Laser-Vision-Based Measurement and Analysis of Weld Pool Oscillation Frequency in GTAW-P

An innovative laser-vision-based sensing method is proposed to measure weld pool oscillation frequency in pulsed gas tungsten arc welding (GTAW-P). A low-power five-line laser pattern is projected onto the entire weld pool surface as well as its reflection is intercepted by an imaging plane and captured by a high-speed camera. By observing and analyzing the change of the captured laser images during the base current period, it is found that the variation of reflected laser lines is periodic and has a strong relationship with the weld pool oscillation. A novel image processing algorithm is also developed for extracting the pool oscillation frequency. Several experiments with varying weld joint penetration for traveling and stationary weld pools were conducted, and the oscillation frequency extracted. Experimental results show that the weld pool oscillation is capable of being observed by this method. The extracted frequencies were verified, and the oscillation frequency of partial penetration is higher than the complete joint penetration, along with an abrupt transition. The image processing method and algorithm demonstrated good robustness and effectiveness, and could be used to monitor and control weld joint penetration in real time.

ABSTRACT

An innovative laser-vision-based sensing method is proposed to measure weld pool oscillation frequency in pulsed gas tungsten arc welding (GTAW-P). A low-power five-line laser pattern is projected onto the entire weld pool surface as well as its reflection is intercepted by an imaging plane and captured by a high-speed camera. By observing and analyzing the change of the captured laser images during the base current period, it is found that the variation of reflected laser lines is periodic and has a strong relationship with the weld pool oscillation. A novel image processing algorithm is also developed for extracting the pool oscillation frequency. Several experiments with varying weld joint penetration for traveling and stationary weld pools were conducted, and the oscillation frequency extracted. Experimental results show that the weld pool oscillation is capable of being observed by this method. The extracted frequencies were verified, and the oscillation frequency of partial penetration is higher than the complete joint penetration, along with an abrupt transition. The image processing method and algorithm demonstrated good robustness and effectiveness, and could be used to monitor and control weld joint penetration in real time.

KEYWORDS

• Pulsed Gas Tungsten Arc Welding (GTAW-P) • Weld Pool Oscillation Frequency • Image Processing Laser Vision • Weld Joint Penetration • Fast Fourier Transform (FFT)

Introduction

In recent years, the trend in high-productivity and high-quality welding has been toward process automation. This has stimulated the increased use of automation and associated systems. When replacing a manual welding machine with an automated system, it is necessary to provide the control system with information about the location of the weld bead and weld pool geometry. Therefore, sensing and modeling are becoming the key issues for successful implementation of weld process control. However, a particular problem that occurs in the case of the gas tungsten arc welding (GTAW) process is the difficulty of consistently obtaining complete joint penetration over the entire length of the weld joint. Consistent, complete joint penetration is an essential property of a good weld, especially in the case of the root pass of a thick plate or fillet weld under variable load conditions. In addition, weld joint strength, i.e., tensile strength and fatigue strength, is regarded as another standard of welding quality. The factors affecting the weld joint strength, which include external loads, cross-sectional area of the weld bead, etc., have been investigated and it was found that the cross-sectional area plays an important role in determining the weld joint tensile strength (Refs. 1, 2). Incomplete penetration/fusion can reduce the effective working cross-sectional area of the weld bead, which may reduce the weld joint strength when keeping the external loads constant. An incomplete penetration defect could also lead to serious stress concentrations in case of the fillet or T-joints. The presence of stress concentrations cause the later cracking and reduce fatigue life. However, too much penetration results in melt-through. Repairing inadequately penetrated welds is time consuming and costly. This makes the measurement and real-time process control of weld joint penetration highly attractive, especially in the case of welding austenitic stainless steel where so-called cast-to-cast variation in penetration may occur. Many attempts have been made to monitor and control the weld joint penetration using various sensing methods, such as temperature field (Refs. 3, 4), machine vision (Refs. 5–8), ultrasonic (Ref. 9), arc acoustics (Refs. 10, 11), radiography (Ref. 12), and others. Machine-vision sensing methods that provide direct feedback information of the weld pool geometry have been increasingly investigated. Particularly, in the manual GTAW process, a skilled welder can observe and obtain suffi-
cient information from the weld pool surface to estimate the degree of weld joint penetration, and then adjust the position or traveling speed of the weld torch to achieve a complete joint penetration (Ref. 13). The top and backside geometry of weld pool was acquired by a charged coupled device (CCD) camera, and its characteristic parameters were obtained by a specialized algorithm. Based on the above information, the neural network models of the top geometric parameters and the backside width of weld pool were established, and the control experiments were conducted on the workpiece of varying widths at the length of the direction (Refs. 14–16). Unfortunately, the correlation between the frontside weld pool geometry and the weld joint penetration should be researched further to facilitate real-time penetration monitoring and accurate penetration control of the GTAW process. The robustness of vision-based sensing methods is reduced due to interference from the arc light. Hence, they are not widely applied to practical joint penetration measurement.

Researchers have demonstrated that the oscillation frequency of a weld pool has a strong relationship with its volume size in the stationary GTAW process (Refs. 17, 18). Furthermore, extraction of the oscillation frequency for sensing and control of weld penetration has been a topic of interest since the 1980s (Refs. 19–22). These approaches are based on the principle that the change of arc length, which is caused by the weld pool surface oscillation in the vertical direction, results in a linearly simultaneous change of arc voltage, and the oscillation frequency is obtained by monitoring the arc voltage. However, the small amplitude of weld pool oscillation, which causes an unobvious change of arc length, and the other interferences, such as surface roughness, instability of weld power supply, welding environmental changes, result in poor signal-to-noise ratio (SNR) of the arc voltage. Extracting the oscillation frequency from the arc voltage is very difficult, and can only be applied to the very slow moving/traveling weld pools. Another way to monitor the weld pool oscillation is monitoring the intensity of the arc light as the arc voltage, the arc light intensity is also dependent on the arc length. Yoo et al. (Ref. 23) reported that the arc light sensor has a higher sensitivity compared with the voltage sensor. Barborak et al. (Ref. 24) observed that the sensing through arc voltage can be reliably utilized for travel speeds up to 3.83 mm·s⁻¹, while the arc light sensor can be used for speeds as high as 6.35 mm·s⁻¹. In comparison with voltage measurements, however, arc light monitoring is less practical since it requires additional equipment and needs a larger access area. These two methods to monitor the weld pool oscillation frequency cannot completely meet the requirements of the modern high-efficiency welding. Therefore, a rapid, simple, and effective sensing approach needs to be developed for measuring and control of weld joint penetration of the GTAW process in real-time.

Recently, a vision-based sensing system for the GTAW process has been developed in the University of Kentucky Welding Research Laboratory under Dr. YuMing Zhang’s supervision (Refs. 25–27). The three-dimensional weld pool surface can be reliably reconstructed in real-time and characterized by its width, length, and convexity (Ref. 28). The weld joint penetration was estimated by using the proposed optimal model and weld pool geometric parameters with an acceptable accuracy (Refs.

### Table 1 — Experimental Parameters

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Pulse Frequency (Hz)</th>
<th>Pulsed Current (A)</th>
<th>Base Current (A)</th>
<th>Average Current (A)</th>
<th>Duty Cycle – Ratio (%)</th>
<th>Welding Speed (mm/s)</th>
<th>θ (deg)</th>
<th>D (mm)</th>
<th>L (mm)</th>
<th>Arc Length (mm)</th>
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θ — The angle between laser generator and workpiece; D — Distance from weld tungsten to imaging plane; L — Distance from laser generator center to weld pool center.
29–31). However, for control of weld joint penetration, the welding parameters such as welding current, welding speed, and arc length should be adjusted. It is unclear if these characteristic parameters might be capable of predicting the weld joint penetration with acceptable accuracy when the weld pool varies substantially. In this paper, an innovative method is proposed and applied to monitor the weld pool oscillation, whose fundamental principle is the specular reflection of weld pool surface and the optical magnification of the weld pool oscillation amplitude on the imaging plane. A five-line laser pattern is projected onto the weld pool surface under the electrode at a certain angle that covered the entire weld pool. Then, the reflected laser lines are intercepted by an imaging plane and captured by a high-speed camera with filter components in the pulsed GTAW process. To extract the weld pool oscillation frequency from the captured laser images, a new image-processing algorithm is also proposed and developed. Several experiments with varying degrees of weld joint penetration were conducted and the pool oscillation frequency was extracted. The robustness and effectiveness of the developed image-processing algorithm was also demonstrated. The weld joint penetration for traveling and stationary welding was estimated based on the extracted oscillation frequency. The experimental results provide a new way to sense and predict the weld joint penetration from the top side of the weld pools by detecting the weld pool oscillation frequency.

Fundamentals of the Laser-Vision-Based Sensing Method

In this section, the principle of triggering the GTA weld pool surface by pulsed current is detailed based on the phenomenon that the arc creates a plasma jet, traveling from the electrode toward the workpiece. The impingement of the plasma jet on the weld pool surface tends to depress the center of the weld pool, hence providing stimulating energy to the oscillation system (Ref. 32). For clearly observing and investigating the oscillation behavior of weld pool during the GTAW process, pulsed current is utilized, which can produce different magnitudes of arc force imposed on the weld pool surface. During the pulsed current period, the weld pool surface is depressed by the increased arc pressure, and during the base current period, the distortion of weld pool surface gradually restores to its original state since a force balance exists between the external pressure (arc pressure) and the internal pressure (surface tension, gravity, and liquid buoyancy of weld pool) after releasing the pulsed current. The situation is schematically shown in Fig. 1 (Ref. 33).

By choosing a proper waveform of pulsed current, the weld pool surface will be periodically oscillated. The control of weld joint penetration would
thus be carried out through controlling the pulsed current frequency and base current time. The variation of weld pool surface in one rectangular pulsed current period is shown in Fig. 2. After observing the dynamic weld pool surface of the GTA welding process, it can be shown that the vertical oscillation amplitude of weld pool surface is very small and decays rapidly. The weld pool presents a damped oscillation. Therefore, it is very hard to directly measure the weld pool oscillation frequency. Based on the oscillation phenomenon of the weld pool, a novel approach named laser vision is proposed to measure the oscillation frequency of weld pool in this paper — Fig. 3. When the weld pool surface is depressed by the increased arc force during the pulsed current period, the weld pool surface is oscillated by elastic restoring force at the base current period. Figure 3 shows the oscillation states of weld pool surface change from state 1 to 2. The change of the reflected angle of incident laser ray is very obvious, the length of $|ao|$ is magnified to $|a'o|$ and the length of $|bo|$ is magnified to $|b'o|$. As a result, the variable height of weld pool surface can be calculated with geometric transformation, because the arc radiation decays very fast with increasing travel distance while the reflected laser light retains its original intensity, it is possible that not only the reflection of projected laser can be clearly imaged on the interception plane but also the dynamic reflected images of laser lines are captured by the high-speed camera.

**Experimentation**

**Sensing System**

The original three-dimensional weld pool surface measurement system is described in Ref. 34. The measurement system has been improved in this work, and is shown in Fig. 4. This system is comprised of a structured-light laser generator, imaging plane, a GZL-CL-22CSM-C high-speed camera produced by Point Grey Research Co., and a composite filter lens that consists of a neutral light-reducing piece and 10-nm band-pass filter centered at a wavelength of 685 nm. A 500-mW StockerYale LasirisTM SNF continuous illumination laser with variable focus is used to generate a structured-light pattern, such as a dot-matrix, five lines, etc. The laser pattern is projected onto the weld pool under the electrode at a certain angle and covers the entire weld pool surface. The high-speed camera can acquire 60 to 1800 frames per second and is used to capture the reflected images on the imaging plane (thin glass with a sheet of white paper attached). Without filler metal, the GTAW-P is applied. The welding direction is along the negative Y axis. Being fixed perpendicularly to the workpiece, the welding torch is stationary while workpiece is traversed below. Meanwhile, the laser generator is fixed

<table>
<thead>
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<th>Table 3 — Geometric Parameters of Weld Bead Shape</th>
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<tr>
<td>Experiment</td>
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at the backside of welding torch. As the base metal is melted by the arc and forms a liquid weld pool, the specular reflections of projected laser lines occur and are intercepted by an imaging plane fixed vertically at the opposite side of the welding torch. The laser generator is projected onto an OYZ plane at 30 deg with a distance of 40 mm away from welding pool center. The welding torch, laser generator, and imaging plane are carefully aligned. In order to diminish the influence of strong arc light, the high-speed camera is fitted with a 10-nm band-pass filter centered at a wavelength of 685 nm. Thus, most of the arc radiation interference, which is distributed along the entire visible wavelength spectrum, is eliminated.

**Experimental Results**

Several experiments with the Table 1 parameters have been conducted to measure the weld pool oscillation frequency. Three-mm-thick Type 304 stainless steel plates are used as the workpiece. Typical reflected laser images from the traveling and stationary GTA weld pools are, respectively, shown in Fig. 5. The sampling frequency of the high-speed camera was 800 Hz. The shielding gas was pure argon and its flow rate set at 15 L/min. Figure 5A shows the reflected laser images of experiment 1 in traveling welding process, and Fig. 5B shows the captured laser images of experiment 3 in the stationary welding process. For each case, images 1 and 2 were captured during the pulsed current period, while images 3–36 were captured during the base current period. It was shown that the reflected laser lines have been distorted by the weld metal through observing Fig. 5. Moreover, the variation of the reflected laser lines is regular and periodic contraction or expansion during the base current period.

Because the projected laser lines cover the entire weld pool surface and the captured distorted laser lines are reflected by the weld metal surface, the change of reflected laser pattern can represent the variation of the weld pool surface, and its periodic variation shows the periodic change of weld pool surface. Furthermore, the melt and solidification of a weld pool is a very rapid process. From a mechanical equilibrium point of view, in the weld pool, there exists a balance between the external and internal forces; however, it’s a very complicated problem to precisely illustrate the oscillation phenomenon owing to the complex flow pattern of liquid metal in the weld pool. There is an ideal illustration for the restoring force compounded by surface tension and gravity acting on the weld pool during the base current period. With the action of internal forces (such as liquid viscous force, liquid friction force) in the weld pool, the amplitude of weld pool oscillation is changed and decays rapidly (Ref. 35). From an energy equilibrium point of view, this phenomenon is mainly caused by the energy losses of the oscillation: loss of kinetic energy due to solidification of the liquid weld metal at the boundary of the weld pool and dissipation of energy due to the viscosity of liquid metal (Ref. 36).

By analyzing the experimental results, it is found that the clear images can be acquired by the proposed method, and its variation can completely characterize the dynamic process of the weld pool in real-time. The acceptable clearness of the images demonstrated that they can be processed to accurately extract the laser lines shaped by the specular weld pool surface and be used to extract the weld pool oscillation frequency.
Image Processing and Results Analysis

The reflected laser lines are distorted by the irregularities of the weld pool surface. Observation of the reflected images in Fig. 5 shows that the captured images include noise as the laser lines are crossed with each other, gathered in a small area on the imaging plane, or separated from each other. Therefore, to extract the characteristic weld pool oscillation frequency from these images, a new image processing algorithm was developed and the extracted flow chart is shown in Fig. 6, where PSD refers to the power spectral density of signal transferred by the Fast Fourier Transform (FFT) in the frequency domain field.

Image Preprocessing

Being influenced by many factors, such as arc brightness, signal transmission, camera surroundings, and camera scene change, the image is distorted by noise signals. In order to avoid aliasing of the extracted weld pool oscillation frequency and further reducing the influence of noise, the original image is processed by cutting, filtering, and binarizing technology. Since the media filtering can protect the sharp edge information, get rid of the smooth pulse noise in images, and elapse less time, it is adopted in this algorithm. Image 16 in Fig. 5A is selected for illustrating the process. Because the change of gray level between the background and the objective (laser lines) is clear, the threshold segmented method is used to segment the reflected images. The threshold was set at 60. The cut, filtered, and binarized images are shown, respectively, in Fig. 7B–D.

Binarized Image Calibration with Rectangular Window

After the completed image binarization process, the periodic contraction or expansion of the laser lines in certain areas become obvious. Within a small rectangular area, its brightness of contraction or expansion differs greatly. In addition, with the corresponding brightness value periodically changing, the reflected laser lines periodically change, too. Therefore, using the brightness value of rectangular area can determine the weld pool oscillation frequency. To further extract the oscillation frequency of the weld pool, a fixed area on the image was selected, and the gray level value of the pixels in this area was calculated as well as the sum of them referred to as the value of the weld pool oscillation amplitude.

Different magnitude rectangular windows as shown in Fig. 8 are selected to calculate the gray level value of the pixels in binarized image. With the larger rectangular window, the more elapse time is needed to calculate the sum of gray level value of the pixels. If the smaller size window is selected, such as rectangular window 1, useful information about the weld pool oscillation may be lost. Hence, it is very important to select a reasonable size window for processing reflected images in
In this paper, an automatic window selection scheme is proposed and shown in Fig. 9, which consisted of the following steps.

Step 1: Input the binarized laser image.

Step 2: Build the image plane coordinate system — Fig. 8.

Step 3: The image is scanned along with the scanning direction, namely the positive x axial.

Step 4: Calculate the sum of gray level value of pixels including the AB line and ensure its center point O'.

Step 5: A rectangular window whose center is point O' is selected, and its brightness value is calculated.

Step 6: Analyze the change of brightness value in time domain field, which is calculated in step 4. If the change is unobvious, the selected window is too small or large. Then, the selected window must be expanded or contracted. Next, repeat step 5 until a suitable window is achieved, where the brightness value of fixed area varies clearly and regularly in the time domain field.

Step 7: In consideration of the requirements for real-time measurement, the selected window in step 6 may need to be further adjusted.

Equation 1 was used to calculate the brightness value of the rectangular window. The image processing algorithm was developed with Matlab2010b software. Taking experiment 1, for example, the continuous 257 images acquired during the base current time were selected from the reflected laser images, and the brightness values of various rectangular window sizes were calculated in the time domain (Fig. 10), respectively.

Figure 10 depicts how the extracted signal changes periodically in the time domain, but this cannot characterize its frequency information. What’s more, the curve includes obvious sharpness. By increasing the magnitude of the rectangular window, the variation of the brightness value becomes irregular and the periodicity of the extracted signal becomes less obvious. Therefore, it is important to optimize the size of the rectangular window in order to robustly determine the signal’s frequency.

Extraction and Analysis of the Weld Pool Oscillation Frequency

From the transform theory of the signal time-frequency domain, a periodic signal cannot show its frequency in the time domain, but its frequency can be more easily determined in the frequency domain. The relationship between the brightness of reflected laser images and the weld pool oscillation are therefore investigated in the frequency domain. The mapping relationship of the time and frequency domains is set up by the Fast Fourier Transform (FFT) and its inverse transform. A limited long sequence x[n] is supposed, and its discrete FFT is shown in Equation 2 (Ref. 37).

Figure 10A shows where the change of periodicity is the most obvious for three rectangular windows. An 81 × 31-pixel rectangular window was selected.
to explain the extraction process. The gray level value of pixels of continuous 257 images was transformed by the FFT into the frequency domain — Fig. 11. It was found that the extracted frequency from the sequential reflected laser images is approximately 100 Hz. This only, however, represents the change frequency of the 257 images, which needs to be further demonstrated if using the extracted result calculates the practical weld pool oscillation frequency at the same time.

**Demonstration of the Image Processing Algorithm’s Effectiveness and Robustness**

In order to verify the effectiveness and robustness of the image processing algorithm system, two traveling welding experiments, denoted as experiments 2 and 5, and two stationary welding experiments, denoted as experiments 3 and 4, were conducted with the Table 1 parameters, respectively. The reflected laser images of traveling and stationary welding processes were captured with the high-speed camera and processed — Fig. 6.

**Measurement of Weld Pool Oscillation Frequency in a Traveling Welding Process**

According to the flow chart (Fig. 6), the captured images are first preprocessed to minimize the environment influence. The cut, filtered, and binarized images are shown in Fig. 12B and G, C and H, and D and I, respectively.

After preprocessing the image, a 81 × 31-pixel rectangular window was selected and utilized to calibrate the binarized image, and its brightness value was calculated by using the image processing algorithm. Figures 13A and 14A show that the change of brightness is regular and periodic in the time domain field. At the same time, the characteristic frequency of weld pool oscillation, as shown in Figs. 13B and 14B, respectively, was obtained by the FFT.

Figure 13B shows the weld pool oscillation frequency of experiment 2 ranges from 105 to 110 Hz. The frequency of experiment 5 ranges from 110 to 125 Hz. It is obvious that the frequency of experiment 5 is higher than experiment 2. This is due to the difference in average current utilized for each experiment. When the welding speed is the same as welding time, the heat input to the workpiece increases with the average current increasing. To verify the extracted oscillation frequency accuracy of experiments 2 and 5, the practical oscillation frequencies were obtained by a manual count process, which can be operated by the following three steps.

**Step 1**: Separate the pulsed current time and the base current time images, which have been automatically framed by a high-speed camera, and calculate the frames of base current time images in one pulse period.

**Step 2**: Calculate the number of oscillations from the reflected images in the base current period.

**Step 3**: According to the sampling frequency and step 2 results, the oscillation frequency can be obtained.

The practical weld pool oscillation frequency of experiments 2 and 5 is 108 and 120 Hz, respectively, by manual count of the framed laser images. The results show that the extracted oscillation frequency by the proposed image processing algorithm agrees well with the manual count verification.
Measurement of Weld Pool Oscillation Frequency in Stationary Welding Processes

The same strategy of processing reflected laser images is used in traveling welding processes, and the typical reflected laser images are processed — Fig. 15. The 81×31-pixel rectangular window was also selected for calibration of the binarized image. The variable curves of the weld pool oscillation in the time domain field are shown in Figs. 16A and 17A, respectively. The corresponding characteristic frequency of experiments 3 and 4, as shown in Figs. 16B and 17B, respectively, was achieved by the FFT.

When the welding time and the arc length remain a constant in stationary welding processes, the heat input to the workpiece and the volume of melt pool increases with increasing the average welding current. Figures 16 and 17 show that the oscillation frequency of complete joint penetration drops rapidly at the same welding time — 0.32 s. To this end, the correlation of weld pool oscillation frequency and heat input of the workpiece needs to be further investigated based on the achieved characteristic oscillation frequency extracted by the proposed image processing algorithm. If a mathematical model between the welding parameters, i.e., current, welding speed, or arc length, and the weld pool oscillation frequency can be established, the weld joint penetration may be controlled.

A comparison between the extracted frequency and manual count frequency for two cases is conducted and shown in Table 2. From Table 2, it can be seen that both results agree well, and the effectiveness of this proposed image processing algorithm is further demonstrated.

Robustness of the Image Processing Algorithm

The effectiveness of the proposed algorithm has been demonstrated by the four welding experiments described in the previous section. However, the influence of various external or internal factors should be considered when applying the developed image process algorithm to practical applications, thus its robustness needs to be demonstrated. For this purpose, the captured images using the high-speed camera are not preprocessed, such as image filtering and denoising. The information about pool oscillation is directly extracted by the image processing algorithm. In practical applications, traveling welding is used more widely than stationary welding, thus the traveling welding case is only investigated in this section. The original nonpreprocessed reflected laser images for different welding parameters of traveling welding process are shown in Fig. 18. The waveform of experiment 2 in the time domain field and the curve of power spectral density (PSD) are shown, respectively, in Fig. 19A, B. The results of experiment 5 are shown in Fig. 20A, B.

Being compared with Fig. 12, the binarized image of Fig. 18 contains some sharpness. Further analysis of the image processing process determined that the noise produces sharpness, but the characteristic oscillation frequencies are similar to those obtained by the proposed algorithm and verified by the manual count (Figs. 13B and 19B, Figs. 14B and 20B). For example, the characteristic oscillation frequency of Fig. 20B changes from 120 to 130 Hz, which is within the required bounds. Therefore, the influence of noise can be neglected for practical application. This makes it available to use a simpler, real-time image processing algorithm that provides relatively accurate pool oscillation frequency estimates. Therefore, requirements of image processing in real-time are satisfied.

Feasibility Demonstration of Using the Extracted Frequency to Predict the Weld Joint Penetration

Although the proposed laser-vision-based sensing system is able to measure the weld pool oscillation frequency at low pulsed current (the average current is less than 160 A), and the effective-
ness and robustness of the developed image processing algorithm have been demonstrated, its feasibility to monitor and predict the degree of weld joint penetration in a traveling GTA welding process needs to be further investigated. To demonstrate the correlation between the extracted weld pool oscillation frequency and the weld joint penetration, the weld bead and its cross-sectional shape with varying weld joint penetration, respectively, are shown in Fig. 21. The measured top width, backside width, depth, and width/depth ratio are shown in Table 3.

Figure 21A, B shows that the complete joint penetration is achieved. The cross-sectional shapes in Fig. 21A, B show that the backside width of experiment 4 is wider. Figures 16B and 17B show that the oscillation frequency of experiment 4 is lower than experiment 3. They are all less than 100 Hz.

It is known that the weld metal mass or gravity with a given density has a positive relationship with its volume. Hence, the above experimental results further show that the change of pool backside width affects the oscillation frequency, namely as the pool backside width increases, the oscillation frequency decreases for stationary welding process. In traveling welding process, the weld joint penetration increases with increasing the average current for the same welding speed and pulsed current duty-ratio, which can be demonstrated in Fig. 21C–E. Figures 11, 13B, and 14B show that the oscillation frequencies of partial penetration weld pools of experiment 2 and 5 are higher than the frequency for complete joint penetration in experiment 1, and there is an abrupt transition in the frequency from the partial penetration to complete joint penetration. In addition, the smaller weld joint penetration has a higher oscillation frequency of the weld pool.

By analyzing the correlation of weld joint penetration and oscillation frequency for traveling and stationary weld pools, it is demonstrated that the extracted pool oscillation frequency by proposed method is capable of detecting the degree of weld joint penetration.

Discussion

In the past, many researchers have investigated the dynamic behavior of weld pool to monitor and control the weld joint penetration in real-time with many sensing methods as discussed in the introduction. However, each of these methods has its own disadvantages. The machine-vision based method of viewing on the torch side yields only information about the top side shape of the weld pool and no information about weld joint penetration can be obtained. In the case of infrared monitoring the surface temperature distribution, the degree of weld joint penetration can be determined indirectly. However, this technique requires an accurate description of the weld joint and doesn’t respond to the changes of material’s thickness well. Another way is monitoring the change of arc voltage or arc light emissions that are caused by the weld pool oscillation to measure the degree of weld joint penetration. But, it is very difficult to achieve an accurate signal that reflects the pool oscillation frequency due to the poor signal-to-noise ratio (SNR). To easily and precisely measure the pool oscillation frequency, a new monitoring method was proposed and developed in this paper. Test experiments have been conducted to demonstrate the feasibility of this sensing system. After observing and analyzing the experimental results (Fig. 5), it can be found that the change of reflected images during the base current period is periodic and can represent the variation of weld pool surface through analyzing the fundamental frequency of the measurement. In addition, because the laser light has a higher brightness, good direction, monochromaticity, and coherence, and the strength of arc-plasma radiation rapidly decreases with in-
creased distance from the weld pool, the appropriate position that is placed the imaging plane can be determined and the relative clear reflected laser image can be obtained. Hence, contrasting to the machine-vision method, the arc interference in the images can be effectively avoided.

Since the weld pool oscillation is a damped oscillation during the base current period, further investigation is needed to obtain the characteristic oscillation frequency from the periodic reflected laser images. Thus, a new image processing algorithm was developed and successfully applied. In this algorithm, the brightness value of a rectangular window was selected to characterize the signal of oscillation. There were two advantages for using this signal to calculate the oscillation frequency of weld pool. One is that the change of brightness can directly reflect the contraction and expansion of laser lines, without interference from the bright arc light. The other is that the processing algorithm is simple, requiring minimal processing time and thus can be implemented in real-time. In addition, the selection of rectangular window size plays an important role in achieving a precise oscillation frequency. Three window sizes, 81 × 31 pixels, 12 × 101 pixels, and 181 × 121 pixels were adopted to extract the oscillated signal in the time domain. By comparing and analyzing each curve, as shown in Fig. 10A–C, respectively, it was found that the change of brightness value became more and more irregular by increasing the size of the rectangular window. Next, the signal in the time domain was transferred to the frequency domain by FFT, and the extracted frequency is shown in Fig. 11. The frequency of reflected laser images was verified by manual count of the framed images, and the results agreed very well.

To demonstrate the feasibility of using the oscillation frequency to predict the magnitude of weld joint penetration, several experiments utilizing the Table 1 parameters were conducted, and the corresponding oscillation frequency is measured, as shown in Figs. 13B, 14B, 16B, and 17B, respectively. After analyzing Figs. 13B and 14B, it was found that the oscillation frequency of a larger volume pool is lower than a smaller pool volume. This phenomenon may be explained based on the analysis of causality of the pool oscillations and the influence of various fluid dynamic forces. From the literature (Refs. 38, 39), the reason can be illustrated that the restoring force that acts on the weld pool increases with the volume of weld pool increasing, hence, the weld pool oscillation under higher average current decays more rapidly, and the frequency of experiment 2 is smaller than experiment 5. Furthermore, it has been confirmed that the volume of weld pool has strong relationship with the weld pool oscillation frequency (Ref. 40).

Finally, there can be found a phenomenon that the oscillation frequency of weld pool had an abrupt transition from the partial penetration to complete weld joint penetration. Further, the oscillation frequency of partial penetration is always higher than the complete weld joint penetration in a welding process. The above results provide a new method to monitor multiple transition frequency for controlling the complete weld joint penetration.

Although the weld pool oscillation frequency of GTAW-P can be obtained using the developed image processing algorithm offline, its accuracy still needs to be proved by accurate control experiments of weld joint penetration in practical engineering. In addition, the image processing algorithm will be optimized to monitor and control the weld joint penetration in real-time.

Conclusions

A measurement system and an image processing algorithm have been proposed and investigated for monitoring the weld pool oscillation frequency. The following can be concluded from the successful experimental results:

1. The proposed laser vision-based sensing system provides a new way to successfully sense weld pool oscillations.

2. A new image processing algorithm is proposed, which uses the change of gray level of pixels of a binarized laser image to reflect the variation of weld pool oscillation and successfully extract the oscillation frequency. The extracted oscillation frequency from the reflected laser images agrees very well with the manual count results. Moreover, this algorithm quickly and effectively processes the reflected laser images within 20 ms, which may completely satisfy the requirement of measuring the oscillation frequency of weld pool in real-time.

3. The image processing algorithm for extracting the oscillation frequency was accurate and robust, as demonstrated by several offline experiments.

4. The oscillation frequency extracted by this method has a strong relationship with the weld joint penetration in traveling GTA welding process, which is capable of being used to monitor the weld joint penetration. The proposed measurement system provides a good foundation for accurate, real-time control of weld joint penetration.

Acknowledgments

This work was funded by the 973 Program Prophase Research Project of China (#2014CB660810), National Natural Science Foundation of China (#51305189), State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals of China (SKLAB 02014208), National Science Foundation of Gansu Province of China (145RJZA119), the Hong Liu Outstanding Talents Training Plan of Lanzhou University of Technology of China (#J201201), and Young Creative Talent Support Programs of Long Yuan of China. The authors would also like to thank Dr. YuMing Zhang for supporting this research at the University of Kentucky.

References


**Appendix**

\[ B = \int |S(e)|^2 = \sum_{k=1}^{n} |x(k)|^2 \]  

(1)

where the \( x(k) \) is the amplitude of sampled data.

\[ X(n) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j2\pi nk/N} \]  

(2)

where \( X(k) \) is the discrete FFT of \( x(n) \); \( N \) is the number of sampling data; \( j \) represents the plural unit; and \( n \) is the nth sampling data.