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Thermomechanical analysis for Laser + GMAW-P hybrid welding process

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ABSTRACT

A three-dimensional transient model is developed for numerical analysis of the coupled heat conduction and residual stress and distortion phenomena in laser beam welding plus pulsed gas metal arc welding (GMAW-P) hybrid process. Based on an adaptive combined volumetric heat source model, the transient temperature field is computed, and then the thermal analysis data are utilized as input of subsequent thermomechanical analysis. The residual stress distributions of test plates are calculated for both GMAW-P and Laser + GMAW-P hybrid welding processes. Experiments are made to measure weld dimensions and residual stresses. The weld residual stress distributions of GMAW-P and Laser + GMAW-P hybrid welding are compared under the conditions of the nearly same weld penetrations. The predicted results of the weld shapes and residual stresses are in agreement with the experimental measurements. The simulated results show that the residual stresses and distortion of test plates made by Laser + GMAW-P hybrid welding is lower than those by GMAW-P.

1. Introduction

The combination of laser welding with pulsed gas metal arc welding (GMAW-P) forms Laser + GMAW-P hybrid welding which can not only enhance capability of the two processes, but also compensate the deficiencies of each individual. Its main advantages compared to two individual components are deep and stable weld penetration, gap-bridging ability improvement, low distortion and easy filler metal addition. The combination of these two welding processes can also improve the weld bead shape quality, possibly reduce the porosity and increase welding speed [1]. Therefore, Laser + GMAW-P hybrid welding is an increasingly accepted joining technology for a variety of industrial sectors [2–5]. As applications become more widespread, there is growing need to understand the fundamental issues of this new welding process, such as the relationship between the numerous process parameters and the weld quality. For key factors determining the weld quality, the temperature history and thermal stress and distortion have significant effects on the microstructure and properties of weld joint. For example, residual stresses pose significant problems in the precision fabrication of structures because those stresses heavily induce brittle fracturing and degrade the buckling strength of welded structures [6]. Therefore, predicting the magnitude and distribution of weld residual stresses and characterizing the effects of certain welding conditions on the residual stresses are of great significance for more widespread applications of Laser + GMAW-P hybrid welding.

A great deal of investigations has been made to advance the fundamental insight into the complex thermomechanical phenomena in welding. Over the last decade or so, there has been enormous progress in understanding weld residual stresses and distortions [6–8]. However, these advances are mostly associated with typical welding processes, such as arc welding or laser beam welding. For Laser + GMAW-P hybrid welding, which is increasingly applied in manufacturing industry, fundamental investigations involving mathematical modeling and associated experiments have been carried out only to a limited extent [3,4]. Though some work has been conducted for modeling and simulation of heat and fluid flow in hybrid welding [9–12], there is still a lack of thermomechanical analysis of residual stresses and distortion for this new process.

In this work, adaptive volumetric heat source models are developed to predict the temperature profiles in both GMAW-P and Laser + GMAW-P hybrid welding, which are subsequently used to calculate the thermomechnical stresses in and around

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the weld pool to perform a sequentially coupled heat transfer and thermomechanical analysis for both processes. The residual stresses and distortion for GMAW-P and Laser + GMAW-P hybrid welding are compared with each other. Experiments are performed to measure the relevant weld dimensions and residual stresses. The computed results are validated by the experimental measurements.

2. Formulation

2.1. Thermal analysis

Establish 3D Cartesian coordinate system on the workpiece with y-axis along the welding direction, z-axis along the thickness direction, and the origin locating on the workpiece surface and moving at the speed v_0. The transient heat conduction equation is written as

$$\rho C_P\left[\frac{\partial T}{\partial t}+(-v_0)\frac{\partial T}{\partial y}\right]=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q_v \tag{1}$$

where ρ, C_p and k respectively denote density, specific heat and thermal conductivity of material; T and t refer to temperature and time variable respectively; Q_v depicts internal heat generation per unit time and unit volume, and v_0 denotes the welding speed.

The associated boundary conditions for Eq. (1) is expressed as follows.

On the top surface of the workpiece, the balance of the energy can be given as

$$-k\nabla T\cdot\vec{n}_t=q_a(r)-q_{cr}-q_{evp} \tag{2}$$

$$q_{cr}=\alpha_{cr}(T-T_\infty) \tag{3}$$

$$q_{evp}=m_{er}L_b \tag{4}$$

where $\vec{n}_t$ denotes the unit normal vector of top surface, $q_a(r)$ refers to the imposed heat flux on top surface, q_{cr} refers to the heat loss by convection and radiation, q_{evp} refers to the heat loss by evaporation, r is the distance from a point on the surface to the centre of the heat source, α_{rc} refers to the lumped heat transfer coefficient combining the convective and radiative heat loss, m_{er} and L_b respectively refer to the rate of vaporization and latent heat of boiling, and T_∞ is the ambient temperature.

On the bottom surface of the workpiece,

$$-k\nabla T\cdot\vec{n}_b=-q_{cr} \tag{5}$$

$$q_{cr}=\alpha_{cr}(T-T_\infty) \tag{6}$$

where $\vec{n}_b$ refers to the unit normal vector of bottom surface.

Similarly, on the two ends of the workpiece,

$$-k\frac{\partial T}{\partial y}=\alpha_{cr}(T-T_\infty) \tag{7}$$

On the side of the workpiece,

$$-k\frac{\partial T}{\partial x}=\alpha_{cr}(T-T_\infty) \tag{8}$$

The initial condition is written as

$$t=0,\ T(x,y,z,0)=T_\infty \tag{9}$$

2.2. Models of heat sources

The terms Q_v and $q_a(r)$ in Eqs. (1) and (2) refer to the internal heat generation rate inside the workpiece and the heat flux on the top surface of workpiece, respectively. Appropriate description of these terms is prerequisite to conduct thermal analysis. They take different forms for GMAW-P and Laser + GMAW-P hybrid welding processes.

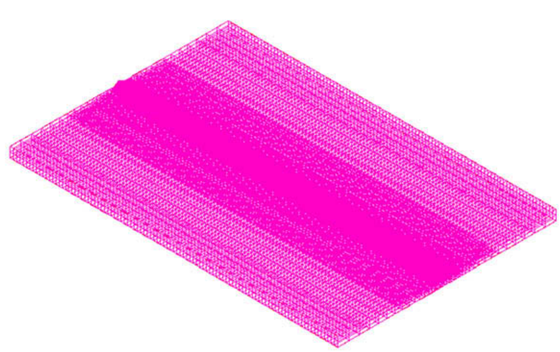
For GMAW-P, the double-ellipsoidal heat source distribution may be utilized to describe the term Q_v. The expression of the heat intensity distribution of the front half and rear half ellipsoid are expressed as

$$q_f(x,y,z)=\frac{6\sqrt{3}(f_fQ)}{a_fb_hc_h\pi\sqrt{\pi}}\exp\left(-\frac{3x^2}{b_h^2}-\frac{3y^2}{a_f^2}-\frac{3z^2}{c_h^2}\right),\quad y\geqslant 0 \tag{10}$$

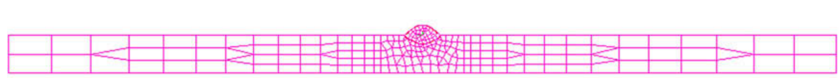
$$q_r(x,y,z)=\frac{6\sqrt{3}(f_rQ)}{a_rb_hc_h\pi\sqrt{\pi}}\exp\left(-\frac{3x^2}{b_h^2}-\frac{3y^2}{a_r^2}-\frac{3z^2}{c_h^2}\right),\quad y<0 \tag{11}$$

where (a_f, a_r, b_h, c_h) are the distribution parameters, (f_f, f_r) respectively refer to the fraction of the heat input for the front and rear ellipsoid, and Q is the effective arc power. According to the coordinate of a point locating ahead or behind the arc centerline, Q_v takes Eqs. (10), (11), and $q_a(r)$ employs Eqs. (10) and (11) with $z = 0$.

For Laser + GMAW-P hybrid welding, the weld is in most cases more laser-like at the bottom and more arc-like on the top due to the two process contributions. When the keyhole state is achieved, the laser beam enters the keyhole and undergoes



(a) 3-D drawing of mesh



(b) mesh at transverse cross-section

Fig. 1. Schematic of mesh generation.