Penetration control of GTAW process for aluminum alloy using vision sensing

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Abstract. Unpredictable and inevitable perturbations during welding have adverse effects on the uniformity of weld penetration degree. Hence feedback control of weld penetration is necessary for assuring the welding quality. The backside weld bead width, regarded as a representation of penetration state, is measured usually by a structured-light sensor during the welding process. However, the structured-light method can only measure the width of the solidified weld behind the weld pool, but not the weld pool width, owing to the specular weld pool surface, thermal radiation and the possible arc light. It will introduce a time delay into the penetration control system. A novel low-cost visual technique of acquiring the backside weld pool width is developed in this paper, and the closed-loop control of weld penetration is achieved during gas tungsten arc welding (GTAW) for aluminum alloy. The parallel light is projected onto the weld pool backside, and the outline of the weld pool is highlighted because of the different reflection from the plate’s flat surface and the weld pool’s convex surface. Changes in the plate geometry are introduced during the experiments to perturb the welding process. Results show that stable penetration is maintained despite the perturbation.

1. Introduction
Weld penetration is one of the most important factors in judging the quality of a welding joint. It is difficult to assure uniform penetration only by the specified welding parameters. The varied heat transfer condition, the installation error, the welding distortion and the fluctuation of welding parameters could lead to inconsistent weld penetration during the welding process and thus increased post-process work and a larger production cost. Feedback control of welding quality is always an active area of research.

Many sensing techniques have been developed by researchers to monitor the penetration state and improve the quality of welds produced by automated welding systems. Hardt and Katz [1] used ultrasonic pulse-echo measurements to determine the size of a stationary weld pool. However, the ultrasound transducer required to be attached to the workpieces, and the ultrasound reflection distortion caused by the thermal gradients in welding precludes the use of the method. Some researchers [2-3] managed to predict and control the weld penetration directly through features of the arc sound signal during gas tungsten arc welding (GTAW). But the accuracy of the prediction model was not sufficient for industrial applications and the approach was sensitive to the noise in fabrication environments. Studies have also been conducted in infrared sensing of welds. Wikle et al. [4] measured the temperature of the area adjacent to the weld pool by a point infrared sensor and...
performed a closed-loop control of weld penetration. The problem was that the arc light disturbs the infrared thermometry. Researchers [5] also exploited the possibility of identifying the penetration state via fusion of sound, voltage and spectrum signals.

Among various monitoring techniques, vision sensing is often adopted by researchers due to its non-contact feature, anti-electromagnetic interference, and rich information [6-8]. Zhang et al. [9] projected structured light onto the weld bead to acquire the front-face weld width and the average weld depression depth. A relationship between the front-face geometrical parameters and the back-face weld width was established, producing the final welding penetration feedback. Recently, Shi et al. [10, 11] captured the images of the laser stripe pattern reflected by the weld pool surface and obtained the pool oscillation frequency via the periodic variation of the images. It was confirmed that the oscillation frequency indicated joint penetration state. But the method involved time-consuming computation and was not suitable for real-time control. Chandrasekhar et al. [12] acquired infra-red thermal images of the weld pool and developed adaptive neuro fuzzy inference systems and artificial neural network based models for estimating weld bead width and penetration depth from thermal images. Liu et al. [13] designed an adaptive neuro-fuzzy inference system based on the 3D vision information of the weld pool to imitate human welders’ experience and achieved a uniform penetration. When the backside of the weld pool was accessible, some researchers [14, 15] measured directly the backside weld bead width using structured light. But the structured-light method can only get the width of solidified weld bead behind the weld pool only, but not the width of the weld pool, since the specular weld pool surface causes the loss of the laser stripe, which introduces a time delay into the penetration control system. And the high-precision structured-light sensor is expensive.

In this paper, an innovative vision-based method is developed to acquire the backside weld pool width and is applied to the penetration control of GTAW process for a typical aluminum alloy in the aerospace industry. The proposed control principle is shown in Figure 1. The backside weld width, namely the weld penetration feedback, is obtained through a vision sensor and the corresponding image processing. The vision sensor utilizes parallel rays to illuminate the back-face of the workpieces. In the captured image, the gray value of the weld pool is distinct from that of the workpieces, due to the difference in angles of reflection. The backside contour of the weld pool, and thus the width is extracted by image processing. And the welding current is altered by a proportional-integral controller to adjust the heat input during welding.

![Figure 1. Vision-based control of full penetration during GTAW.](image_url)

2. Experiment scheme

2.1. Vision sensing for the backside of the weld pool
The vision sensing system is shown schematically in Figure 2. The camera is focused on the backside surface of the workpieces under the welding torch where a weld pool can be observed. Parallel light rays are projected onto the same area, and the angle of incidence is designed to make incident rays...
reflected right into the camera lens, supposing that the surface of workpieces is specular. When there is a weld bead or a weld pool on the workpieces, the reflection changes. The flat surface of workpieces and the convex surface of the weld bead have different normal directions, causing different directions of reflected light, as illustrated in Figure 3. The majority of the light reflected by the weld bead (marked with red) is not received by the camera. So the weld bead and the weld pool are presented as a dark area in the captured image, as shown in Figure 4(d), whereas the other area is bright.

**Figure 2.** The visual method of measuring the backside width of the weld pool. The parallel light is cast on the backside surface of the workpieces. The angle $\alpha$ between the axis $l_2$ of the parallel light and the normal $l_1$ of the workpiece surface is equal to the angle $\beta$ between the lens axis $l_3$ of the camera and $l_1$. The parallel light is reflected into the camera by the flat surface of the workpieces.

**Figure 3.** The difference of propagation directions of light rays reflected by the weld bead surface and the other area.

Figure 4 shows typical images of the backside weld under different light conditions. Only part of the weld pool can be observed in the image owing to the thermal radiation when the image is taken without extra illumination, as described in Figure 4(a) and 4(b). It is hard to distinguish the edge of the weld pool from the background. A larger exposure time helps enhance the edge yet decreases the sample rate and prolongs the control cycle of the feedback control system. Under diffused natural light, the weld pool and the weld bead are distinct from the workpieces in Figure 4(c), while the contour is still blurry. In Figure 4(d), parallel rays highlight the gray value’s difference between the weld zone and the base metal. And a clear outline and the backside weld pool width is available through the following image processing:

(a) selecting the region of interest (ROI) and reducing noise;
(b) extracting the foreground by binarization and morphological operations;
(c) extracting the contours of the foreground;
(d) finding the contour of the maximum area as the edge of the weld zone;
(e) calculating the backside weld pool width.

The steps above are demonstrated in Figure 5. The image processing algorithm has been tested on extensive images and performs reliably. The statistics based on 1,500 frames of images give an average processing time of 1.0 millisecond. The vision sensing method of measuring the backside pool width is considered to be real-time, compared with the sample rate of 32 Hz.

![Figure 4](image1.png)

**Figure 4.** Images of the backside of the weld pool and the weld bead under different light conditions. (a) Exposure time is 15 ms without illumination; (b) exposure time is 20 ms without illumination; (c) exposure time is 20 ms with the illumination of natural light; (d) exposure time is 0.3 ms with the illumination of parallel light.

![Figure 5](image2.png)

**Figure 5.** Image processing. (a) The original image and its ROI; (b) noise suppression by a median filter; (c) binarization and morphological opening operation; (d) contour extraction; (e) finding the contour with the largest area and taking it as the outline of the weld zone.
2.2. Experiment configuration

Figure 6 presents the diagram of the experimental system for GTAW. The system consists of welding equipment, a vision sensor, an industrial personal computer and a linear table for moving the workpieces. The welding torch and the vision sensor are stationary during welding, while the workpieces move along with the linear table. A groove is made through the linear table for observing the backside of the weld seam. The camera has been calibrated to determine the conversion relationship between the pixels and the physical length in millimeters. The computer processes the digital images and adjusts the welding current via an analog signal. A proportional-integral controller is used, and the control frequency is 32 Hz, the same as the camera’s sample rate.

![Diagram of the experimental system](image)

**Figure 6.** The experimental system.

The experiment material is 2219 aluminum alloy, with its chemical compositions shown in Table 1. The 2219 aluminum alloy maintains outstanding mechanical properties and good resistance against stress corrosion from -253 °C to 200 °C. And the weld joint has low hot-crack sensitivity and high low-temperature toughness. Hence, the material is widely used in large-scale structural components in the aerospace field [16].

| Cu     | Mn     | Ti     | Mg    | Zn     | V     | Fe    | Si    | Zr    | Al     |
|--------|--------|--------|-------|--------|-------|-------|-------|-------|--------|
| 5.8-6.8| 0.2-0.4| 0.02-0.1| 0.02  | 0.10   | 0.05-0.15| 0.3   | 0.2   | 0.1-0.25| Bal.   |

The geometry of the weld specimen is depicted in Figure 7. Two plates of 6 mm thickness form a tight butt joint, and the oxide layer is removed by a scraper. The varying heat-transfer condition is emulated by the geometrical change of the workpieces. The width of the cross-section in the middle is smaller than that of both ends, indicating a bigger risk of collapsing in welding. The welding parameters are listed in Table 2.

**Table 1.** Chemical compositions of 2219 aluminum alloy (in wt.%).

| Parameter | Value       |
|-----------|-------------|
| Initial welding current | 165 A      |
| Arc length | 3 mm       |
| Traveling speed | 270 mm/min |
| Shield Gas | 15 L/min He |
| Electrode diameter | 1 mm      |
| Tip angle | 40°        |

**Table 2.** The selected welding parameters.
3. Experiment result

The open-loop and the closed-loop results are shown in Figure 8, 9, and 10. An initial welding current of 165 A is used, which is able to maintain stable penetration on ordinary workpieces with the open-loop control, as illustrated in Figure 8(a). However, Figure 8(b) demonstrates that the fixed welding parameters do not perform well under varying heat transfer condition. The backside weld bead width is larger in the middle section than that of the both ends, owing to worse heat transfer condition. This corresponds to Range II in Figure 9. The graph of the backside weld bead width along the weld seam is fluctuant rather than a smooth “bell curve” shape, since unpredictable random perturbations exist, like the transient variation of shield gas flow and the local joint misalignment. The arc voltage shows a similar tendency and reaches its maximum in Range II, indicating a deeper depression in the middle section of the weld seam. For the whole weld seam, the backside weld bead width varies up to 11 mm, with the standard deviation of 3.7 mm. The arc voltage has a fluctuation of nearly 4 V.

In the closed-loop control, the desired weld bead width is set as 8.3 mm. The weld geometrical parameters are well maintained despite the variation of heat-transfer condition, as shown in Figure 10, meaning a constant penetration. The error of the weld bead width is less than 1 mm, and the root-mean-square error is 0.4 mm. The variation of arc voltage is approximately 1 V. It is observed that the welding current decreases in the Range II and then resumes in Range III automatically. The closed-loop control is capable of handling the change in heat transfer condition. The effectiveness of the proposed vision sensing method and the control system is verified by the experiment results. Furthermore, overshooting happens when the closed-loop control just starts, and the welding current and the weld bead width oscillate during welding. Better results are expected to be obtained by optimization of controller parameters.

Figure 7. The geometrical configuration of the workpieces.

Figure 8. The backside of the weld bead. (a) The open-loop control experiment on ordinary workpieces; (b) the open-loop control experiment under varying heat transfer condition; (c) the closed-loop control experiment under varying heat transfer condition.
Figure 9. Welding current, voltage and backside width of weld bead in the open-loop control experiment. Range I, II and III represent the start section, the middle section and the finishing section of the weld seam, respectively. The heat dissipation rate in Range II is less than that in Range I and Range III due to the change of workpieces’ cross-section.

Figure 10. Welding current, voltage and backside width of weld bead in the closed-loop control experiment. Range I, II and III represent the start section, the middle section and the finishing section of the weld seam, respectively. The heat dissipation rate in Range II is less than that in Range I and Range III due to the change of workpieces’ cross-section.
4. Conclusions
A novel approach has been proposed for real-time measurement of the backside weld pool width and has been applied in penetration control of GTAW for aluminum alloy. The parallel light rays are used to distinguish the weld zone from the base metal and get a clear outline of the weld pool. The method is real-time with the image processing time of 1.0 millisecond. The uniform penetration is maintained by the feedback control throughout the welding process regardless of the varying heat transfer condition. The backside weld bead width keeps an error of less than 1 mm. Compared with the ultrasonic technique, the arc sound method and the infrared measurement, the presented visual method has the advantages of small computation, reliability, anti-interference and low cost. It is worth to mention that the method is suitable only for the situations when the backside of the weld joint is accessible, such as the internal circumferential welding of pipelines and the longitudinal joints of large fuel tanks. To circumvent the access problem due to the light source size and the camera size, the optical fiber bundle is an alternative method of transmitting light and images.

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