Journal of Manufacturing Processes 20 (2015) 215–223

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Effect of fluid flow in the weld pool on the numerical simulation accuracy of the thermal field in hybrid welding

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ARTICLE INFO

Article history:
Received 8 July 2015
Received in revised form 1 August 2015
Accepted 3 August 2015
Available online 24 August 2015

Keywords:
Fluid flow
Heat transfer
Keyhole
Thermal cycle
Laser + GMAW-P hybrid welding

ABSTRACT

To further improve the accuracy of the numerical computation of heat affected zone (HAZ) geometry and thermal cycles for hybrid welding, it is necessary to consider the influence of the fluid flow in the weld pool with a keyhole on the hybrid welding temperature field. To this end, the coupled model of heat transfer and fluid flow is developed for the laser + GMAW-P hybrid welding of TCS stainless steel. Based on this coupled model, numerical simulation is conducted to predict the temperature field, the fluid flow in the weld pool of hybrid welding when the quasi-stable keyhole exists, and the thermal cycles in HAZ. Simulation results show that the calculated thermal cycles are more reasonable than those predicted by the pure thermal conduction model. Good agreements are observed between the simulation results and the experimentally measured ones. This investigation clarifies the effect of fluid flow in the weld pool on the temperature field in hybrid welding of TCS stainless steel, thus, contributes to an improved prediction accuracy of thermal cycles and HAZ shape and size.

1. Introduction

In recent years, low-cost ferritic stainless steel with good corrosion resistance has been developed by Chinese steel companies for the application of manufacturing railway vehicles, which is referred to as the TCS stainless steel [1]. Unfortunately, when TCS stainless steel structures are constructed by arc welding, thermal cycles experienced during the welding process will lead to unfavorable grain growth in heat affected zone (HAZ). Thus, the microstructure and mechanical properties of the joint are degraded, and cannot meet the practical requirements [2,3]. Hybrid welding process which combines the two heat sources (one is laser beam while another is pulsed gas metal arc) together can produce the modified temperature profiles and history on the TCS stainless steel workpieces so that unfavorable grain growth in HAZ may be avoided. Such a welding process is termed as laser + GMAW-P (pulsed gas metal arc) hybrid welding, which enhances capability of two processes (laser beam welding or pulsed gas metal arc welding alone) and compensate deficiencies of each individual. There are many advantages of the hybrid laser + GMAW-P (pulsed gas metal arc welding), such as higher welding speed, lower thermal load, narrower HAZ, deeper weld penetration, good gap-bridging ability, and higher process stability [4,5]. Thereby, it has significant potential to solve the challenging problems of welding TCS stainless steel. However, the number of process parameters is increased in laser + GMAW-P hybrid welding process because it involves not only the parameters of individual process, but also the new parameters resulting from the combination of two processes, such as the relative position and posture between the laser head and GMAW torch [6,7]. Though the increased number of process parameters arises a flexible adjustment of the thermal behaviors in hybrid welding process, the process development and optimization become more complex. Thus, it is essential to fully understand the underlying thermo-physics in hybrid welding of TCS stainless steel, such as the heat transfer, fluid flow, temperature profiles, and the dynamic characteristics of the thermal cycles in HAZ.

Temperature field during hybrid welding depends on the value and distribution of heat input, generated by two coupled heat sources: electric arc and laser beam [6]. To represent the heat density of both laser beam and GMAW, Xu et al. [7] developed a combined volumetric heat source model to conduct the thermal analysis of hybrid welding and predict the shape and size of hybrid welds, but only thermal conduction phenomena was taken into account. Guen et al. [8] also used a similar approach to model 3D heat transfer in hybrid laser–GMA welding. There has been a growing recognition of the fact that convection in the weld pool is one of the dominant phenomena contributing to the dynamic behaviors and the shape & size of the weld pool [9,10]. The motion of

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http://dx.doi.org/10.1016/j.jmapro.2015.08.001
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Nomenclature

A	small constant in Eq. (2)
A_s	surface tension gradient
C	mushy zone constant in Eq. (2)
C_j	enhancement factor
c_p	specific heat
$C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}$	constants in Eq. (10)
f_d	drop generation rate
g_j	gravitational accelerationtd:paraenter
G_k	generation of turbulent kinetic energy due to the mean velocity gradients
G_b	generation of turbulent kinetic energy due to buoyancy
h	enthalpy of material
H	thickness of the workpiece
H_{dr}	droplet heat content
H_v	average liquid pool heat content
I	effective electric current
$i, j\; x, y, z$	component $(1, 2, 3)$
k	turbulent kinetic energy
L_f	latent heat of fusion
p	pressure
r	distance to heat source center
r_a	heat distribution parameter
r_A	arc current flux distribution parameter
r_w, r_d	wire and droplet radius
S_j	source term in Eq. (2)
S_1, S_2, S_3	electromagnetic force in x, y, z direction
T_m	Melting temperature of material in Eq. (2)
T_S, T_L	solidus and liquidus temperature
T_0	ambient temperature
T_{evp}	evaporation temperature
U	effective electric voltage
u_i	velocity component
u_1, u_2, u_3	velocity in x, y, z direction
v_w	wire feeding speed
v_0	welding velocity
Y_M	contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
Greek symbols	
α_c	heat transfer coefficient
β_0	thermal expansion coefficient
γ_m^0	surface tension of pure metal at the melting point
$\mathrm{d}\gamma/\mathrm{d}T$	temperature gradient of surface tension
ε	rate of dissipation
ε_t	emissivity
η	arc efficiency
λ	thermal conductivity
μ	effective viscosity
μ_0	magnetic permeability
μ_t	turbulent viscosity
ρ	density of material
ρ_w	density of the electrode wire
$\sigma_k, \sigma_\varepsilon$	turbulent Prandtl numbers
σ_t	Stefan–Boltzmann constant

molten metal in the weld pool affects the heat transfer and the temperature distribution in welded base metal, in consequence having significant influence on the microstructures and properties of weld joints [11]. Therefore, it is crucial to develop a thermo-fluid model to simulate the entire welding thermal process to obtain the accurate weld zone profile and thermal history for microstructural analysis. Zhou et al. [12] proposed two dimensional model involving the temperature field, fluid flow, free surface evolution, droplets and multiple reflections in keyhole to study the transport phenomena in spot hybrid laser–GMA welding. Cho et al. [13] developed a transient three-dimensional model to simulate the interaction between droplets and weld pool, the dynamic keyhole evolution, bubble formation and the flow patterns of the molten pool in hybrid laser–GMA welding. These models revealed complicated phenomena during hybrid laser welding globally, keeping the cumbersome and time-consuming numerical calculations [14], but they did not focus locally on specific areas to dig out the detailed information such as the effect of fluid flow in the weld pool on the temperature field and thermal cycles. To reduce computation complexity and time, simplified numerical analysis to understand the influence of the most important molten fluid flow phenomena on the temperature field, thermal cycles and the geometry of welded joints is done in the present work.

In this study, a simplified three dimensional model of coupled fluid flow and heat transfer is developed for laser + GMAW-P hybrid welding of TCS stainless steel, which describes the most important thermal phenomena. It is used to analyze the effect of fluid flow in the weld pool on the temperature field and weld formation, and to obtain the temperature field and thermal cycles in hybrid welding with sufficient computation accuracy. The validity of the simulation results is confirmed by comparing with the corresponding experimental results.

2. Experiments

Laser + GMAW-P hybrid welding tests were conducted on TCS stainless steel plates of thickness 6 mm. This steel has the following composition: 0.022 wt% C, 0.32 wt%, 1.63 wt% Mn, 0.018 wt% P, 0.018 wt% S, 11.48 wt% Cr, 0.68 wt% Ni, 0.012 wt% Nb, 0.06 wt% Ti, 0.012 wt% Ti, and balance Fe. During the hybrid welding experiments, the laser is leading and normally acts on the work-piece, the arc is tilted backwards by 30°relative to the laser head, and the separation distance between laser focal point and arc electrode is 2 mm. An overview of some welding parameters used in experiments is listed in Table 1. Other welding conditions are given as follows: the location of laser focus is −2 mm, the focal diameter is 0.4 mm, the wire diameter is 1.2 mm, the wire extension is 18 mm, and the shielding gas is Argon + 3% carbon dioxide. After welding, photographs of weld cross-section were made.

3. Mathematical formulations

3.1. Governing equations

The mathematical model is based on the following simplified assumptions:

(i) Only the quasi-steady state of heat and mass transfer is considered;
(ii) The weld pool surface is assumed to be flat, and the keyhole geometry is fixed based on balancing the recoil pressure with the surface tension and the hydrostatic pressure;
(iii) the molten metal is assumed as incompressible Newtonian fluid;
(iv) The physical properties of TCS stainless steel listed in Table 2 are not readily available for the temperature range of interest. Therefore, constant values of these parameters are utilized in calculation.

The governing equations describing the thermal process of laser + GMAW-P hybrid welding involve the mass conservation, momentum conservation, and energy conservation equations.