X-Ray Imaging of Complex Flow Patterns during Tungsten Inert Gas Welding

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Fusion welding techniques such as tungsten inert gas (TIG) welding process have been widely used in industrial and construction applications. The molten metal flow in the weld pool has a major impact on the microstructure evolution, chemical element distribution and defects formation during solidification, which subsequently determines the performance of the welds. However, limited real-time experimental data availability of internal flow behavior has been considered as a major barrier to achieve a thorough understanding and development of accurate weld pool prediction models. In situ x-ray imaging with the tracking particles facilitated us to visualize the flow evolution during the solid–liquid–solid transformation. Experimental results indicated the flow patterns are progressively becoming complicated with the expansion of the melt pool. The shape of the melt pool also changed according to this flow evolution. Our analysis of flow patterns concerning the underlying variation of the driving forces suggests that gravity-derived buoyancy has a considerable effect on determining fluid flow at the melt pool periphery compared to other regions.

Keywords arc welding, buoyancy effect, melt pools, x-ray radiography

1. Introduction

Fusion welding can be considered as a prominent effective and economical way to join metallic materials. Tungsten inert gas (TIG) is one of the most widely employed fusion welding. In the TIG process and many other electric arc welding processes, an electric arc is formed between the tungsten cathode and the metal anode (workpiece) during the welding, which melts the sections of the metals to be joined, creating a melt pool. Molten metals then rapidly solidify to make the joints, once the arc is discontinued (Ref 1–3). The formation of weld pool is a thermophysical process that involves heat transfer, fluid flow and instantaneous phase transformation, which directly influence the qualities and shapes of the weld joints. Complex metal transfer and molten metal flow dynamics are closely linked to the driving forces within the melt pool (Ref 4–6). Previous investigations on driving forces of molten metal flow indicate that buoyancy, arc and electromagnetic force, Marangoni force and recoil pressure (for heat input with high energy mode) dictate the flow mechanisms within the pool. As a result of outward flow caused by negative surface tension gradient (driven Marangoni force) and buoyancy, the melt pool shape can be shallow and wide. In contrast, the depth of melt pool formed with inward flow driven by positive surface tension gradient and arc forces are deeper (Ref 7–11). There are numerous other fusion welding methods available. However, when fundamental driving forces acting on the melt pool is concerned, TIG welding represents a simplified and reasonably overall representation of arc welding methods. Conventionally, most microscopy (Optical and SEM) techniques can only investigate the weld pool ex situ, once it solidified or limited to the melt pool surface during the welding process. The critical information on the temperature distribution and dynamic flow conditions inside the molten alloys can be hardly obtained through these ex-situ methods, which are crucial for validating and improving the numerical simulations (Ref 12–17). With the recent advances in synchrotron x-ray characterization, in situ investigations became a powerful tool to study melt pool dynamics in welding and additive manufacturing processes (Ref 10, 18–22). In addition, three-dimensional information related to melt pool evolution has also been investigated through multiple optical camera arrangements (Ref 23, 24). However, optical imaging was limited to collect surface details of the weld pool. Thus, in this contribution, we utilized a fast synchrotron x-ray imaging with tracer particles to measure and study the flow circulations characteristics inside the weld pool during the rapid phase transformation process.

2. Experimental Setup

In situ fast x-ray imaging experiments were performed at the I12 beamline of the Diamond Light Source, UK. The field of view of the camera used was approximately 12×8 mm² with
~10 μm pixel size. LM24(A380) alloy was selected as the experimental material with 25 mm (Length) × 12 mm (Height) × 6 mm (Width) samples. TIG welding was used to demonstrate general and common representative conditions of the melt pool phenomenon that occurs in a majority of the arc-based fusion welding process. Tungsten carbide particles were used as tracking particles for flow, and their average radius was around 15 μm. These particles were placed on the top surface of the sample using an adhesive (superglue) that leaves nearly no residues. The chemical composition of the samples is shown in Table 1. Figure 1 shows a schematic representation of the experimental setup. Further experiment details can be found in Ref. (Ref 10, 25).

| Elements, wt.% | Al  | Si  | Cu  | Mg  | Fe  | Mn  | Zn  | Ni  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| LM24/A380      | Balance | 8.9 | 3.2 | 0.2 | 0.6 | 0.23 | 2.4 | 0.03 |

3. Results and Discussion

The representative evolvement and quantitative geometric changes of the melt pool as well as the motion of tungsten particles are presented in Fig. 2. Under the present experimental parameter, an elliptical melt pool formed in the initial 1 s with a well-marked convex shape appeared under the welding tip. A small number of tracers made inward circular motion along the axis of symmetry of the melt pool during this period. As the arc continued, further expansion of the melt pool size occurred and the center area became concave, and the tracers gradually moved outward. When the center surface of the melt pool declined as the enlargement of the melt pool size occurred, some of the aggregate or large particles demonstrated a notable vertical downward movement. Definitely, these unique morphological changes of the melt pool are analogous under other parameters. In addition, the depth of the melt pool grew flatly through the whole welding process compared with the increment of width/diameter of the melt pool; this is commonly referred as the dominant driving forces variation in the arc welding process. As the negative surface tension gradient-driven Marangoni force and gravity-driven buoyancy are the

![Fig. 1](image_url) Schematic experimental configuration that represents the Synchrotron x-ray beam passing through the object

![Fig. 2](image_url) (A) Typical molten pool evolution and tracers motion trajectory. (B) Dynamic change of melt pool depth, diameter, and molten volume. Process parameter: 100 A, 11.5 V, Alternative Current (AC), 3 s

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main driving forces (occupying most of the time when the metal is in the liquid state), the outward flow of molten metal tends to form a wider but shallow shape. Figure 2B shows the quantitative variation of the molten volume. With some minor deviation in the symmetry and/or overall shape of the melt pool, molten metals volume increases steadily. The volume growth rate of the molten pool increases from 80 mm³/s at 1 s to 125 mm³/s by 1.6 s, compared with relatively slower average rate of 40 mm³/s within initial 1 s. Significant increase in both the depth and the width/diameter contribute to this surging volume of the liquid metal.

The actual velocities of tracking particles are affected by the density difference between themselves and the substrates (Al). According to the Olson formula, the average velocities difference due to the sinking effect is approximately $\pm \frac{6}{C_0}$ 10% (only low Reynolds numbers and laminar flow conditions are considered), which is inappreciable contrast to the ultra-high dynamic molten metal flow (Ref 26, 27). Moreover, the effect of gravity-induced sinking is inconspicuous until it becomes the main driving force within the melt pool. Thus, in this paper, tracking particle movement is used as a direct representative for the actual flow evolution. The parameters chosen to reveal and analyze the molten metal flow conditions are 100 A AC and 3 s. Figure 3 visually displays the flow of particles in the melt pool at each 1 s over the phase transformation duration, and individual vectors represent one particle’s motion within 0.1 s. Those gray and blue outlines convey the shapes of the melt pools at the beginning and end of the time node, respectively, while the purple line depicts the axis of symmetry. With the heat began to transfer to the substrates, alloys started to melt and the flow in the central area showed significant inward movement, with the velocities above 45 mm/s as opposed to the slower flow speed at the boundary (about 15 -30 mm/s) in Fig. 3(a). In the next second, the peak velocities area gradually shifts outward from the center. Although the flow velocities at the bottom and edge of the melt pool did not change much, there was a clear upward movement of particles from the base region. The clearly evident outward flow trend at the center region appeared after the arc continued to work for about 2 - 3 s, while at this period, the flow at the peripheral area showed mainly vertical movement. When the arc is extinguished, the majority of the tracking particles began to move vertically downward, accompanied by few rapid upward movements.

In order to further extended analyses of the flow variation inside the melt pool, we extracted the flow in single directions (horizontal and vertical) and used the interpolation method to fully demonstrate the complex flow behavior. As shown in Fig. 4, the positive value in the horizontal direction represents an outward movement (away from the center of the melt pool) and an upward movement. As the arc existed, the horizontal flow changed from negative to positive along with the expansion of the melt pool, and most of the flow in this direction appeared outward when the arc existed for 3 s. As measured vertically, the velocity of tracking particles is mostly positive while turned to negative along the boundary region. This means that the influence of gravity-driven buoyancy on the melt pool, especially the boundary area, gets more noticeable with the increasing melt volume.

To date, a number of previous studies have investigated the effects of different driving forces on the molten metal flow in the welding process (e.g., (Ref 28–30)). From these studies, it is noted that surface tension-driven force is regarded as the most influencing one, which received the greater attention. However, the results highlighted here show the additional effects caused by the gravity-driven buoyancy forces, which made the flow more complicated. In general, as melt pools are formed, arc force is thought to be primarily responsible for causing the melt pool to flow inward. The heat accumulation on the substrates stepwise changed these simple flow patterns, resulting in surface tension forces replacing the main driving force. Although the overall
flow conditions gradually changed outward, some small inward flow in the center region is still controlled by the arc force. The complication of the flow patterns also comes from the increasing influence of gravity with the increasing melt volume. It contributed more to the border(outer) area as the melt pool grows larger once the arc ends. Therefore, multiple forces caused the flow patterns to evolve from simple to complex, from one vortex to manifold vortices.
4. Summary

In this paper, we have briefly presented the high energy x-ray radiographic imaging approach, which was set out to explore the internal flow conditions during the fusion welding process. Through the analysis of tracers trajectories, simple to intricate flow evolution patterns in the melt pool are represented. The overall results of spatiotemporal distribution of molten metal flow combined with the consideration of underpinning melt pool driving forces provide a comprehensive reference to understand the flow evolution fundamentals in the weld pool. With the specific focus on gravity effects, it is possible to understand that gravity exerts more influence on the fluid flow at the melt pool’s peripheral area along with the rapid growth of pool size, which facilitates gravity to dominate the convection with soaring self-weight.

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