4.1 Wire-feed rate controller

Wire-feed rate (v_f) is the key factor to compensate for changes in the gap (g) that occur during welding process. In fact, there is a mapping function between v_f and g in the stable welding process.

In this research, we studied the backing weld of aluminum alloy plates with groove, whose reinforcement was required to be in the range of -0.5 ~ 0 mm and zero being most desirable. If we suppose that the reinforcement is zero and all the wires is used to fill the seam. Then the volume of the metal (V) that is needed to fill the seam is equal to the volume of metal (V') that is fed by the wire feeder. Figure 7 shows the sectional sketch of the joint.

Then V and V' are represented as follows:

$$\begin{cases} V = \left[\left(h_2^2 \times \mathrm{Tan}(\alpha) + gh\right) \times V_\mathrm{w} + K_l(t)\right] \times t \\ V' = \left[\pi \times \left(\frac{\phi}{2}\right)^2 \times v_f\right] \times t \end{cases} \tag{2}$$

where V_w is the welding speed, t is the welding time and ϕ is the diameter of the welding wire. $K_l(t)$ is the volume of the metal count of the root reinforcement which is usually the same size with the welding backing.

According to the analysis above, the relation is shown as follows:

$$\pi\left(\frac{\phi}{2}\right)^2 \cdot v_f = \left(h_2^2 \cdot \mathrm{Tan}(\alpha) + gh\right) \cdot V_\mathrm{w} + K_l(t) \tag{3}$$

If the welding process is very stable, the change of $K_l(t)$ is subtle. So, we may neglect its change with time. Then:

$$\Delta v_f(t) = \frac{4h}{\pi\phi^2} \cdot V_\mathrm{w} \cdot \Delta g(t) \tag{4}$$

where $\Delta v_f(t)$ and $\Delta g(t)$ are the changes of v_f and g with time, respectively.

According to the relation represented in equation (4), there is an approximate linear relation between Δv_f and Δg. So, the PID terms as shown in equation (5) is used in the wire-feed rate controller.

$$\Delta v_f(k) = k_\mathrm{p}\Delta e(k) + k_\mathrm{i} e(k) + k_\mathrm{d}[\Delta e(k) - \Delta e(k-1)] \tag{5}$$

where $\Delta v_f\,(k)$ is the adjustment of the wire-feed rate, $\Delta e(k)$ is the change of the seam gap, k_p is the proportional gain, k_i is the integral gain and k_d is the derivative gain.

The k_p, k_i and k_d can be ensured according to the sound welding procedures for the products having been acquired as shown in Table II. The welding procedures in Table II are the most stable for different gaps. Actually, certain a scope of the welding current and the wire-feed rate can be used for a constant gap size. For example, in this research, if the gap is in the range of $0 \sim 1.2$ mm, the well weldment also can be obtained when the current is 255A, which is used in the welding current controller.

Figure 6 Block diagram of process controller

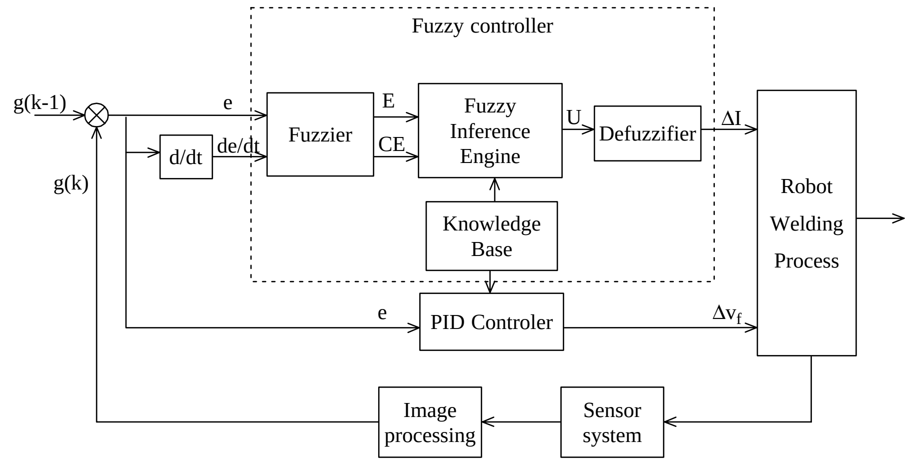


Figure 7 The sectional sketch of the flat butt weld

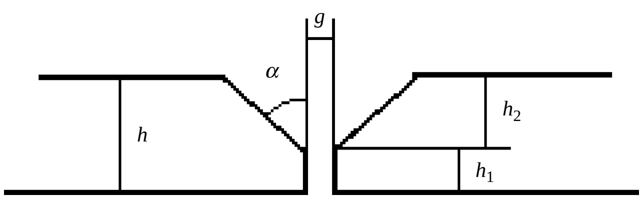


Table II The sound welding procedures for the products

Gap (mm)	Welding current/A	Wire feeding rate (mm s^{-1})	Welding speed (mm s^{-1})
0	260	20.10	2.67
0.5	255	24.73	2.67
1	250	28.72	2.67
1.5	240	31.84	2.67
2	235	35.40	2.67

4.2 Welding current controller

A Fuzzy controller has been chosen to adjust the welding current. Supposed that all the conditions excepting the welding current are constant, if g is increasing, I should be decreased in order to prevent the over heat input, but v_f is increased according to equation (4), which causes that I should be increased to provide more heat to melt the wire. Therefore, supposed that the welding current is I_0 and the wire-feed rate is v_{f0} when g is zero, the function can be expressed as follows:

$$I(t) = f(\Delta g(t), \Delta v_f(t)) + I_0 \tag{6}$$

Because of the equation (4), another relation can be represented as follows:

$$I(t) = f'(g(t), g(t-1)) + I_0 \tag{7}$$

Then:

$$\Delta I(t) = F(g(t), g(t-1), g(t-2)) \tag{8}$$

The relation F between ΔI and g is quite complicated and difficultly expressed with a exact mathematic function. So, the fuzzy controller has been built depending on the experience. The proposed fuzzy logic takes two variables to be fuzzified, as shown in Figure 6. One is e(k), which is the error of a gap ($G(k)$) from the reference gap ($G(k-1)$) at the previous one ($k-1$), and the other is the change of an error, de(k)/dt (Δe(k)).

The following knowledge is used to acquire a new welding current:

- If gap is small (e(k) $>$ (0) and becomes smaller (Δe(k) $>$ (0), then set much bigger welding current ($I > 0$).
- If gap is big (e(k) $<$ 0) and becomes bigger (Δe(k) $<$ (0), then set much smaller welding current ($I = 0$).
- If gap is big (e(k) $<$ (0) and becomes smaller (Δe(k) $<$ (0), then set small welding current ($I < 0$).
- If gap is small (e(k) $>$ (0) and becomes bigger (Δe(k) $>$ (0), then set bigger welding current ($I > 0$).

The fuzzy rule base has been constructed on the sound welding procedures shown in Table II. Each fuzzy subset for an error is set to correspond to an error of $0, \pm 0.5, \pm 1, \pm 1.5, \pm 2$ mm, respectively; each fuzzy subset for the change of an error to correspond to the change of an error of $0, \pm 0.5, \pm 1, \pm 1.5, \pm 2$ mm, respectively; and each fuzzy subset for the change of a welding current to correspond to the change of a welding current of $0, \pm 5, \pm 10, \pm 15, \pm 20$A, respectively. The process input (ΔI) can be obtained by defuzzifier using the center of gravity method. So, the welding current can be updated in a control period of 0.2 s using an industrial computer with PIII 1.7G–Hz CPU and 512 M memory.

5. Experiment results

Welding experiments have been conducted using a GTAW robot system to evaluate the feasibility of controlling the weld pool during the backing welding of an aluminum weld joint. The specific parameters are given in Table III.

The butt weld work-pieces with two segments having gaps of 2 mm have been designed to demonstrate the ability of the controller to accommodate such changes in gap (for different gap as shown in Figure 8). The original welding procedure was used to weld the seam with no adaptive control and the results are shown in Figure 9. When the gap first changes

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Table III Aluminum alloy welding parameters

Parameter	Value
Process	AC GTAW at 60 Hz
Material	6mm thick LD 10 aluminum alloy plate with a *Y*-groove of 80°
Thickness of root face	2 mm
Backing bar	1Cr18Ni9Ti
Original welding current	255 A
Original wire-feed rate and the wire type	20.10 mm s^{-1} BJ380A
Welding speed	2.67 mm s^{-1}
Shielding gas	Ar

Figure 8 The work-pieces with two segments having gaps of 2 mm

from zero to 2 mm, the heat input is too large and there is no enough wire fed, so the seam is burned through. At the second gap slot, the seam is not burned through as the thermal distortion caused the gap to close with the result that the reinforcement is sunken at least 2 mm.

Compared with Figure 9, Figure 10 shows the results using the process control as described above. The curves of the gap, welding current and wire-feed rate during the welding process are shown in Figure 11. In Figure 12, the sample points from Nos 160 to 250 are zoomed to show that the controller switches between the two types of control (v_f/v_f and I). The wire-feed rate is always controlled with the change in the seam gap. The welding current is only adjusted between the sample points from Nos 160 to 204, and the welding current is 255A after No.204.

Then we can see the result of the product that is welded by welding robot with the original welding procedures in Figure 13. Figure 14 shows the result with the process control. Both, the topface and the underside have a good forming and the quality met the standard of first-order (highest quality according to standard QJ2698-95) welding seam in terms of dimensions and soundness as demonstrated by X-ray inspection.

6. Results

This paper has researched a welding process control for "teach and playback" robot with computer vision. It has been demonstrated the feasibility that the visual sensing technique can be use to detect the seam gap during the continuous GTAW process. The stable image processing algorithms used to measure the gap size can cope with images in different levels of welding current. The weld-penetration problem is solved well only to detect the topface geometrical properties of the weld pool. Process control has been implemented in the form of a PID method that adjusts the wire-feed rate and the form of a Fuzzy method that adjusts the welding current. The proposed technique has been applied in the "teach and playback" robot-welding process, which helps the robot choose the corresponding welding procedures with the gap variation. The quality of the products welded with the robot using the process control has reached the standard of first-order (highest quality according to standard QJ2698-95) welding seam in terms of dimensions and soundness as demonstrated by X-ray inspection. At present, the proposed system has been applied to assist the production.

Future work should improve the optical filters and the image analysis algorithm to deal with the images in other welding procedures, such as MIG/MAG. The vision sensor also should help the robot track the seam in real time. Another CCD camera should be added to view the weld pool from its rear to obtain more information of the weld pool for a penetration control.

Figure 9 The weldment with two segments of 2 mm gap without control: (a) topface; (b) underside

(a) (b)

Figure 10 The weldment with two segments of 2 mm gap with control: (a) topface; (b) underside

(a) (b)

Figure 11 The curves of the gap, welding current and wire-feed rate for the testing work-piece

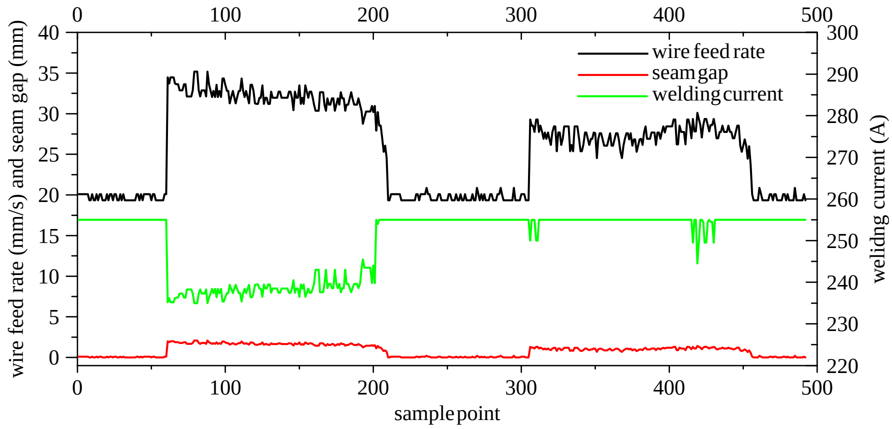


Figure 12 The curves of the gap, welding current and wire-feed rate between sample points from Nos 160 to 250

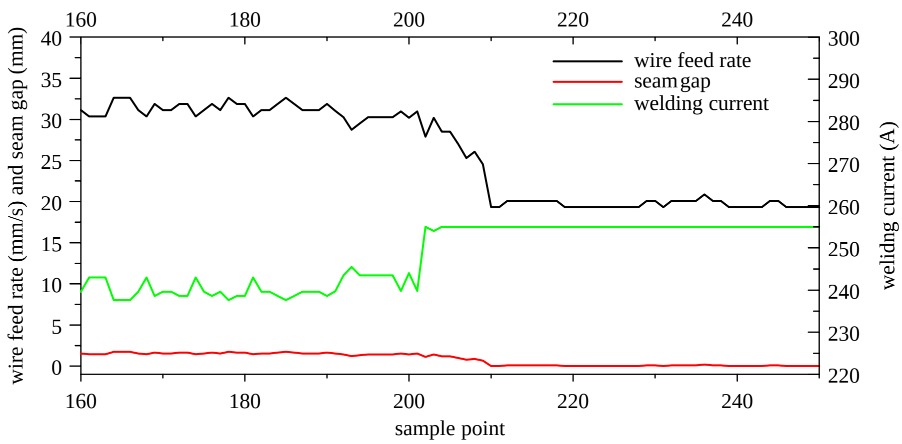
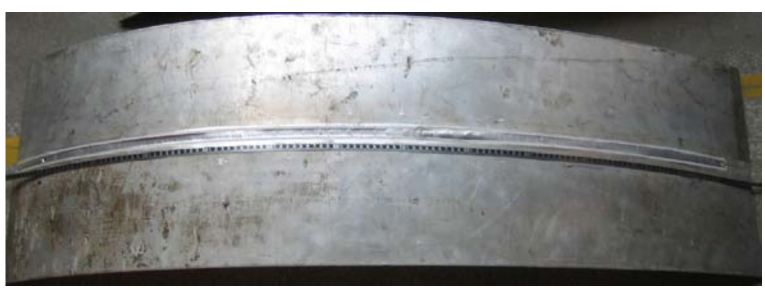


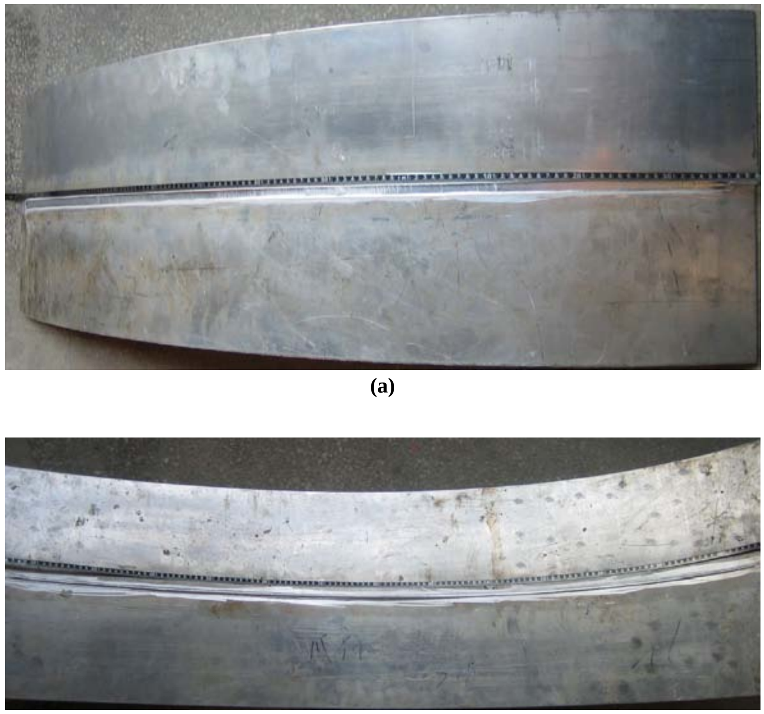
Figure 13 The result of the product without the process controller: (a) topface; (b) underside



(a)

(b)

Figure 14 The result of the product with the process controller: (a) topface; (b) underside



(a)

(b)

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Corresponding author

H.Y. Shen can be contacted at: shenhhy@sjtu.edu.cn