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Characterization of molten pool behavior and humping formation tendency in high-speed gas tungsten arc welding

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The humping defect which easily forms in high-current and high-speed gas tungsten arc welding (GTAW) severely deteriorates the homogeneity of weld properties. However, the complicated and multi-coupled transport phenomena in molten pool make the quantitative characterization of humping formation tendency difficult. In this paper, dimensionless groups containing characteristic heat and fluid-flow variables of molten pool are determined based on Buckingham π-theorem. These groups with clear physical implication correspond to important and peculiar molten pool behaviors during humping formation, and they can be combined to evaluate humping formation tendency. Scaling analysis is then employed to study the molten pool behaviors in high-speed GTAW, in which the analytical equations between characteristic molten pool variables and process variables are formulated. The scaling laws are well verified and calibrated by numerical data from a numerical heat transfer and fluid flow model. The dimensionless groups and scaling equations show an explicit relation between process variables and humping formation tendency. The proposed methodology has low computational intensity, and can be easily applied to give a quantitative description of humping formation tendency at different welding parameters and to predict humping formation.

1. Introduction

The gas tungsten arc welding (GTAW) is a critical joining technology in a wide variety of industries. With the development of modern industry, it gives rise to the demand of higher productivity. However, it has been generally accepted that higher productivity of GTAW can hardly be achieved by proportional increase of welding current and welding speed due to the occurrence of humping defect in high-current and high-speed category [1,2]. Humping defect is defined as periodic severe undulation of the weld bead along welding direction. It deteriorates the homogeneity of weld property and may cause stress concentration.

Humping formation is closely related with the heat and mass transfer in molten pool, and several theoretical models based on experimental observation or analytical derivation have been proposed to explain the humping mechanism from different aspects of Marangoni stress [3], compound vortex [4], hydraulic jump [5] and arc impact [6], etc. In order to make the problem tractable, humping formation is usually ascribed to one dominant factor or balance between two factors in these models. However, considering the complicated transport phenomena in molten pool, this treatment may be over-simplified. Additionally, humping formation can only be depicted qualitatively and cannot be predicted by the above explanatory models due to the lack of accurate experimental temperature and fluid flow data in molten pool.

The accurate temperature distribution and fluid velocity of molten pool can be calculated by numerical models, which offers the possibility of explaining humping formation comprehensively. The detailed humping morphology or critical welding parameters can also be predicted. Three-dimensional numerical models of high-speed GMAW were developed by Cho et al. [7], Chen et al. [8], Xu et al. [9] and Wu et al. [10] to study the heat transfer and liquid metal flow during humping formation. The capillary instability and rapid solidification of necked channel are revealed to be responsible for humping occurrence. The transport phenomena and the associated humping formation in laser welding were also studied numerically by Zhou et al. [11]. Kumar and DebRoy combined the numerical model and Kelvin-Helmholtz instability theory to predict GTAW humping and to identify the influential factors [12]. Meng et al. proposed a computational fluid dynamic (CFD) model to calculate the temperature distribution, fluid velocity, free surface deformation and solidified weld bead profile in high-speed GTAW, in which the detailed morphologies of undercut and humping were simulated [13–15]. The numerical simulation

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provides a powerful method to describe humping formation tendency. However, it is generally computationally intensive and time-consuming. Several hours or even tens of hours may be needed for one simulation case, which may reduce the serviceability.

The objective of this paper is to propose an easy-to-apply methodology for quantitative characterization of humping formation tendency in high-speed GTAW. Firstly, dimensionless groups containing characteristic heat and fluid-flow variables of molten pool are determined by dimensional analysis. The dimensionless groups are not derived arbitrarily but with clear physical implication to provide a quantitative evaluation of humping formation tendency. Then, characteristic molten pool variables are scaled and expressed explicitly with welding process variables using scaling analysis. The obtained scaling laws are verified and calibrated by numerical data from a well experimentally-tested CFD model. The proposed method can be easily used to evaluate formation tendency of humping defect at different welding parameters without high computational intensity, and provides a potential way to predict humping formation.

2. Proposition of methodology

The molten pool free surface under electrode is significantly depressed in high-current and high-speed GTAW, and the majority of liquid metal is transferred to the trailing region through lateral channel, as shown in Fig. 1. Several important and peculiar molten pool behaviors are identified during humping formation [5,6,13–15], including significant free surface deformation, trailing accumulation of liquid metal and elongation and premature solidification of lateral channel. Complicated and multi-coupled transport phenomena of molten pool are involved during the humping formation, which cannot be described by one specific variable.

2.1. Dimensional analysis of molten pool

The Buckingham π theorem is applied to determine some physically meaningful dimensionless groups containing characteristic variables of molten pool and material properties. If a system can be defined by *m* variables which can be expressed by *n* fundamental units, this system can be described by *m-n* dimensionless groups [16]. Eight variables are chosen to define the molten pool system in high-speed GTAW, and they can be expressed using four fundamental units of mass (kg), length (m), time (s) and temperature (K), as shown in Table 1. The whole molten pool volume (V_w) and temperature rise (ΔT) give a basic thermal state of molten pool, and the maximum backward velocity (v_{max}) and gouging region length (L_g) describe important flow behaviors in high-speed GTAW. The effect of driving forces on humping formation has been studied systematically using sensitivity analysis in the authors' previous work, in which the gravity and viscous force are revealed to show minor roles on humping formation in GTAW [14]. Therefore, the terms of gravitational acceleration and viscosity are excluded from the dimensional system.

Many trial-and-error efforts may be needed to form reasonable dimensionless groups, which is not presented in this paper for the purpose of conciseness. Using the above eight variables, four appropriate dimensionless groups with explicit physical implications are obtained as follows:

$$\pi_1 = \frac{v_{max}^2}{c_p \Delta T} \tag{1}$$

$$\pi_2 = \frac{L_g}{V_w^{1/3}} \tag{2}$$

$$\pi_3 = \frac{\rho v_{max}^2 L_g}{\gamma} \tag{3}$$

$$\pi_4 = \frac{L_g^2 k}{c_p \rho v_{max} V_w} = \frac{L_g / v_{max}}{V_w / L_g \alpha} \tag{4}$$

π_1 is Eckert number which represents the ratio between kinetic energy and enthalpy. It is apparent that increasing backward velocity (kinetic energy) promotes liquid metal to accumulate at trailing region and increasing temperature (enthalpy) provides more sufficient time to eliminate trailing swelling. However, π_1 only contains variables of fluid status without any molten pool dimension. It can be modified using dimensionless group of π_2 which is a dimensionless gouging region length.

$$\pi_5 = \pi_1 \times \pi_2 = \frac{v_{max}^2}{c_p \Delta T} \times \frac{L_g}{V_w^{1/3}} \tag{5}$$

The magnitude of π_5 is small (about 1×10^{-7}), indicating that the interaction between mechanical energy and thermal energy is negligible in molten pool, but π_5 can still embodies a strong positive correlation with the trailing accumulation [13]. Higher π_5 value means higher trailing accumulation tendency of liquid metal.

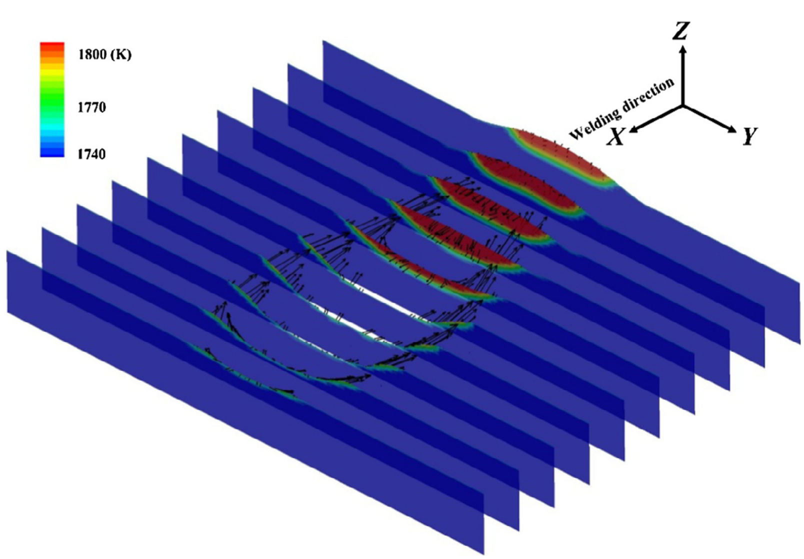

Fig. 1. Typical 3D velocity flied of molten pool during humping formation.