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The effect of humping on residual stress and distortion in high-speed laser welding using coupled CFD-FEM model

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ABSTRACT

A three-transient numerical model is developed to study the high-speed laser welding. Humping defect commonly occurs in high-speed laser welding, which reduces the strength of weld joints. The major physical factors, such as melting, resolidification, vaporization inducing recoil pressure, surface tension, buoyancy force, heat transfer and fluid flow are considered in this model. The free surface deformation and humps formation are simulated using dynamic mesh method. A sequentially coupled thermo-hydro-mechanical analysis is carried out to study the effects of humping on joint properties. The results show that keyhole plays significant role in the hump formation. It is found that the humping defect will increase the localized von mises stress. The distortion is not sensitive to the hump. The simulated weld bead profile agrees well with the experimental results.

1. Introduction

Laser welding has been widely applied in aerospace, automotive, energy, electronic and medical industries [1]. Because of its advantages including small thermal deformation, cost saving, small heart affected zones, high welding speed and elimination of the need for a vacuum chamber [2], it has been one of the most efficient and economical methods for joining structures. However, humping defect often occurs in high-speed laser welding, which reduces the strength of weld joints. At the higher welding speed (above 18 m/min), the hump is gradually formed, which results in weld beads with a periodic occurance of beadlike protuberance. This defect constitutes a major obstacle to the development of high-speed laser welding.

Various reseaches on modelling of welding were conducted over the past decades. In 1940s, Rosenthal [3] proposed a mathematical model to study the moving heat source. After this work, various studies were performed on welding simulation to investigate fluid flow in the molten pool, heat transfer and stress distribution. The simulative studies on welding broadly fall in two categories, i.e., studies on molten pool behavior using computational fluid dynamic (CFD) model [4–10] and sequentially coupled thermo-structral analysis using finite element method (FEM) model [11–14].

The molten pool behavior is important for the understanding of welding process, which associates with temperature distribution, keyhole evolution and weld bead formation. Chakraborty et al. [4] studied the effects of Prandtl number of the molten metal in weld pool convection. A regime diagram was constructed to indicate the different flow regime. Srinivasan and Basu [5] studied the surface tension driven flow in laser welding and found that the buoyancy force is negligible compared to the Marangoni force. Rai et al. [6] developed a 3D convective heat transfer model to study the laser welding. They found that high recoil pressure play a significant role in the formation of humped root surface. Furthermore, Amara and Fabbro [7] developed a comprehensive model incorporating melting, resolidification and recoil pressure, to simulate the humps formation at high welding speeds. Tan and Shin [8] proposed a numerical model to investigate the dynamics of the keyhole in continuous laser welding. The results show that the addition of assisting gas flow can change the keyhole shape. Recently, Pang et al. [9] developed a 3D multiphase model incorporating the keyhole freesurface revolution to investigate the oscillation of keyhole depth. They found that the amplitude of keyhole depth oscillations in single beam laser welding is higher than that in dual beam laser welding. Liang et al. [10] developed a 3D transient computational fluid dynamic model to investigate molten pool behavior and weld bead formation in dissmilar laser welding. The results show that there is an asymmetric behavior in weld bead profile.

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Numerical predictions of stress distribution are often obtained by sequentially coupled thermo-structral analysis. These analysis are mainly based on pure conduction model using the finite element method (FEM). Josefson et al. [11] predicted the residual stress field in multiphase welding using ABAQUS code. Muránsky et al. [12] studied the effect of plasticity theory on predicted residual stress distribution using ABAQUS code. Sahin et al. [13] predicted residual stress distribution and distortion in dissimilar welding using FEM. Deng [14] used FEM to investigate the effects of solid-state phase transformation on welding residual stress and distortion. The results show that the residual stresses and distortion of medium carbon steel seem to be siginifcantly affected by the martensitic transformation. CFD models can predict the temperature history incorporating fluid flow in the molten pool but will not be able to calculate the stress field. FEM models can predict temperature and stress distribution, but they are mainly based on conduction heat transfer and often assume that the surface of the weld is flat. Marimuthu et al. [2] developed a coupled CFD-FEM model to investigate the effect of laser parameters on surface topology of the weld bead and structural properties. From the above view, it is found that the effect of surface defects on weld joint strength have not receive much attention.

In this paper, a three-dimensonal transient coupled thermo-structural model is developed to study the effect of humping defect on weld joint strength. In the first part, a CFD analysis is performed to predict the temperature history and weld bead profile, which incorporates recoil pressure, buoyancy and surface tension. In the second part, an FEM analysis is performed using temperature history and weld bead profile obtained from the first part. The model is validated by comparing the calculated weld bead profile with experimental results under identical parameters.

2. Modeling

The schematic diagram of laser welding and dimensions are shown in Fig. 1. During the process of laser welding, the different regions representing the molten pool, keyhole, and weld bead are sketched in Fig. 1. A variable spacing grid system of 500 × 60 × 10 is utilised, the smallest grid is 0.1 mm. The grid size is dense in the region of molten pool and its vicinity to guarantee a more accurate simulation while the grid size away from the heat source is coarse to save computational time.

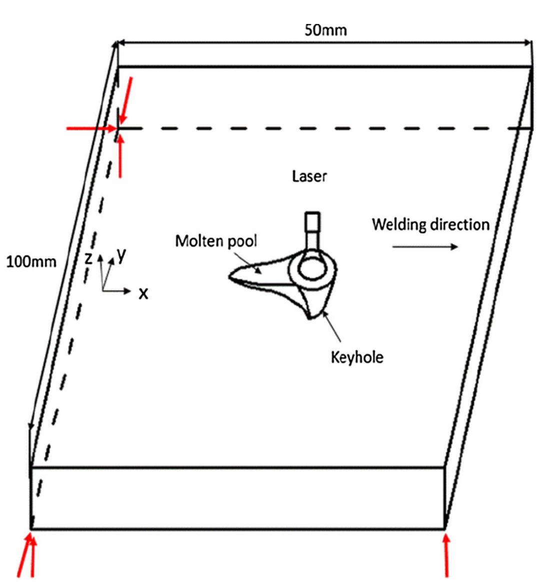

Fig. 1. Schematic of laser welding and mechanical boundary condition.

2.1. The heat transfer and fluid flow analysis in CFD simulation

In this part, the complicated physical factors, such as recoil pressure, buoyancy force and surface tension are considered. The heat transfer and fluid flow in the laser welding are performed using finite volume based code, FLUENT 15. The governing equations are composed of the conservation of mass, conservation of momentum, and conservation of energy, which can be expressed as Eqs. (1)–(3):

$$\frac{\partial(\rho)}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \tag{1}$$

$$\frac{\partial(\rho \vec{V})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla_p + \mu \nabla^2 \vec{v} + S_W \tag{2}$$

$$\frac{\partial}{\partial t}(\rho H) + \nabla(\rho \vec{V} H) = \nabla(k \nabla T) + S_H \tag{3}$$

where $\vec{v}$ is the velocity vector, ρ is the density, t is the time, p is the pressure, μ is the viscosity, S_w is the momentum sink, $H$is the enthalpy.

In this study, enthalpy-porosity technique is used to handle melting and solidification process. The partially solidified/melted region (mushy region) is treated as a porous medium. The momentum sink (S_w) takes following form [15]:

$$S_w = v \rightarrow \frac{(1-\beta)^2}{\beta^3 + \varepsilon} A_{mush} \tag{4}$$

where ε is a very small number (0.0001) to avoid division by zero, A_{mush} is a mushy zone constant. β refers to liquid fraction which is defined as follows:

$$\beta = \begin{cases} 0, & T < T_s \\ 1, & T > T_l \\ (T - T_s)/(T_l - T_s), & T_s < T < T_l \end{cases} \tag{5}$$

where T_s and T_l are the solid and liquid temperatures, respectively.

A volumetric heat source with a Gaussian distribution is applied in this study, which is expressed as [16]:

$$Q(x, y, z, t) = \frac{3P}{\pi abd} \exp\left(-\frac{3(x - x_0 - V_w t)^2}{a^2}\right) \exp\left(-\frac{3y^2}{b^2}\right) \exp\left(-\frac{3z^2}{d^2}\right) \tag{6}$$

where P is the input laser power, V_w is the welding speed, a and b are equal to the focal radius of the laser beam, d is the depth of the volumetric heat source, x_0 is initial positon.Surface tension γ plays a significant role in acting on the fluid flow in the molten pool, which can be expressed as:

$$\gamma = \gamma_0 + A_s(T - T_0) \tag{7}$$

where T_0 is the reference temperature, A_s is surface tension gradient.

The weld bead surface deformation resulted from keyhole and humps formation is studied using dynamic mesh method [7,17]. Also, the model is based on the assumptions that shielding gas jet has insignificant effects on molten pool behavior. A subroutine written in C programming language as user-defined functions (UDFs) is used to describe these physical factors and linked to the FLUENT software. The workpiece is 304 stainless steel. Thermo-physical material properties are assumed to be homogeneous and listed in Table 1. The density, specific heat and thermal conductivity of 304 stainless steel are temperature dependent and taken from the Ref. [19].