In situ X-ray observations of transient states in arc weld pools

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Abstract. Metallic alloys coalesce via extremely rapid melting and subsequent solidification to form fusion welded joints. The melt pool evolution in melting and solidification sequences during the welding process determines the formation of the final weld joint shape, microstructure and defects. The scientific insight on weld pool evolution and related phenomena can be a key contribution to enhance structural integrity and resilience of the welded structures or components. However, inherent complexity with multi-physics phenomena, associated high temperatures and the rapidness of the processes make direct experimental investigation of welding is extremely demanding. Thus, internal flow behaviour during welding or other melt-pool-based metal processing such as additive manufacturing remains unclear and hinders progression to process optimisation. In this contribution we report the observation of melt pool dynamics that take place during electric arc welding, obtained through in situ synchrotron imaging at millisecond scale. The analysis flow patterns along with the quantified weld pool surface dynamics revealed us to how different contributing forces dictate the flow conditions over the distinct durations of the relatively short existence of the liquid phase. Our preliminary results suggest the existence of arc, surface tension and gravity dominant regimes during the evaluation of the weld pool. Further, we present our observations on how different welding parameters influence these regimes and develop into different transient conditions.

1. Introduction

Fusion welding allows two metallic parts to join through a rapid solid – liquid- solid phase transformation under intense heat load. The process can take place with or without intermediate filler metal. The flow behavior of the liquid phase can significantly dominate the heat and mass transfer during the phase transformations. Thus the flow conditions within the weld pool considerably affecting to the microstructures and defects that appear in the final weld joint [1-6]. The surface tension driven forces, the gravity-driven forces of buoyancy gravity and self-weight are commonly affected in the flow conditions within many hot liquids with free surfaces, such as weld pools. In arc welding, an electric arc is employed as the heat source and therefore electromagnetic forces are also expected to play a role to drive the flow within arc weld pools. The arc force is the common term used for the electromagnetic (Lorentz) force generated as a result of the arc and the drag force of the cathode jet on the liquid surface [7, 8]. Recoil pressure as a result of considerable evaporation can be involved with high-density heat inputs such as laser and electron beam welding, but insignificant in arc welding [9-11]. Typically, the negative surface tension gradient (with increasing temperature) creates the outward fluid flow from the weld center towards the pool periphery [1, 5-6]. By having a surface-active element like sulfur in the weld pool, this can be reversed. In such instances, the surface tension driven flow will become inward resulting in a deep and narrow final weld pool [12-14]. The buoyancy force generally causes outward
flow while the combined drag and electromagnetic (arc) forces cause inward flow. Magnitudes of the flow caused by the gravity-driven mechanisms are commonly considered as relatively smaller than the surface tension gradient driven force [15-17]. The evolution of melt pools, as a result of multiple driving forces, remains a fundamental consideration of the fusion welding and other melt pool based manufacturing techniques, for example, metal additive manufacturing. Synchrotron X-ray techniques emerged as a very attractive experimental tool to study dynamic processes involved with solidification processing, welding and additive manufacturing of metallic alloys [6, 18-20]. Both direct imaging and X-ray diffraction methods have been employed with X-ray investigations (e.g. [18, 21-22]). This contribution presents in situ X-ray observations that facilitate the identification of the time-evolving dominance of the multiple forces acting simultaneously within the arc weld pools.

2. Experimental
In situ X-ray imaging experiments been carried out at the I12 beamline [23] of the Diamond Light Source, UK. The full-field images over 12 mm × 8 mm field of view (FoV) were collected at 500 Hz frame rate during tungsten inert gas welding.

![Figure 1. Schematic experimental configuration with X-ray transmission through the weld pool sample size is 25 mm (L) x 12 mm (H) x 6 mm (T).](image)

The samples were binary Al-8%wt. Si alloy with the dimensions of 6 mm × 12 mm × 25 mm (Thickness × Length × Height). Tungsten carbide particles (diameter range 10-40 µm) were included in the samples as tracking particles for velocity measurements. The gas tungsten arc welding (GTAW or commonly referred as TIG) electrode was fixed vertically above the sample. The electrode tip was kept approximately 1.5 mm above the center position of the 6 mm x 25 mm face of the sample. This synchrotron X-ray beam travels through the sample 6 mm thick side towards the imaging detector, as shown in figure 1. 60 keV monochromatic X-rays were used for the experiments while the imaging system consists of a 1 mm thick Nd:YAG Scintillator which is coupled to a Vision Research Inc. MIRO 310M camera through a visible light optics system that yields 10 µm spatial resolution.

3. Results and Discussion
The evolution of a weld pool during a representative arc welding process (with 100 A welding current, 12 V DC voltage and 2 s) is presented in figure 2. In general, once the arc is activated, the surface of the
weld pool starts to form beneath the tungsten tip and the free surface level rises rapidly as seen in figure 2(b). With the increase of the weld pool size, the peak point of the pool appears dividing. Once this happen, the height of the center surface of the pool drops slightly. Even though the center of the pool drops (relative to its peak position), it remains above the initial solid-air interface position. A relatively short time after stopping the arc (in this sequence just after 2 s), the next major transition starts. In this transition, the top surface of the entire liquid pool drops below the level of the original solid surface level and forms the final solidified shape of the weld pool.

Figure 2. A representative melt pool shape changes with. 100 A DC welding current and 2 s welding time. The top black in the figure is the welding electrode (tungsten), and the dark grey part is the welding material (Al). The orange line represents the initial interface height. Black dots are traced particles (tungsten carbide). The white dotted line is the shape of the melt pool and the blue arrow is the trajectory of particle movement inside the melt pool.

Similar transformations in 4 other comparative welding conditions (with different parameters) are also quantitatively presented in figure 3. The figure quantitatively shows the evolution of the liquid-air interface (free surface) at the weld pool center and the raised interface position close to the circumference of the weld pool.
DC (direct current) power input is compared to same nominal AC (alternating current) power input will take a relatively long time for the center and edge surfaces to reach their peak positions as shown in figures 3(a) and 3(b) (or same welding time but different modes contested in figures 3(b) and 3(d)). This observation is looking more associated with the relatively lower net heating capacity (produced at the sample/substrate). AC mode generates heat nearly half of the time at the sample due to the reversing nature of the polarity. This relatively lower level of heating received at the weld pool is denoted by the slower growth of the pool volume [24]. As a result of higher net heating input at the pool, DC mode appears to enable higher surface tension gradient force driven flow. A higher rate of heating is generated at the center of the pool within a relatively short time compared to the thermal diffusivity in liquid or the heat transferred through the flow [25]. Hence DC input mode appears to support the accumulation of more heat and the resulting increase of the temperature in the center of the melt pool. Thus surface tension force driven flow can be increased as a result of the relatively larger temperature difference across the pool. This is analogous to the conditions between the low and the high welding currents. The diameter of the weld pool with 125 A is expanding faster and the peak values for the free surface levels appear much quicker compared to the case with 100 A (figure 3(c)). Once the pool is big enough, the surface of the melt pool tends to drop below its original solid position, if there no solid boundaries to contain the liquid. This observation indicates the influence of the self-weight of the melt with regard to the behavior of the pool before it solidifies. The dominance of the gravity, on this occasion, over the arc and surface tension forces introduce a major change to the weld pool appearance. If the heating is greater, the free surface of the weld pool is observed to plunge and decant much quicker. As indicated in figure 3(c), when the arc force and the current is relatively high, a faster increase in pool size can enable gravity to dominate with the self-weight faster [7]. Once the arc is stopped; gravity-driven self-weight starts to dominate. This phenomenon is mostly indicated through the decrease of the free surface level. However,
if the weld pool is grown to a given size, the free surface level can drop even with the presence of arc and power input as indicated in figure 3(c), where the net power input is high or as in figure 3(d), where welding time is higher compared to the conditions shown in figure 3(a).

Figure 4. Summarized evolution of the force domination in the arc weld pools and corresponding surface height attributes with respect to the welding power levels.

In overall; at the beginning of weld pool formation, the pool size is relatively small, thus a lower temperature difference across the weld pool results in a relatively weak surface tension gradient driven force. Hence, arc force is appeared to dominate the flow initially a short period. Observation of the inward flow inside the melt pool and an apparent increase of free surface provide direct evidence for this. When more and more heat is fed to the center of the pool while the process continues (despite that the excess heat is transported away), the temperature difference between edge and the center of the weld pool can be considerable, and thus a considerable surface tension difference between the center and the edges of the pool can produce. As a result of this considerable difference, increasing Marangoni forces can become dominant in the pool with the flow of outward direction. This can cause the free surface of the pool interface to rise at the edge as seen in figure 2(c). If the net heat input is higher, the Marangoni force can dominate the flow quicker. In the end, the weld pool is large enough and side walls are already molten, the arc and surface tension forces (both upward) struggle to hold the liquid metal against the gravity. As a result, the liquid metal starts to decant from the sides. If the arc is not stopped and hence both the upward forces exist, the plunging rate of the free can be relatively low. As soon as the arc is distinguished, upward flow diminishes promptly and liquid metal decants much faster. Therefore, the general sequence of the time evolution of the driving forces and the corresponding pool characteristics can be presented as in figure 4. Our observation appeared to be generalized to different metallic materials beyond our observations with aluminum, however, material related physical properties can significantly alter flow condition, see e.g. reference [6]. The outcome presented here can be considered as preliminary guidance to improve numerical modeling of welding. Further analysis with the quantified flow and extended experimental work will provide strong opportunities to validate numerical models and in-depth scientific conclusions.
4. Summary

We have applied X-ray synchrotron imaging to observe the flow in arc weld pools throughout the solid-liquid-solid transformation. The shape evolution of the free surface of the weld pool and the flow patterns suggest the transitions in dominating force regimes that control the flow. Our analysis identifies a general sequence of arc, surface tension, and gravity-driven force domination. Power input of the arc and welding time can alter the dominating period of each type of force, however, the general sequence remains. Weld modeling can be extensively benefited with the real-time information obtained through further studies similar to the one presented here with a wide array of materials and welding techniques.

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