Computational Materials Science 97 (2015) 48–54

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Modeling of keyhole dynamics and analysis of energy absorption efficiency based on Fresnel law during deep-penetration laser spot welding

Bao Hu, Shengsun Hu, Junqi Shen *, Yang Li

Tianjin Key Laboratory of Advanced Joining Technology, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form 4 September 2014
Accepted 22 September 2014
Available online 29 October 2014

Keywords:
Keyhole
Laser welding
Fresnel law
Absorption efficiency

ABSTRACT

Deep-penetration laser spot welding can effectively improve the utilization rate of the laser beam through forming the keyhole. In this paper, a model based on Fresnel law was developed with the computational fluid dynamics (CFD) software FLUENT. By considering the recoil pressure, surface tension, buoyancy and evaporation, a ray tracing technique was proposed to describe the absorption efficiency of the laser beam during the process of keyhole forming. It was found that there was large temperature gradient in the keyhole, recoil pressure and Marangoni flow forced the molten metal liquid to flow from bottom to top. At last it formed a nail head at the bottom and crowned at the top. The energy absorption efficiency rose from 42% to 59% during the keyhole forming, which was approximately linear with the depth of the keyhole.

1. Introduction

Laser spot welding is a highly efficient and precise welding method that is being increasingly used in industrial manufacturing and is of growing importance in industry. With its high energy density, a deep and narrow keyhole forms with lower distortion. The formation of the keyhole improves the energy efficiency of the welding process because of multiple reflections of the laser beam within the keyhole [1]. To analyze the process of deep-penetration laser spot welding, a simulation of the keyhole forming while laser welding is needed.

Related studies have been done over the last several years. Rai et al. [1–3] made a lot of great researches on modeling continuous keyhole laser welding of structural steel, aluminum, titanium and stainless steel in different powers and welding speeds. He et al. [4] modeled the evolution of temperature and velocity fields during laser spot welding of 304 stainless steel without considering the free surface. Jin et al. [5] calculated the energy of the keyhole observed by X-ray transmission. Howere, the method is limited because the equipment is expensive and complex. Solana et al. [6–8] modeled a mathematical model to calculate the keyhole geometry during the laser drilling of metals. Some researchers [9–11] adopted body heat source in the laser beam welding simulation, the power density distribution of keyhole didnot meet the fact. Na et al. [12–14] used ray tracing technique to model a keyhole with multiple reflections in Fresnel absorption, and the simulation results agreed with the experimental ones.

As mentioned above, laser beam welding was studied by a large number of researchers. However, few of them analyzed the utilization rate of the laser beam during spot welding period. In this paper, the VOF method was adopted to track the free surface of the keyhole. Surface tension, recoil pressure, buoyancy and evaporation were considered, and a ray tracing technique was applied in Fresnel law simultaneously. By simulating the process of the keyhole forming, studies were made on the temperature distribution and instantaneous energy absorptivity efficiency of deep-penetration laser spot welding.

2. Physical and mathematical models

2.1. Governing equations

Generally, three governing equations are used to describe heat, mass transfer and fluid flow. The boundary conditions are treated as source terms in the governing equations. The continuity equation is described as

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

* Corresponding author at: Room C0804, Building 25, Tianjin University, Weijin Road 92, Nankai District, Tianjin, China. Tel.: +86 13820453005.

E-mail addresses: hubao@tju.edu.cn (B. Hu), huss@tju.edu.cn (S. Hu), shenjunqi@tju.edu.cn (J. Shen), ly09121885@126.com (Y. Li).

http://dx.doi.org/10.1016/j.commatsci.2014.09.031
0927-0256/

The momentum equations are described as

$$\frac{\partial(\rho u)}{\partial t}+\nabla\cdot(\rho V u)=\nabla\cdot(\mu\nabla u)-\frac{\mu}{K}u-\frac{\partial p}{\partial x}+S_x^{sa}+S_x^{re}+\frac{(1-f_l)^2}{(f_l^3+B)}A_{mush}u \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+\nabla\cdot(\rho V v)=\nabla\cdot(\mu\nabla v)-\frac{\mu}{K}v-\frac{\partial p}{\partial y}+S_y^{sa}+S_y^{re}+\rho g\beta(T-T_{ref})+\frac{(1-f_l)^2}{(f_l^3+B)}A_{mush}v \tag{3}$$

The energy equation is described as

$$\frac{\partial}{\partial t}(\rho H)+\nabla\cdot(\rho V H)=\nabla\cdot(k\nabla T)+E-\frac{\partial}{\partial t}(\rho H)-\nabla\cdot(\rho V H) \tag{4}$$

where V, u, v denote velocity vector, x and y component of velocity in the Cartesian coordinate. ρ, P, g, H, K, μ, β and T_{ref} refer to density, pressure, gravitational acceleration, enthalpy, thermal conductivity, viscosity, thermal expansivity and reference temperature respectively. S^{sa} and S^{re} represent the momentum source term induced by surface tension and recoil pressure, E is the input heat source. T and t stand for temperature and time. The second term of right-hand side of Eq. (3) is the source term by the buoyancy force which uses Boussinesq approximation. The last terms of righthand side of Eqs. (2) and (3) are source terms by the frictional dissipation in the mushy zone. A_{mush} is the constant representing mushy zone morphology, f_l is the liquid fraction, and B is the positive zero used to avoid division by zero.

2.2. Boundary conditions

The schematic illustration of the proposed model is shown in Fig. 1. AB, BD and AC are the boundaries of air phase domain. AB is the pressure inlet, AC and BD are the pressures outlet. CE, DF and EF are the boundaries of workpiece phase domain. CGD is the free surface between the air and workpiece.

In the free surface CGD, convectional heat and radiation heat should satisfy the following equation:

$$k\frac{\partial T}{\partial z}\bigg|_{free}=Q-\sigma\delta(T^4-T_a^4)-h_c(T-T_a)-q_{eva} \tag{5}$$

While Q is the heat source of laser spot welding, q_{eva} is the heat loss induced by evaporation. T_a is the atmospheric temperature, h_c is the convection coefficient, σ is the Stefan–Boltzmann constant, δ is the surface radiation emissivity. The heat loss induced by surface evaporation can be written as

$$q_{eva}=WH_v \tag{6}$$

The evaporation rate can be expressed as

$$log(W)=2.52+\left(6.121-\frac{188836}{T}\right)-0.5logT \tag{7}$$

2.3. Heat source models

During deep-penetration laser spot welding, only the free surface of the workpiece absorbs the laser beam. In this paper, a ray tracing technology [15] is used. As shown in Fig. 1, when the first laser beam reaches point P, the incidence vector is approximate to $\overrightarrow{OP}$. $R(z)$ is the radius of the wave front curvature, z_0 is the distance between the focal plane and the center of the sphere wave front. z_r is the Rayleigh length. P_{laser} is the power of the laser beam, and the laser beam radius $W(z)$ varies with z [16].

$$R(z)=z\left[1+\left(\frac{z_r}{z}\right)^2\right] \tag{8}$$

$$I_c(r,z)=\frac{2P_{laser}}{\pi W^2(z)}\exp\left[-\frac{2r^2}{W^2(z)}\right] \tag{9}$$

$$W(z)=W_0\sqrt{1+\left(\frac{z}{z_0}\right)^2} \tag{10}$$

When the laser beam propagates to the free surface of the workpiece, the incident intensity $I_{r,0}(r,z)$ of the laser beam and the mth multiple reflection intensity $I_{r,m}(r,z)$ at the keyhole wall which are given as

$$I_{r,0}(r,z)=I_c(r,z) \tag{11}$$

$$I_{r,m}(r,z)=I_{r,m-1}(r,z)(1-\alpha_{Fr}) \tag{12}$$

While $I_c(r,z)$ is the original incident laser intensity, α_{Fr} is the Fresnel absorption coefficient. The laser beam propagation direction follows simple vector equation:

$$\overrightarrow{R}=\overrightarrow{I}+2(-\overrightarrow{I}\cdot\overrightarrow{N})\overrightarrow{N} \tag{13}$$

While $\overrightarrow{N}$ indicates the surface normal at point P. $\overrightarrow{I}$ is the incident laser beam, $\overrightarrow{R}$ is the reflected ray. After several reflections on the surface of the keyhole, the final energy absorbed is

$$Q=I_0(r,z)(I_0\cdot n_0)\alpha_{Fr}(\varphi_0)+\sum_{m-1}^{n}I_{in,m}(r,z)(I_m\cdot n_m)\alpha_{Fr}(\varphi_m) \tag{14}$$

$$\alpha_{Fr}(\varphi)=1-\frac{1}{2}\left(\frac{1+(1-\varepsilon cos\varphi)^2}{1+(1+\varepsilon cos\varphi)^2}+\frac{\varepsilon^2-2\varepsilon cos\varphi+2cos^2\varphi}{\varepsilon^2+2\varepsilon cos\varphi+2cos^2\varphi}\right) \tag{15}$$

While φ_m is the included angle between the incident laser beam and the normal direction of the keyhole. I_m and n_m are unit vectors of the incident laser beam and the normal direction of the keyhole. Here, $\varepsilon^2=2\varepsilon_2/(\varepsilon_1+[\varepsilon_1^2+(\sigma_{dc}/\omega\varepsilon_0)^2]^{1/2})$, and while ε_1 and ε_2 represent the real parts of the dielectric constants of metal and plasma; σ_{dc} is the dc conductivity of the material; ε_1 is the permittivity of free space. The value ε is determined from the material properties and the laser type. For a CO_2 laser and steel workpiece, its widely used value is 0.08. However, it is also modifiable because (a) the keyhole wall is boiling and this could affect the Fresnel absorption and (b) the method used to calculate the Fresnel absorption is approximated, and the use of a large value of ε could compensate for the approximations made [17]. This paper suggested the value of ε to be 0.2 and showed that the results are acceptable for mild steel and CO_2 laser, compared with experiments. In this investigation,

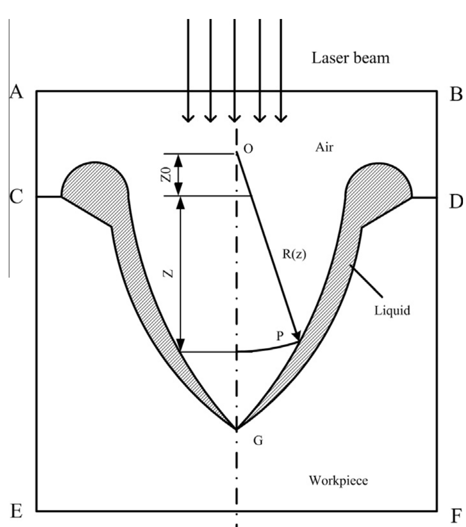

Fig. 1. Schematic illustration of deep-penetration laser spot welding.