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Numerical simulation and experimental investigation of laser overlap welding of Ti6Al4V and 42CrMo

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ABSTRACT

Finite element method (FEM) and processing experiments were utilized to investigate the thermal phenomena and microstructure of laser overlap welding of Ti6Al4V and 42CrMo. A FEM model of temperature field was established, under considerations of thermal contact resistance and forced convection effect of shielding gas flow. Based on the model, temperature field with various laser power values and scanning velocities was calculated to explore the relationship between the process parameters and the interface temperature. Experiments were conducted on a 1 kW Nd:YAG laser materials processing system with five-axis CNC working station. Microstructure, chemical composition and microhardness of the joint were evaluated. From the numerical simulation and experimental investigation, the calculated temperature history at measuring points had the similar tendency to the experimental results. The interface temperature could just reach or be a little higher than the melting point of the lower sheet material 42CrMo by adjusting the process parameters according to the numerical calculation. At the interface, intermetallic compounds TiFe and $TiFe_2$ were detected. The thickness of intermetallic reaction layer containing intermetallic compounds was found to depend on the heat input.

1. Introduction

Turbo disk and turbo shaft of turbo-compressor rotor of some diesel engines, are made of titanium alloy and alloy steel, respectively. Therefore, the technology for joining titanium alloys to alloy steel is required for manufacturing engine turbo components.

Some research for joining of titanium alloys and steels has been carried out. Li et al. (2006) reported vacuum brazing of titanium–aluminum alloy and alloy steel using Ag–Cu/Ti/Ag–Cu filler metal, the author referred to the presence of intermetallic compounds in the reaction layer that weakened the mechanical properties of the joint. Shiue et al. (2008) studied the infrared brazing of Ti–6Al–4V and 17-4 PH stainless steel using two silver-based braze alloys with (Ni)/Cr barrier layer(s) and referred to the inhibition of the interfacial reaction between the 17-4PH SS and the molten braze during brazing. Ghosh et al. (2003) used solid-state diffusion bonding to produce transition joints between Ti–5.5Al–2.4V and stainless steel 304. Sheng et al. (2005) applied phase transformation superplastic diffusion bonding between titanium alloy and stainless steel. It was shown that both the brittle intermetallic compound (FeTi) and the β-Ti based solid solution were formed on the tensile fracture interface. Atasoy and Kahraman (2008) studied the diffusion bonding of commercially pure titanium and low carbon steel using a silver interlayer at various temperatures for various diffusion times. Kundu et al. (2005) and Kundu and Chatterjee (2008) presented the diffusion bonding between pure titanium and stainless steel 304 with different metal interlayer, such as copper interlayer and nickel. Kahraman et al. (2005) studied explosive welding of stainless steel and titanium plates. From their experimental research mentioned above, solid state joining is a feasible method to join titanium alloy and steel for the reason that it could restrain the formation of intermetallic compounds in the welding process, but the joining process needs a vacuum chamber and has low efficiency. The prospect of totally encompassing huge components in a vacuum canopy is not practicable. Explosive welding process is an effective method for producing composite plates but controllability and automation are difficult.

As one of the new joining technologies, laser welding has a number of benefits in comparison with conventional welding techniques. The primary advantages are high efficiency, excellent controllability and the ability to focus laser radiation in a small area producing a high-intensity heat source. Compared to laser butt welding, laser lap/overlap welding could control the temperature and the elements diffusion at the interface effectively. Hiraga et al. (2001) applied a pulse laser lap welding technique to join thin sheets of pure titanium and stainless steel 304. The author discussed the influence of process parameters on the shear strength, but ignored the relationship between temperature field and interface microstructure. Borrisutthekul et al. (2007) studied

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laser welding of steel and aluminum alloy. It was indicated that the thickness of intermetallic reaction layer could be decreased by controlling heat flow during welding process. Moreover, the joining strength increased with decreasing the thickness of intermetallic reaction layer.

With regard to the numerical simulation, an amount of models were proposed to predict temperature distribution for laser welding. Swift-Hook and Gick (1973) formulated the first heat transfer analytical model for continuous laser welding. Mazumder and Steen (1980) developed the first numerical model of the continuous laser welding process. This model considered a three-dimensional heat transfer and implemented the finite difference technique for a Gaussian beam intensity distribution. Lu (1993) calculated the laser induced temperature distribution in substrates with multilayer structures. In that case, the substrates was equivalent to a homogeneous substrate with anisotropic thermal conductivity. Phanikumar et al. (2001, 2004) presented a three-dimensional numerical model of heat transfer for laser welding of dissimilar couples of copper–nickel. Chakraborty and Chakraborty (2007) studied the effects of turbulence on momentum, heat, and mass transfer during laser welding dissimilar materials. Fysikopoulos et al. (2009) described an analytical approach for estimating the energy efficiency of laser manufacturing processes. The above brief review indicates that the numerical modeling is an important issue and the results of the analysis are used for developing processing strategies. However, very few stufies are found to consider the contact resistance and forced convection effect of the shielding gas flow in the models.

In order to implement laser overlap welding of titanium alloy and alloy steel, a mathematical model of heat transfer of the welding process was established. In this model, the contact resistance and forced convection effect of the shielding gas flow were considered. Based on the model, the temperature field with different laser power and scanning velocities was estimated to explore the relationship between the process parameters and the interface temperature. After the overlap welding experiments, microstructure, chemical composition and microhardness of the joint, especially the interface of the overlap sheets, were examined to investigate the weldability of laser overlap welding between titanium alloy and alloy steel.

2. Mathematical modeling

A mathematical model was used to calculate the temperature field with different process parameters. During laser overlap welding process, Ti6Al4V and 42CrMo sheets were used as upper and lower sheet, respectively.

2.1. Assumptions

The comprehensive 3D FEM model to simulate the temperature of the welding process was based on heat conduction. Besides, the following assumptions were made in order to simplify the calculations:

(1) Laser power density was less than 7×10^5 W/cm^2, the welding mode was conduction welding. Therefore, laser power density was assumed to be distributed in a Gaussian manner at the top surface of the titanium alloy sheet.
(2) The shielding gas flow along the top sheet was assumed to be laminar flow. The temperature and the flow velocity of shielding gas were invariable throughout the entire process.
(3) Thermal physical properties parameters of the welding materials were piecewise linear with temperature.

2.2. Governing equation

The heat transfer equation:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c^*}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{1}$$

where λ, c^* and ρ are the thermal conductivity, equivalent specific heat and density of the materials, respectively. It is convenient to regard the latent heat of fusion as a specific heat in the range of phase transition temperature. Thus, the equivalent heat capacity can be formulated as:

$$c^* = \begin{cases} c_S(T) & T < T_S \\ \dfrac{c_S(T) + c_L(T)}{2} + \dfrac{L}{T_L - T_S} & T_S \le T \le T_L \\ c_T(T) & T > T_L \end{cases} \tag{2}$$

where T_S and T_L are the solidus temperature and liquids temperature, respectively, $c_S(T)$ and $c_L(T)$ are the specific heat of solid and liquid dependent on temperature, respectively, and L is the latent heat of fusion.

2.3. Boundary conditions

The contact thermal resistance between upper and lower sheets is defined as:

$$R_c = \frac{l_c}{\lambda_c} \tag{3}$$

where l_c is the characteristic length, taken as the thickness of the contact zone, and λ_c is the thermal conductivity of the contact zone.

The boundary condition of top surface can be expressed as:

$$\lambda\frac{\partial T}{\partial z} = \frac{2P\eta}{\pi r_b^2}\exp\left(-\frac{2(x^2+y^2)}{r_b^2}\right) - h_t(T - T_a) - \sigma\varepsilon(T - T_a) \tag{4}$$

Here, P is the laser power, η is the laser absorption coefficient, r_b is the effective radius of laser beam, h_t is the convection coefficient of the top surface, σ is the Stefan–Boltzmann constant, ε is the emissivity, and T_a is the ambient temperature.

The convection coefficient of top surface under shielding gas is given by:

$$h_t = \frac{\lambda_g}{l} Nu \tag{5}$$

where λ_g is the conductivity of the shielding gas, and l is the characteristic length, taken as the width of the welding specimen and Nu is the Nusselt number. Nu is defined as:

$$Nu = 0.664(Re)^{1/2}(Pr)^{1/3} \tag{6}$$

where Re and Pr is the Reynolds number and Prandtl number of the shielding gas flow, respectively.

$$Re = \frac{\rho_g u_g l}{\mu_g} \tag{7}$$

$$Pr = \frac{\mu_g c_g}{\lambda_g} \tag{8}$$

where ρ_g, μ_g and c_g are the density, dynamic viscosity and specific heat of shielding gas, respectively.

The convection coefficient of symmetric surface is given by:

$$h_s = 0 \tag{9}$$

On other surfaces, the convection condition is set to be natural convection:

$$\lambda\frac{\partial T}{\partial n} = h_c(T - T_a) \tag{10}$$

where h_c is the convection coefficient.