Reflection of illumination laser from gas metal arc weld pool surface

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Abstract
The weld pool is the core of the welding process where complex welding phenomena originate. Skilled welders acquire their process feedback primarily from the weld pool. Observation and measurement of the three-dimensional weld pool surface thus play a fundamental role in understanding and future control of complex welding processes. To this end, a laser line is projected onto the weld pool surface in pulsed gas metal arc welding (GMAW) and an imaging plane is used to intercept its reflection from the weld pool surface. Resultant images of the reflected laser are analyzed and it is found that the weld pool surface in GMAW does specularly reflect the projected laser as in gas tungsten arc welding (GTAW). Hence, the weld pool surface in GMAW is also specular and it is in principle possible that it may be observed and measured by projecting a laser pattern and then intercepting and imaging the reflection from it. Due to high frequencies of surface fluctuations, GMAW requires a relatively short time to image the reflected laser.

Keywords: imaging, specular surface, reflection, arc, welding

1. Introduction
Skilled welders acquire their process feedback through their observation of the weld pool region, i.e. the weld pool surface. While how each welder processes his observation to make decisions on how to change welding parameters (his operation) may differ, the source of information has no difference. Monitoring a three-dimensional dynamic weld pool surface is thus a fundamental issue which must be resolved in order to develop intelligent welding machines which can partially emulate skilled welders.

Pioneering work in this area was conducted at the Ohio State University by Rokhlin and Guu [1, 2], using radiography. The radiation of the received x-ray increases with the depression depth. In a separate effort, Mnich and his colleagues used a stereovision method to determine the three-dimensional shape of the weld pool [3]; its major error may come from the correspondence process of the two cameras used. Another effort used a similar principle but introduced the bipyramidal technique to reduce the number of needed cameras from two to one [4]. Other relatively loosely related work can be seen in [5–8].

In our previous work, a different approach has been proposed to directly observe the three-dimensional surface in gas tungsten arc (GTA) weld pool [9, 10]. It projects a low-power continuous laser pattern onto the weld pool surface and the resultant reflection of the projected laser from the specular weld pool surface is intercepted by a diffuse imaging plane for a camera to view. Because the arc radiation decays quickly and the intensity of the reflected laser does not significantly change over the travel distance, the reflection of the laser pattern was clearly imaged.

Gas metal arc welding (GMAW) [11] is probably the most widely used process for metal joining. In this process, an arc is established between a continuously fed wire, as the electrode, and the work-piece. The arc melts the work-piece forming a pool of liquid metal referred to as the weld pool. Unlike in GTAW where the electrode is tungsten which is not melted, the wire in GMAW is continuously melted. The melted metal is detached from the wire periodically at a frequency up to hundred hertz. The weld pool is thus impacted at such a
frequency and as a result the weld pool surface is much more complex and dynamic than that in GTAW.

Because of fundamental roles of weld pool surface observation and measurement in understanding complex welding processes and emulating skilled welders for control, the University of Kentucky Welding Research Laboratory has been committed to resolve this challenging issue for the GMAW process. To this end, two fundamental questions have to be answered. The first question is if the weld pool surface in GMAW is still specular. If yes, it will still reflect a projected laser specularly like a GTAW weld pool surface and the principle of the reflection-based method for direct observation of the weld pool surface would still apply. Then the second question is how this principle can be used to actually observe and measure the weld pool surface in GMAW. The studies in this paper have been conducted to answer these two fundamental questions.

2. Observation system

The proposed system is shown in figure 1. The process used is a pulsed GMAW in which the welding current periodically switches between the peak and base level. A single line laser pattern with 670 nm center wavelength is projected onto the weld pool surface behind the welding torch. An imaging plane fixed vertically at a known distance with the torch is used to intercept the reflection of the projected laser from the weld pool surface. The image plane consists of two identical parts with a fixed angle of 120° as shown in the figure. A high-speed camera fitted with a 20 nm band-pass filter centered at wavelength of 670 nm views the imaging plane for possible reflection of the projected laser.

The high-speed camera used in this study is an OLYMPUS i-SPEED camera, which is capable of capturing images at a frame rate up to 33,000 frames s⁻¹. Because of the use of the band-pass filter, the disturbance from the arc radiation which spreads in a much wider range of wavelengths is further reduced. Further, the effect of environment lighting which also spreads in a wider range of wavelengths can also be reduced.

The illumination laser used in this study is a 500 mW diode laser. The projection angle of the laser with the y-axis is 35°, and the horizontal distance along the y-axis from the laser to the torch is 140 mm. With a known fan angle of 5° for the laser, the length and position of the projected laser pattern at any position can be conveniently calculated.

Figure 2 shows two images captured from the imaging plane by the camera after image enhancement. The reflection of the laser line is clearly seen in the images. Due to
the specular nature of the weld pool surface, the outgoing
direction of the projected laser pattern is only determined by
the incoming (incident) direction, which is the projection angle
of the laser, and the normal of the local weld pool surface
that intercepts and reflects the projected laser. Therefore, the
distortion of the captured reflection contains three-dimensional
information about the weld pool surface. Since the laser
projection angle is fixed, the three-dimensional shape of the
local weld pool surface where the projected laser is intercepted
and reflected may be estimated from captured images.

3. Weld pool dynamic behavior

Before further experiments are conducted, dynamic behavior
of the weld pool surface in pulsed GMAW needs to be
studied first in order to effectively acquire the reflection of the
projected laser. It is known that in GMAW process, weld pool
surface geometry is determined by the actions of arc pressure,
surface tension, droplet impingement, gravity, fluid dynamics
and sheer stress from the plasma, etc. For a stable GMAW
process, the weld pool boundary profile, such as weld pool
width, weld pool length, height of the weld pool rear boundary,
is relatively constant and may thus be relatively easy to extract [12]. However, the three-dimensional shape of the weld pool surface is subject to highly dynamic changes due to the metal transfer (transfer of the melted wire into the weld pool) and the periodically altering arc pressure which is proportional to the square of the current [2]. As aforementioned, the proposed sensing system takes advantage of the specular nature of the weld pool surface to measure the weld pool surface. A minor change in the normal on the local weld pool surface will dramatically change the reflection direction and therefore change the shape of the reflected pattern. While a dramatic change can benefit improve measurement accuracy, it creates challenges to a successful capture of the reflection.

To better understand experimental results and use the results to improve the capturing capability, the characteristics of the weld pool surface in pulsed GMAW process are studied by directly viewing the weld pool with the high-speed camera without a laser and imaging plane. A set of sequential images captured in a complete pulse cycle during pulsed GMAW are shown in figure 3. The time shown on each image is the time relative to the beginning of the peak current period.

In the peak period (figures 3(a) and (b)), the current is 220 A, which is much larger than 70 A in the base period. The base metal melted by the arc rapidly increases and the melted wire may also be detached from the wire into the weld pool due to the increased electromagnetic force. The volume of the weld pool thus increases rapidly. Further, the arc pressure which is proportional to the square of the current also increases greatly. The liquid metal in the weld pool is pushed downwards and backwards to the rear of the weld pool. As a result, the front of the weld pool during the peak period is relatively flat. In addition, the downward momentum of the impinged droplet together with the dynamic arc pressure (the current is always subject to fluctuation although its average is controlled at approximately 220A) excites strong oscillations in the weld pool. Based on observation of high-speed images, the resultant wave of liquid metal flow propagates from the front of the weld pool to the rear and then bounces back. The superposition of the reflected wave and the new wave caused by the new droplet impingement and arc pressure fluctuation increased and complicated the fluctuation of the weld pool surface.

When the current changes from the peak to the base level, the heat applied by the arc to melt the wire reduces and the resultant electromagnetic force as a detaching force sharply decreases. During the base period, no droplets are supposed to detach and then transfer into the weld pool. With the absence of droplets and the sharply reduced arc pressure, after a short period of time, the weld pool fluctuation dramatically decays and the weld pool surface changes to a relatively smooth surface (figures 3(c)-(f)). The sharply reduced arc pressure together with the weld pool surface tension and gravity causes the liquid metal to move back toward the front of the weld pool. After the new equilibrium is established, the weld pool reaches a quasi-steady state and becomes convex until the next peak current is applied (figure 3(g)).

As aforementioned, the proposed system uses the reflection of a projected laser from weld pool surface to observe it. Therefore, the best time to observe is during the base current period when the weld pool surface is smooth. The arc light is also weaker during this period but the major factor which determines the effectiveness of the reflection-based method is the reflection surface rather than the arc light whose effect on the observation has been effectively removed in this method.

4. Experimental result and discussion

A series of bead-on-plate experiments has been conducted on 10 mm thick mild steel plates using pulsed GMAW process. The pulse frequency is set at 10 Hz with a 220 A peak current and a 70 A base current. The diameter of the wire is 0.9 mm. The distance from the contact tip which passes the current to the wire to the work-piece is 25 mm. The shield gas is pure argon and the torch travels at 3 mm s⁻¹. The waveform of the welding current is shown in figure 4 and major welding parameters are listed in table 1. Calculation and figure 4 show that each peak current period lasts 40 ms and base period lasts 60 ms.

A set of captured images using the proposed system shown in figure 1 is given in figure 5. The image capturing frame
Table 1. Pulsed GMAW experiment parameters.

<table>
<thead>
<tr>
<th>Pulse frequency (Hz)</th>
<th>Average welding current (A)</th>
<th>Peak current (A)</th>
<th>Base current (A)</th>
<th>Shield gas flux (L min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>130</td>
<td>220</td>
<td>70</td>
<td>20</td>
</tr>
</tbody>
</table>

rate used is 3000 frames s⁻¹, which is much smaller than the maximum frame rate. This is because the size of the actual imaging window on the image sensor chip that senses the scene reduces when the camera increases the frame rate. To still comfortably track the laser reflection in a relatively large field of view at a lower resolution, the adjustment range of the lens should be wide. However, the specific camera used only allows specific lenses whose adjustment ranges are not ideally large to allow one to increase the area. For relatively large area the laser reflection may spread and with the lens used, one could not increase the frame rate significantly over 3000 frames s⁻¹.
while still being capable of comfortably tracking the laser reflection. Hence, the authors used 3000 frames s$^{-1}$ in this study.

The time shown on each image is the time relative to the beginning of the peak current period. While in the entire pulse cycle the weld pool surface is convex as can be observed from the captured pattern of the reflected laser in the images, the actual shape and the convex degree of the reflected laser change and are determined by the actual weld pool surface which changes over the time. To help better see the information from figure 5, the original images have been enhanced to improve the contrast as shown in figure 6.

During the peak current period, with the presence of strong arc pressure and droplet impingement, the weld pool surface is flat but fluctuates at high speeds/frequencies. The rapid change of the surface geometry leads to the local surface of the weld pool which intercepts and reflects the projected laser (local normal and position in the three-dimensional world) changing fast. As a result, the reflection of the laser pattern from the weld pool surface scans on the imaging plane from different reflection location with different normal. The image captured as an integration of incident lights on the CCD sensor during the imaging period (1/3000 s in this experiment) which reflects this scan thus does not have the reflection laser at the

Figure 6. Enhanced images for the original image sequence in figure 5.
same location in the image. The area which has been scanned is thus brighter than background and no clear laser reflection can be identified from the area which has been scanned. The resultant images can be seen in figures 5(a) and (b).

In particular, figures 5(a) and (b) are captured at the same current and the arc radiation should have no substantial difference. However, careful observation and comparison show that figure 5(a) is brighter than figure 5(b) in the majority of the area in the image while figure 5(b) has a more distinguishable area from the rest of the area in the image. The enhanced images in figures 6(a) and (b) can further confirm this observation. This implies that the weld pool surface fluctuates at higher speeds or in a larger range at \( t = 10 \text{ ms} \) for figure 5(a) than at \( t = 25 \text{ ms} \) for figure 5(b). While in figure 5(a) the reflected laser scans a larger area in the image, the range the reflected laser scans during the imaging period (1/3000 s) for figure 5(b) is much reduced. However, the range of the scan is still larger than needed to clearly image the reflected laser which should be a curved thin line at any instant.

Figures 5(a) and (b) verify that the weld pool surface is indeed specular in both cases. If the surface were not specular, the large area that is relatively bright in the image in figure 5(a) would be not explainable. This is because no other diffuse reflection can be as strong as the arc radiation but the arc radiation is not visible. Hence, this relatively bright area in figure 5(a) must be caused by specular reflections. In figure 5(b), the bright area due to specular reflection is significantly distinguishable from the rest.

Figure 5(c) is imaged at \( t = 40 \text{ ms} \). This is the end of the peak current period and the beginning of the base period. Careful observation of this image from different angles can allow one to recognize the presence of a convex continuous laser line, with wider spread on the top and narrower on the sides. (This can be easily observed from the enhanced image in figure 6(c).) Because, as has been seen above through comparison between figures 5(a) and (b), the arc radiation does not have an observable effect in the image, it is apparent that the weld pool surface in figure 5(c) fluctuates at much lower speeds than those in figures 5(a) and (b). However, the authors believe that this reduction in fluctuation speeds was not initiated by the rapidly reducing current (thus arc pressure) because newly initiated movements would take longer time to effect.

When the welding current completely changes to the base level, no droplet impingement would exist to initiate new surface fluctuations. As a consequence, the localized waves of high frequencies, which can only be initiated by high currents/pressures and their fluctuations, decay. In the meantime, the average pressure is reduced and the liquid metal in the weld pool moves back to the front of the weld pool but the movement of the liquid flow is more global at lower speeds. The weld pool surface thus tends to be less fluctuating. As a result, the change of the local weld pool surface, which intercepts and reflects the projected laser, reduces significantly and the range of the scan of the reflected laser much reduces. Clear lines of the reflected laser are thus imaged in the base period as shown in figures 5(d)–(f) and they can be easily detected and identified as can be seen from the enhanced images in figures 6(d)–(f). When the new peak current is applied at \( t = 100 \text{ ms} \), the weld pool surface starts to fluctuate at high speeds and the image becomes blurred again.

In short, as can be seen from the experimental results and analysis/discussion above, the key to successful imaging of the reflected laser which can be used to derive the weld pool surface is that the fluctuation of the weld pool surface must be relatively slow in comparison with the time interval during which the incident lights are integrated on the CCD sensor to form the image. However, during the peak current period, the impingement of the detached droplets on the weld pool may create many local waves of liquid flow of high frequencies. Also, because the current does fluctuate and the arc pressure is proportional to the square of the current, the resultant fluctuations due to current fluctuation during the peak current period are large. Further, the arc pressure is a distributed field. The change in the arc pressure field is thus large and not uniform and would further contribute to initiating local waves of liquid flow of high frequencies. As a result, the fluctuations of the weld pool surface are complex and the surface may not be globally smooth. Sharp edges may exist on the weld pool surface to divide the weld pool surface into multiple local specular surfaces during the peak current period. However, such edges should not affect the effectiveness of the reflection-based method as long as the imaging time is short enough. Also, it is suspected that these edges may also be observed from the pattern of the reflected laser using a much shorter imaging time.

5. Conclusion and future work

(1) The weld pool surface in GMAW is always specular and a projected laser must specularly reflect from it like from that in GTAW. In principle, it is possible to observe and measure it by projecting a laser and then intercepting its reflection.

(2) To be imaged, the laser reflection must be intercepted by an imaging plane. This work did not address much on how the laser reflection should be effectively intercepted. Effective interception of the reflected laser should be an urgent issue for future studies.

(3) Once the laser reflection is intercepted, the imaging time must be sufficiently small in comparison with the scanning of the laser reflection caused by the surface fluctuations. The integration of the reflected laser on the image sensor during the small imaging time must be sufficiently large. Studies are needed to determine what the intensity of the reflected laser must be for a given image sensor (camera, spectral response characteristics) and optical settings such as frame rate (imaging time), etc.

(4) The frequencies of the surface fluctuations are much reduced in the base period in comparison with the peak current period. The frequencies of the fluctuations play a much more significant role in determining the range and speed of the scan of the reflected laser than the amplitudes. For the base period with a base current of 70 A, 1/3000 imaging time appears to be in the range needed to clearly image the laser reflection.
(5) It appears that the arc pressure, its fluctuations and the impingement of droplets are the major causes for high frequencies of the surface fluctuations observed during the peak current period in GMAW. It is suspected that the specular weld pool surface during the peak current period may consist of multiple local areas divided by sharp edges. Although these edges, if they exist, should not affect the effectiveness of and may be detected by the reflection-based method, further studies are definitely needed before it can be concluded.

(6) The front of the weld pool surface during the peak current period is relatively less convex than that in the base current period although the movement and fluctuation of the liquid flow have much higher frequencies. More studies are needed to accurately determine the amplitudes of the surface fluctuations during the peak current and compare them with those in the base period. To this end, the weld pool surface needs to be observed at much higher frame rates and a much higher illumination laser intensity may possibly be needed in order to produce significant output on the imaging sensor over an extremely short period of imaging time.

(7) The pattern of the projected laser needs to be appropriately selected/designed in order to facilitate an accurate, convenient and fast computation of the three-dimensional weld pool surface during GMAW, which is much more dynamic than in GTAW.

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References