Flowing model of weld pool during vacuum electron beam welding

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Abstract: The flowing behaviors of weld pool during electron beam welding (EBW) were investigated using T2 copper by physical experiments. A flowing model of weld pool is developed basing on the morphologies observation and analysis. The flow of weld pool for fully penetrated weld is composed of upward convection flow around the keyhole, horizontal flow toward fusion line near top surface and bottom surface, and horizontal flow backward alone weld direction. According to the flowing model, the formation of cavity defect and characteristic of weld in cross-section can be understood.

1. Introduction

Due to high energy density of electron beam, the keyhole surrounded by a high temperature molten metal, that is weld pool, will be induced during welding process. It is believed that the formation, even the mechanical properties of the weld is determined by the flow of weld pool. Although the coupling behaviors between the keyhole and weld pool have been extensively investigated in theoretical calculation, it is rare in the physical experimental investigations, especial the flowing model of weld pool. In last decades, the heat conduction of EBW process was attended greatly and calculated based on different heat source models [1-3]. Although the simulated weld profiles agreed with the experimental results, the dynamic behaviors of the keyhole and the weld pool were not accurately described by these models. Though neglecting some fundamental physical effects such as recoil pressure, surface tension to drive the flow of molten metal, the keyhole profile, marangoni fluid flow were simulated with some quasi-steady models [4-6]. Recently, a novel three-dimensional mathematical model was reported to understand the characteristics of the dynamical keyhole and flow patterns in the weld pool [7, 8]. The simulation results indicated the recoil pressure, surface tension and impacting force of the molten metal flow are the main forces dominating the keyhole instability. Although some experimental efforts were made to understand the keyhole and flow of weld pool with CCD, metal tracer to observe the keyhole evolution and flow of weld pool [9, 10], the physical experimental model is not perfect to predict the formation role such as defect forming, even understanding on the flow of weld pool. Therefore, in this study, the flowing model of weld pool is developed with T2 copper and the formation role of the weld is discussed with this model.
2. Experimental
The butt-joint of T2 copper plate with the size of 70mm×40mm×2mm was fabricated by EBW with the welding parameters of working distance 300mm, focus coil current 502mA, accelerating voltage 60kV, welding speed 800mm/min, beam current 27mA, and triangle wave scanning at the KS15-PN150KM machine. The surface morphologies were observed by SVS3020 3D vision instrument. The microstructure in cross-section of weld was analyzed with XJP-2C optical microscope after etched with the reagent of FeCl3 10g+HCl 6mL+C2H5OH 20mL+H2O 80mL for 5–10 seconds.

3. Results and discussions
The surface morphologies of the fully penetrated welds are shown in Fig.1. It can be observed that the weld surface is smoothing and the width is near 2mm. No evident defect such as spatter, undercut, overlap is formed on the top surface and bottom surface. In the cross-section surface, the straight weld is obvious, and some gas pores along the fusion line can be observed in Fig.2(a) and Fig.2(b). It is evident that some regular line is leaved in weld, which is defined as solidification line due to the segregation of alloy elements resulted from the rapid cooling during solidification, and the flow of molten metal can be deduced from the distribution of solidification line [10]. The temperature gradient (Tg) during the cooling process can be estimated from the solidification line as shown in Fig.2(b) and Fig.2(c)), which means the last solidification of the molten metal in the center of the weld. A 3D morphology is assembled with the morphologies in transverse, longitudinal and horizontal section, as shown in Fig.2(d).

![Fig. 1 Surface morphologies of joints fabricated with different waveform electron beam, (a) and (b) non-scanning, (c) and (d) triangle-wave-scanning](image)
Fig. 2 The morphologies in transverse and longitudinal cross-sections and 3D model of joints fabricated with different waveform electron beam, (a) non-scanning, (b) triangle-wave-scanning, (c) longitudinal section, (d) 3D morphology

As well known, the vaporization of metal in keyhole and the high-temperature weld pool surrounding the keyhole is resulted from the impact of the high speed electrons. The flow of molten metal in weld pool is driven by several forces such as recoil pressure, Magangoni shear stress, surface tension, hydrodynamic and hydrostatic pressure, and gravity. Pang [7] thought that the main driven forces for the flow of weld pool was the recoil pressure, surface tension and thermo-capillary force. The recoil pressure was a drilling force that determined the keyhole and penetration depth, the high-speed molten metal flow. The littler is the surface tension and thermo-capillary force, the weaker is the flow in the weld pool. The larger is the gravity and the buoyancy force, the faster is the convection velocity of gas phase in weld pool [11]. Wang [12] thought the flow of metal is attributed to the surface tension and recoil pressure. According to the characteristic of the solidification line and the force applied the molten metal, the flow of metal in weld pool for fully penetrated weld is supposed to consist of upward convection flow around keyhole (flow A), horizontal flow toward the fusion line near top surface (flow B) and bottom surface (flow C), and horizontal flow backward alone weld (flow D), as shown in Fig.3(a). The flow A is mainly driven by the recoil pressure raised from the metal vapor and the flow B is driven by the surface tension on the top surface. The flow C is induced by the impact force of electron beam and surface tension on the bottom surface. The flow D is pushed by hydrostatic pressure in the horizontal direction when the electron beam is moved forward alone weld.

When the energy desity is enough for the fully penetrated weld, a straight weld can be form, as shown in Fig.2(a), Fig.2(b) and Fig.3(b) (a joint of GH3039/IC10, accelerating voltage 60kV, welding speed 800mm/min, beam current 27mA). The molten metal is driven by recoil pressure, and flows upward top surface. If the upward speed of flow A is enough, the metal will run out top surface, and a weld reinforcement will form after solidification. Due to the surface tension difference induced by the temperature gradient, some molten metal near top surface before solidificated will flow toward fusion line. Since the barrier of the outside solid metal, the accumulating molten metal coming from the flow B will flow down alone the fusion line. On the other side, the molten metal near bottom surface (flow C) will accumulate at fusion line and then flows upward alone fusion line as the increasing pressure. So two cycles of flow for the molten metal in weld pool will be formed in the thickness of weld. With
the opposite direction compared to the molten metal flow and the high thermal conductivity of T2 copper, the bubble flow is impeded, and the bubble will be caught easily near fusion line at the lower zone of weld, as shown in Fig.2.

When the energy density is too little, no keyhole will be formed in the weld pool. Then the flow A and flow C will disappear and the a bow weld will be formed, which is also validated in the literature [13]. With the increase of the energy density, the keyhole will be developed surrounded by a high temperature weld pool. The flow A and flow B will be main factor, and the flow C will not be formed, therefore, a wedge weld can be observed on the cross-section as shown in Fig.3(c) (a joint of TC4 plate with 20mm in thickness, accelerating voltage 60kV, welding speed 480mm/min, beam current 90mA). Since the high weld speed, the weld width is narrow and the cycle flow can’t be formed in the thickness. The cavity defect in the bottom of wedge weld (Fig.3(d)) is determined by the speed of the flow D and the rate of solidification. As the welding speed decrease, the input energy in per unit length weld will increase, which is benefited to a flow of molten metal flowing downward near a fusion line, therefore, the weld width in the thickness of weld direction will be enlarged, and a nail weld will form, as shown in Fig.3(e). since a lower thermal conductivity of TA15 comparing to T2 copper, the bubble can be caught in the middle of weld (Fig.3(f) [14]), a similar phenomenon can be predicted in the literature [8].

4. Conclusion

(1) A flowing model of weld pool is established for electron beam welding. In this model, the flow of weld pool for fully penetrated weld is composed of upward convection flow around the keyhole, horizontal flow toward fusion line near top surface and bottom surface, and horizontal flow backward alone weld direction.

(2) The formation of cavity defction and characteristic of weld can be predicted with this model.

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