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Study on weld pool behaviors and ripple formation in dissimilar welding under pulsed laser

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A three-transient numerical model is developed to study the dissimilar metal welding under pulsed laser. The melting, resolidification and vaporization inducing recoil pressure are considered in this model. Their effects on molten pool dynamic and the weld bead formation are studied. The similar metal welding and dissimilar metal welding under pulsed laser are respectively simulated by using this model. It is found that surface ripples are caused mainly by the periodical laser and molten pool solidification. In the first, this model is validated by the weld bead geometry comparison between the simulated and experimental results in similar metal welding. Then, this model is applied to simulate the dissimilar metal welding under pulsed laser. The results show that the distributions of the temperature, melt-flow velocity and surface ripples are asymmetric due to the differences in physical properties of the materials. The higher pulse overlapping factor decreases the solidification rate, leading to the more uniform penetration depths and the finer ripples. Good agreements between the experimental observations and simulation results are obtained by the proposed model.

1. Introduction

Laser welding of dissimilar material has gained greater popularity for its advantages in both technology and economics. Because of the small heat input and short welding cycle, pulsed laser welding can reduce problems in dissimilar welding [1]. The weld bead profile, which has great influences on the reduction of weld strength and fatigue life, is one of the critical measures for assessing weld quality [2]. In each pulse, the laser heats and melts the base metal to form a point-like molten pool. The weld ripples are formed after the molten pool is solidified, which are often observed in the pulsed laser welding. The surface rippling is not just a surface phenomenon and is generally associated with the melting, recoil pressure induced by the vaporization, the phase interactions and the resolidification process. In pulsed laser welding, surface rippling is a significant phenomenon and should be considered for its effects on weld bead formation.

Up to date, a few studies on the laser welding have focused on the fundamental understanding of possible mechanisms that lead to the surface deformation. It has been found that more than one mechanism influences the surface deformation. Semak et al. [3] studied the energy balance in the laser-metal interaction zone through theoretical analysis. Samokhin [4] investigated the influence of evaporation on the melt behavior during laser interaction with metal. Bunkin et al. [5] studied the phenomenon of deep melting penetration of metals under the action of laser radiation. For pulsed laser welding, in addition to the recoil pressure induced by the evaporation, the formation of ripples is mainly caused by the interplay between the periodic laser beam and the molten pool solidification.

Numerical and experimental investigations of molten pool dynamics and weld bead formation have been the subject of intensive research over two decades. In the earlier years, the numerical study was limited in two-dimensional space. Fabbro et al. [6] proposed a 2-D model to calculate the keyhole profile and study the keyhole geometry as a function of the main operating parameters. Later on, the computational modeling has been extended to three-dimensional space. A 3-D transient modeling based on the numerical resolution of the fluid flow and the heat transfer equations is developed to investigate the humping phenomenon at high welding speeds [7]. Esfahani et al. [8] developed a 3-D multiphase computational fluid dynamic model to investigate the molten pool dynamic and the hump formation at the interface of the materials in laser welding of low carbon steel and stainless steel. Hu et al. [9] developed a 3-D transient model to study the molten pool fluid flow and the formation of ripples in the moving GMAW. Numerical and experimental investigations were carried out for better

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understanding of continuous wave fibre laser polishing process and the results showed that surface roughness depended on the molten pool velocity [10]. A few studies [11–13] focused on the modeling of molten pool fluid flow and keyhole dynamic during the pulsed laser welding. Zhou et al. [11] investigated the heat transfer, fluid flow and keyhole dynamics during a pulsed laser welding. The results showed that the recoil pressure is the main driving force for keyhole formation. Tan et al. [12] developed a 3-D transient model to investigate the dynamics of keyhole, together with the vapor plume and molten pool. Torkamany et al. [13] studied the effect of process parameters on keyhole formation and weld quality during a pulsed laser welding through experiments. Few of the above models focused on the dissimilar welding under pulsed laser. The experimental studies on dissimilar pulsed laser welding of niobium and Ti-6Al-4V were conducted [14,15]. Effects of process parameters on the melt profile on both sides of the weld line were investigated and optimization of the process parameters was obtained. However, it is rather difficult to experimentally measure the parameters such as temperature and velocity in the molten pool. From the above review, it is found that the effects of the welding parameters on the weld bead formation and surface ripples in dissimilar pulsed laser welding have not received much attention, and the fundamental mechanisms have not been understood well.

In this paper, a three-dimensional transient computational fluid dynamic model is developed to study the molten pool dynamic and weld bead formation. The temperature distribution and flow velocity in the molten pool, the material concentration, and the surface ripple formation for dissimilar welding under pulsed laser is analyzed. The surface deformation resulting in keyhole and ripples formation is studied using dynamic mesh approach. The calculated material concentration and weld bead geometry is compared with experimental results obtained under similar parameters.

2. Modeling

2.1. Surface deformation and liquid movement

A complex problem involving surface deformation and inducing liquid movements in the molten pool is considered. The involved physical mechanisms are the absorption of the laser beam, the melting, the vaporization inducing recoil pressure and the resolidification. The free surface deformation resulting in keyhole and ripples formation is studied using dynamic mesh method. Firstly, the sample surface was assumed to be flat at the initial time $t = 0$ s. During the process of welding, the different regions representing the keyhole, the molten pool and the laser beam are sketched in Fig. 1.

When the local laser absorbed energy is beyond the base metal vaporization threshold, the surface deformation should be considered. Semak et al. [3] have proposed the local "drilling" velocity to simulate the surface deformation and Amara et al. [7] have applied this approach in a 3-D calculation by considering the normal vectors on surface elements. In this paper, this approach has been applied in a 3-D calculation of dissimilar welding under pulsed laser.

The surface deformation caused by the "drilling" velocity is given by

$$v_d = KI_{abs}\cos(\beta) \tag{1}$$

where K is a proportionality factor, I_{abs} the absorbed laser intensity, and β the incident angle over the surface element.

In this study, it is assumed that the mixing of two dissimilar materials did not occur at the process of keyhole formation. Due to the difference of thermal properities, the absorbed laser energy induces a different drilling velocity and the surface deformation was not similar on the both sides.

As an illustration, Fig. 2 shows the 3-D schematic of the keyhole and the surface elements in pulsed laser dissimilar welding. The local incident angles of the laser beam over the surface element on the Ti-6Al-4V side and pure niobium side are represented by β_1 and β_2, respectively. The A_{x1}, A_{y_1} and A_{z1} represent the vector components. The $\overrightarrow{A_{N1}}$ and $\overrightarrow{A_{N2}}$ represent the normal vector at each surface element. Thus the incidence angle can be expressed as:

$$\cos(\beta_1) = \frac{A_{z1}}{|\overrightarrow{A_{N1}}|} \tag{2}$$

$$\cos(\beta_2) = \frac{A_{z2}}{|\overrightarrow{A_{N2}}|} \tag{3}$$

where A_{z2} represent the vector component in the direction of z.

The absorbed laser intensity, assumed to be distributed in a symmetric Gaussian manner, can be expressed as:

$$I_{abs} = \begin{cases} A(2P/\pi r_l^2)\cos(\beta_1)\exp(-2r^2/r_l^2) & y > 0 \\ A(2P/\pi r_l^2)\cos(\beta_2)\exp(-2r^2/r_l^2) & y < 0 \end{cases} \tag{4}$$

where A the absorption coefficient of the material, P the laser power, and r_l the beam focal spot radius. The position r is calculated such as $r = [(x - x_0 - v_w t)^2 + y^2]^{1/2}$, where x_0 the initial position of the laser beam on the surface, and v_w the welding speed.

2.2. Boundary conditions

At the top surface of the work piece, a heat flux with a Gaussian distribution is appled in this study, which is expressed as:

$$Q(x, y, t) = \frac{2P}{\pi r_l^2}\exp\left(-\frac{2(x - x_0 - v_w t)^2 + 2y^2}{r_l^2}\right) \tag{5}$$

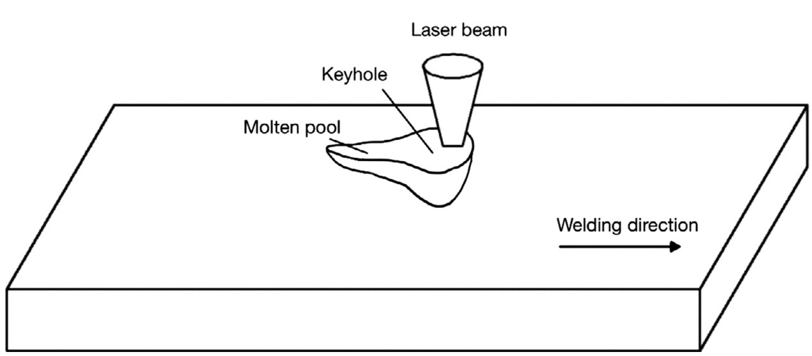

Fig. 1. Schematic of laser welding process.