International Journal of Heat and Mass Transfer 104 (2017) 634–643

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Understanding of humping formation and suppression mechanisms using the numerical simulation

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ARTICLE INFO

Article history:
Received 1 July 2016
Accepted 31 August 2016

Keywords:
Weld pool convection
GMAW
Humping
Twin wire GMAW
FLOW3D

ABSTRACT

Three-dimensional numerical models are established to investigate the convection in normal and high speed GMAW processes. A high speed photography system is used to capture the transient images of the weld pool. Based on the simulation and experimental results, the differences of weld pool formation, convection and stability are researched. The humping formation mechanism in high speed GMAW process, and humping inhibition mechanism in the twin wire GMAW process are also discussed. The results show that in normal speed GMAW process, a clockwise circulation and a backward fluid flow pattern exist in the weld pool behind the arc. While in high speed GMAW process, three main factors are responsible for the humping formation: the high momentum of the backward fluid flow, the large variation of the capillary pressure of the liquid channel in the welding direction, and the capillary instability. The first two factors impede the backfilling of molten metal, and make the liquid channel susceptible to premature solidification, the final factor makes the weld pool unstable and susceptible to collapse. In the twin wire GMAW process, these factors are suppressed, in order to obtain sound weld bead, the trailing wire current should not be larger than the leading wire current.

1. Introduction

Humping bead is a typical weld defect in high speed gas metal arc welding (GMAW) [1], its occurrence limits the increasing of welding speed and the improvement of welding efficiency. Therefore, it is of great significance to study the formation of humping, and put forward methods to suppress it.

Many kinds of models had been proposed to investigate the humping phenomenon. Based on experimental results, Bradstreet [2] suggested that the instability caused by surface tension force was responsible for humping. Nguyen [1,3] used a LaserStrobe video imaging system to obtain transient images of the weld pool during the formation of a hump, he proposed that the strong backward fluid flow caused by various forces was the major factor responsible for the initiation of humping. Cho [4] used simulation and experimental methods to study the humping phenomenon, and pointed out that the thin liquid channel caused by elongation of the molten metal, and the premature solidification of thin liquid channel were the two requirements for humping formation. Chen [5] developed a mathematic model to quantitatively analyze the formation mechanism of humping, the momentum and heat content of the backward flowing molten metal were considered. The humping formation in high speed laser welding and gas tungsten arc welding was also researched [6–9]. Many methods have been proposed to inhibit the formation of humping, such as laser + GMAW hybrid welding process [10–11], DE-GMAW[12], twin wire GMAW process [13]. An external magnetic field is exerted into the weld pool to suppress the humping [14–15]. Among these methods, the twin wire GMAW process is widely used in the industry for its low cost, high melting efficiency, low heat input, and sound weld seam quality [16].

The fluid flow that influenced by droplet impinging momentum, electromagnetic force and surface tension is a key factor that influences the welding process and determines the final weld shape [17–18]. Sound weld bead can be obtained in normal speed GMAW process, humping appears in high speed GMAW process, but disappears in twin wire GMAW process. There are great differences of convection in these welding processes. In previous researches, investigations of humping phenomenon focused on the weld pool formation in high speed GMAW process, the differences of weld pool convection in normal and high speed GMAW processes, and twin wire GMAW process, are lack of researching. Deeper

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.08.110
0017-9310/

understanding of these differences is needed to study the humping and suppress it.

In this article, three-dimensional numerical models are established to investigate the convection in normal and high speed GMAW processes, the VOF method is utilized to trace the deformation of the free surface. The high speed photography system is used to capture the transient images of the weld pool. The differences of weld pool formation, convection and stability between normal and high speed GMAW processes are researched, the factors that influence the humping formation are analyzed. Based on prior work of the authors [13], the humping suppression mechanism in the twin wire GMAW process will also be discussed.

2. Experimental procedure

The experimental platform can be seen in Fig. 1. Two (Panasonic) YD-500GR3 welders are used, materials selected for the welding experiments are 8 mm-thick A36 steel and 1.2 mm diameter of JM53 welding wire, thermo-physical material properties of A36 steel are shown in Table 1. In normal and high speed GMAW processes, the welding current is 280 A, welding voltage is 30 V, the welding speed is 0.5 m/min and 1.5 m/min, respectively, 98% Ar–2%CO_2 is used as shielding gas, the gas flow is 20 L/min, contact-tip-to-work-distance is 15 mm. In twin wire GMAW process, the welding speed is 1.5 m/min, the distance between the two wires is 20 mm. Two groups of different welding parameters are used in the experiment. In the first group, the welding parameters of leading wire and trailing wire are same, the welding current is 280 A, the voltage is 30 V. In the second group, the leading wire current is 250 A, the voltage is 28 V, the trailing wire current is 300 A, the voltage is 33 V.

During the welding experiments, images of the arc and the weld pool are captured by the high speed CCD camera with a 808 ± 10 nm band pass filter. The band pass filter is used to filter out unwanted arc light, the frequency is one frame/3 ms. The transverse sections of the welds in normal and high speed GMAW processes are obtained after the experiments, and shown in Fig. 2.

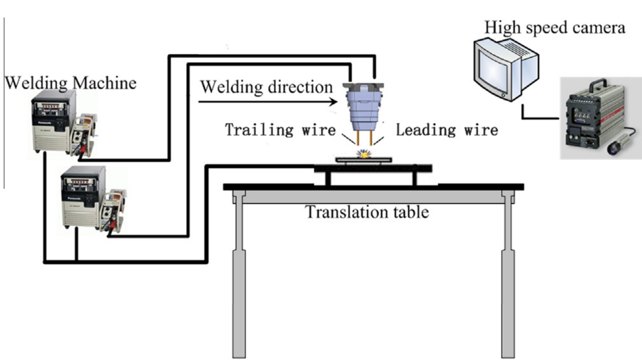

Fig. 1. Diagram of the experimental platform.

3. Mathematical model and numerical simulation

Three-dimensional mathematic models are developed to study the weld pool convection in normal and high speed GMAW processes. The governing equations are solved using the FLOW3D software. The flow is laminar, the liquid metal is considered to be a Newtonian and incompressible fluid. The volume loss of liquid metal due to the metal evaporation is ignored. The droplets are modeled as a source term that carry mass, momentum and energy in the computational domain.

3.1. Governing equations

The GMAW weld pools are modeled using 3D Cartesian coordinate system, the governing equations are mass, momentum, and energy equations. The free surface deformation of the weld pool can be traced using the VOF (Volume of Fluid) method [19]. Fluid configurations are defined in terms of volume function $F(x, y, z, t)$.

$$\nabla \cdot \vec{V} = \frac{R_{SOR}}{\rho} \quad (1)$$

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla)\vec{V} = -\frac{1}{\rho}\nabla P_h + \mu \nabla^2 \vec{V} + f + \frac{R_{SOR}}{\rho}.\vec{V} - K\vec{V} \quad (2)$$

$$\rho\left(\frac{\partial h}{\partial t} + (\vec{V} \cdot \nabla)h\right) = \nabla(\kappa \nabla T) + R_{ISOR} \quad (3)$$

$$\frac{\partial F}{\partial t} + \nabla(\vec{V}.F) = F_s \quad (4)$$

An additional advection relationship is used to expressed the convection of volume fraction in the fluid flow at the weld pool [19]. The energy source term R_{ISOR} can be calculated from the heat structure and fluid temperature.

$$\frac{\partial \rho}{\partial t} + \nabla(\vec{V}.\rho) = R_{SOR} \quad (5)$$

$$\rho = \rho_0 F \quad (6)$$

$$R_{SOR} = \rho_0 F_s \quad (7)$$

$$R_{ISOR} = hW_A(T_w - T) \quad (8)$$

3.2. Enthalpy-temperature relationship

The energy-temperature relationship can be used to model the solid–liquid phase change. The fluid temperature in each cell can be determined from its enthalpy, the cell will become a part of mushy zone if the temperature is between liquidus and solidus temperature. The porous media drag concept can be used to model the flow in the mushy zone [19].

Table 1
Thermo-physical material properties of A36 steel used in simulation.

Nomenclature	Value	Nomenclature	Value
Density	7800 (kg/m^3)	Liquidus temperature	1798 (K)
Viscosity	6×10^{-3} (kg/m·s)	Solidus temperature	1768 (K)
Thermal conductivity(s)	32.3 (W/m·K)	Vaporized temperature	2900 (K)
Thermal conductivity (l)	26 (W/m·K)	Heat transfer coefficient	100 (W/m^2·K)
Specific heat(s)	686 (J/kg·K)	Emissivity	0.5
Specific heat (l)	866 (J/kg·K)	Magnetic permeability	1.26×10^{-6} (H/m)
Latent heat of fusion	2.77×10^5 (J/kg)	Coefficient of thermal expansion	10^{-4} (K^{-1})
Latent heat of vaporization	7.34×10^6 (J/kg)	Surface tension	1.2 (N/m)
Environment temperature	300 (K)	Surface tension gradient	−0.0003