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A three-dimensional model of coupling dynamics of keyhole and weld pool during electron beam welding

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ABSTRACT

In electron beam welding (EBW), the coupling dynamics between the keyhole and the weld pool play significant roles in joint quality, yet the mechanisms of these dynamics have not been well understood, since the rise of EBW in the 1960s. The present study reported a novel three-dimensional mathematical model of EBW and used it to theoretically understand the coupling behaviors between the keyhole and the weld pool during EBW of a Ti-6-Al-4V alloy. A new phenomenological heat source model, dependent on the dynamic keyhole profile and temperature, was developed. The physical effects, including the beam reflection and absorption of the keyhole wall, scattering of secondary electrons, keyhole evaporation heat loss and beam defocus, were rigorously treated in the heat source model. The transient free surface keyhole dynamics were tracked with a high-resolution level set method (LSM). On the free surface boundary, the majority of the key physical effects, such as the recoil pressure, Marangoni shear stress, the surface tension and hydrodynamic pressure of the molten liquid, were incorporated using a recently developed sharp interface model. The coupling behaviors of the three-dimensional keyhole evolutions, heat transfer, and fluid flow in the weld pool as a function of the process parameters in the EBW of Ti-6-Al-4-V alloys were simulated, of which the results reasonably agreed with independent experimental data. The dynamical keyhole violently exhibited fluctuations within the sub-millisecond characteristic time in the radial direction. The oscillations of the keyhole, which were characterized by its surface area and volume, were theoretically studied as a function of the welding speed and surface tension coefficient. The welding speed has stabilization effects on the keyhole and fully stabilized the keyhole under certain high welding speed conditions, an effect similar to that observed in keyhole mode laser welding. The surface tension governed the keyhole oscillation periods and was proposed as a major source of oscillations. In addition, the complex and violent flow patterns of weld pool were predicated and consistent with the well-accepted X-ray imaging experimental results. The EBW transient keyhole and weld pool dynamics were self-consistent. The present study is to present the successful development of EBW, thereby allowing the establishment of the self-consistent keyhole and weld pool dynamics as a function of the process parameters and material properties, to provide a promising avenue for process optimizations in industrial applications.

1. Introduction

EBW is a fusion joining process in which a beam of high energy of electrons is applied to material that is to be welded in a vacuum chamber. A slender dynamic vapor cavity, called the keyhole surrounded by a high-temperature molten weld pool, is produced in EBW due to the high-energy density of the electron beam. Although coupling behavior complications have been observed between the keyhole and weld pool in the welding process since 1960s, the physical mechanisms governing the couplings of the keyhole and the weld pool during EBW are still not well understood.

Many experimental efforts have been previously made to understand the keyhole and the weld pool dynamics in EBW. Studies have shown that the keyhole in general is not static and the morphology of the keyhole exhibits violent oscillations. In the 1960s, Tong et al. [1,2] first demonstrated the existence of the keyhole and observed its oscillation by using a high-energy pulsed X-ray source. Similarly, Mara [3] made reports about the keyhole in EBW. Later, Arata [4,5] utilized cine-fluoroscopy and a metal

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tracer to experimentally observe the time-dependent keyhole evolution and fluid flow of the weld pool in the EBW process. Petrov et al. [6] diagnosed the formation of the weld pool and the keyhole using a collector for secondary emitted particles, light photo diodes and CCD techniques. Although these experiments provided significant insights on the keyhole and the weld pool behaviors of EBW, current experimental studies only provide a qualitative understanding of these behaviors.

In the past decades, many theoretical studies have been proposed to understand the keyhole and the weld pool behaviors during EBW. However, due to the very complicated physics, these earlier EBW modeling studies typically limited to heat transfer investigations that employed analytical or semi-analytical solutions. For example, Elmer et al. [7], Hemmer et al. [8], Couedel et al. [9], Rouquette et al. [10] and Lacki et al. [11] calculated the heat conduction of the EBW process based on different heat source models such as the point, line, and distributed source models. Although the computed fusion zone profiles agreed with the welding experiments, the physics of the keyhole and the weld pool dynamics were not accurately described by these models. Wei et al. [12,13] presented a method to calculate the quasi-steady keyhole profile as a function of the welding parameters and different volatile alloy elements based on the momentum balance and energy balance of the keyhole wall. Moreover, Wei et al. [14,15] and Rai et al. [16,17] calculated the possible Marangoni fluid flow inside the weld pool and along the keyhole wall in the EBW process. However, the keyhole in these EBW models [12–17] was assumed to follow quasi-steady behavior and its profile did not interact with the fluid flow of the weld pool. Moreover, several fundamental physical effects, such as recoil pressure and surface tension, to drive the keyhole and the weld pool, were neglected. Recently, Liu et al. [18] proposed a three-dimensional mathematical model, that adopted a keyhole-tracing heat source to analyze the fluid transport phenomena and spiking defect formation in EBW. However, their study was concentrated on a stationary EBW. The coupling mechanism between the keyhole and the melt pool during a moving EBW remained unclear.

Many modeling studies of the keyhole and the weld pool behaviors in laser welding have been recently proposed [19–27]. For instance, Ki et al. [19], Pang et al. [20–23], Zhao et al. [24], Geiger et al. [25], Cho et al. [26], and Zhang et al. [27] reported several prominent laser welding models that consider the self-consistent coupling of keyhole dynamics and the weld pool dynamics and include the most important physical factors of laser welding. The major physical factors, such as the multiple reflection Fresnel absorption, and the solid-liquid and liquid-vapor phase transformations, as well as the roles of the Marangoni effect, surface tension, and recoil pressure during the laser welding processes were self-consistently incorporated. However, to the best of our knowledge, no such phenomenological EBW model is available that can self-consistently simulate the transient keyhole free surface evolutions, heat transfer, and fluid flow of the weld pool in the welding process.

The present study first proposed a three-dimensional transient model for the self-consistent keyhole and the weld pool dynamics that occurred in EBW. A novel heat source model, self-consistently correlated to the keyhole profile and temperature, is first proposed. Physical effects including beam reflection and absorption of keyhole wall, scattering of secondary electrons, evaporation heat loss of keyhole, and beam defocus are included. Transient keyhole dynamics are tracked with a high resolution level set method (LSM). On free surface boundary, most of the key physical effects, such as recoil pressure, Marangoni shear stress, surface tension and hydrodynamic pressure of molten liquid, are also incorporated by using a recent developed novel sharp interface model. The coupling behaviors of the three-dimensional keyhole evolutions, heat transfer, and fluid flow in the weld pool as a function of the process parameters in the EBW of Ti-6-Al-4-V alloys are simulated and discussed by comparing the results with theoretical and independent experimental data.

2. Modelling methods

2.1. Overview of the novel mathematical model

The proposed time dependent self-consistent EBW model is schematically presented in Fig. 1. Given that the keyhole typically presents oscillations, the beam energy absorbed by the keyhole wall should vary with time and be dependent on the keyhole characteristics. Therefore, a novel phenomenological heat source model, was first developed as a function of the dynamic keyhole profile and temperature, acceleration voltage, beam current, and defocus distance. A level set method was then adopted to track the keyhole evolutions, as it is highly accurate in calculating the geometrical characteristics, such as the normal and curvature. The crucial physical factors governing the motions of the keyhole and the weld pool, such as the recoil pressure, Marangoni shear stress, surface tension, and hydrodynamic and hydrostatic pressures of the molten liquid were accurately incorporated using a recently developed high-resolution sharp interface method. The fluid flow and heat transfer due to conduction and convection as well as the phase transformations in the interaction zone of the electron beam, were considered in the self-consistent EBW model.

2.2. Dynamic keyhole-dependent heat source model

The proposed heat source model is illustrated below in detail. Firstly, the current distribution of the cross section of the electron beam, j_e, assumed to be Gaussian, as follows:

$$j_e(x,y,z) = \frac{8I_e}{\pi d_{ez}^2} e^{-\frac{8(x^2+y^2)}{d_{ez}^2}}, \tag{1}$$

where I_e is the beam current, d_{ez}, the beam diameter at z distance from the beam focus, can be expressed as follows:

$$d_{ez} = \sqrt{d_{ef}^2 + [tg\gamma(z - z_f)]^2}, \tag{2}$$

where γ and z_f represent the angle of divergence and the distance from the focus position to the workpiece, respectively, d_{ef} is the beam diameter at focus position, which is closely related to beam current I_e and acceleration voltage U_e, as follows [28]:

$$d_{ef} = S_0 \left(\frac{I_e}{U_e}\right)^{3/8}, \tag{3}$$

where S_0 is the parameter related with electromagnetic lens, that determined by the experimental data.

When the electrons bombards on the keyhole wall, they can be reflected and absorbed. The reflected electrons can be re-absorbed as secondary electrons. The absorption coefficient and secondary absorption coefficient can be respectively written as

$$\varepsilon_e = 1 - k_r R = 1 - k_r m (CZ)^{-1/3}, \tag{4}$$

$$\varepsilon_r = k_r R \left(\frac{Z_k}{Z_k + d_t + d_b}\right), \tag{5}$$

where $k_r = 0.45$—0.50 is the remaining energy coefficient after electron beam reflection [29,30], C is a constant, M is atomic mass, Z_k is the keyhole depth, d_t, d_b are the diameter of the top and the bottom of the keyhole. Therefore, the absorbed energy on the keyhole wall can be formulated as follows [30]:

$$q[x,y,Z_k(x,y)] = (\varepsilon_e + \varepsilon_r)U_e j_e - q_v, \tag{6}$$