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Three-dimensional model for numerical analysis of thermal phenomena in laser–arc hybrid welding process

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ABSTRACT

This paper describes mathematical and numerical models of thermal phenomena developed for computational analysis of the laser–arc hybrid welding process. The mathematical and numerical models were established to estimate temperature field and velocity field of melted material in the welding pool. Different heat source power distribution models for electric arc and laser beam, latent heat of fusion and latent heat of evaporation as well as buoyancy and liquid material flow through a porous medium were taken into consideration in the computational model. The results of computer simulation of laser–arc hybrid welding process, including temperature field and melted material velocity field, are presented in this study. The correctness of elaborated models is verified by experimental results.

1. Introduction

Laser–arc hybrid welding is a modern welding technology, which is very popular in many areas of industry because of its economic and technological advantages. By combining the laser beam and electric arc, material deep penetration is obtained with a good gap filling capabilities, which contributes to the improvement of weld quality and reduction of disadvantages of each method used separately [1–3]. In comparison with the laser beam welding, the laser–arc hybrid welding greatly reduces welded material evaporation, which occurs due to activity of highly concentrated energy on a small area of the workpiece, and also reduces formation of hardening structures in the weld and heat affected zone by decreasing the cooling rates in the joint [4–7]. Moreover, the hybrid welding technique allows for greater tolerances in fit-up, and also reduces weld distortion caused by heating the workpiece into high temperatures while increasing welding speed in comparison to laser welding, which is very important during welding of long plates [4,6,7].

Understanding the thermal phenomena accompanying laser–arc hybrid welding process is required for appropriate use and optimization of this welding technique. In works focused on mathematical and numerical modeling of hybrid welding, the model is mainly based on the solutions used in the modeling of autonomous laser welding or arc welding processes [8,9]. Temperature field during heating the material in hybrid welding depends on the value and distribution of heat input, generated by two coupled heat sources: electric arc and laser beam. Heat transfer and convective motion of liquid material in the welding pool determine the size and geometry of the weld [10–15].

A very important step in the modeling of thermal processes in welding is the selection of heat source parameters. The most appropriate model for the electric arc heat source, which was confirmed experimentally, is a 'double ellipsoidal' Goldak's heat source model [11,16,17]. The laser beam is a high energy concentration source with a high power. In the numerical analysis of laser beam welding, models of heat sources are often used with change in power density at the penetration depth and the laser energy absorption by welded material taken into account. Mostly Gaussian distribution of a heat source is assumed, usually modified on the basis of experimental studies [18–20]. A universal heat source model, which allows for modeling of variety concentrated heat source shapes form parabola to a point, was proposed by Ranatowski [20]. In this model Gaussian distribution is assumed in the radial direction with exponential decrease of heat source power input with material penetration depth.

The motion of liquid material in the welding pool plays important role in the analysis of thermal phenomena occurring during welding processes [21–23]. Physical phenomena mostly analyzed in literature include: the movement of liquid material in the melted zone, mixing of the weld material with electrode material, dynamics of the electrode droplet flowing into the welding pool and flow through the porous medium [21]. However, despite of the enormous development in computer sciences and numerical

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Nomenclature

$\mathbf{v}$	velocity (m/s)
T_{ref}	reference temperature (K)
f_l	porosity coefficient
f_s	solid fraction
T_S	solidus temperature (K)
T_L	liquidus temperature (K)
C_{ef}	effective heat capacity (J/m^3 K)
T_b	boiling point (K)
a, b, c_1, c_2	arc heat source geometry coefficients
f_1, f_2	arc power distribution coefficients
I	arc current (A)
U	voltage (V)
$k = 3/r_0^2$	factor designating the heat source concentration (m^{-2})
$K_z = 3/s$	involution factor of a heat source (m^{-1})
s	heat source penetration (m)
$u(z-s)$	Heaviside's function
c	specific heat (J/kg K)
H_L	latent heat of fusion (J/kg)
H_b	latent heat of evaporation (J/kg)
K_{ij}^e	local conductivity matrix
V_{ij}^e	convection matrix
S_{ij}^e	matrix of coefficients
$Q_j^e(t)$	vector of internal heat sources
$\mathbf{g}$	acceleration of gravity (m/s^2)
T_0	ambient temperature (K)
K	porous medium permeability (m^2)
K_0	basic porous permeability (m^2)
d_0	average diameter of solid particle (m)
$\tilde{Q}$	volumetric heat source (W/m^3)
q_o^s	welding heat flux (W/m^2)
q_v^s	evaporation heat flux (W/m^2)
Q_L	laser beam power (W)
r_0	laser spot radius (m)
r	current laser beam radius (m)
M_{ij}^e	is a heat capacity matrix
$\tilde{q}_j^e(t)$	vector of boundary fluxes

Greek symbols

ρ	density (kg/m^3)
β_T	expansion coefficient (1/K)
μ	dynamic viscosity (kg/m s)
λ	thermal conductivity (W/m K)
α	convective coefficient (W/m^2 K)
ε	radiation coefficient
σ	Stefan–Boltzmann constant (W/m^2 K^4)
η	efficiency of the heat source
ϕ	weigh function
ϑ	time weight function
β	time integration coefficient

models of complex, coupled phenomena occurring in the welding processes, calculations are very time consuming [14,21]. That's why the computational models are often simplified in practice, to represent the most important phenomena having a major influence on the shape, size and mechanical properties of welded joints. In the modeling of thermal phenomena with considered convective motion of liquid material in the welding pool, the problem is analyzed in different manner and the numerical solution is obtained using popular numerical methods like: finite volume method (FVM), finite element method (FEM) and volume of fluids (VOF) [14,21–25].

The hybrid welding process involves a large number of technological parameters that should be correctly set to achieve stable process and best possible weld quality [6,7]. Numerical analysis of thermal phenomena, including heat transfer and motion of liquid material in the welding pool, can be used as a cheaper alternative to experimental studies, allowing appropriate selection of process parameters used to obtain a desired shape and width as well as appropriate mechanical properties of welded joint.

This paper presents a three-dimensional model of thermal phenomena in the laser–arc hybrid welding process and numerical analysis of these phenomena including temperature field and melted material velocity field in butt-welded flat made of steel. Temperature field was obtained by the solution of the energy conservation equation in FEM [24] and the velocity field of molten metal in the welding pool was obtained by the solution of the momentum conservation equations using the projection method and FVM [25]. Latent heat of fusion with assumption of linear approximation of solid fraction in solid–liquid region [14,21,26,27,29] and the latent heat of evaporation in temperatures exceeding the boiling point, with linear approximation of liquid fraction in liquid–gas region [18,28] were taken into account in numerical model. The liquid material motion was assumed as a laminar flow of incompressible, viscous fluid. It was also assumed that the motion of liquid metal is generated by the natural convection and fluid flows through a porous medium in the mushy zone. Laser beam heat source power distribution was modeled using cylindrical-involution-normal (CIN) model, while electric arc heat source power distribution was described by Goldak's model.

On the basis of elaborated mathematical and numerical models, computer solver was developed for simulation of hybrid welding process. Results of numerical analysis include velocity field of liquid material in the welding pool and temperature field in hybrid welded flat made of low-carbon steel. The influence of chosen process parameters and liquid metal motion on the weld shape and size is analyzed. Results of numerical analysis are verified by experiment.

2. Mathematical model

Schematic sketch of considered system is illustrated in Fig. 1. The workpiece is melted by electric arc and laser beam acting in tandem. Welding speed as well as electric arc and laser beam heat sources power distribution and they relative arrangement affect heat conduction in the flat. Liquid material flow is mostly driven by the buoyancy in the melted zone. In the mushy zone, between solidus and liquidus temperatures liquid metal motion is assumed as a flow through porous medium. Moreover, phase

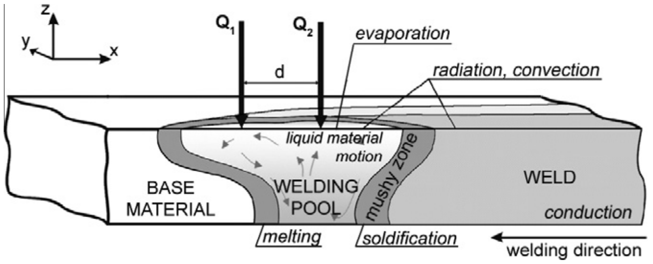

Fig. 1. Schematic sketch of laser–arc hybrid welding simulation.