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Numerical investigation of weld pool behaviors and ripple formation for a moving GTA welding under pulsed currents

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ABSTRACT

The complex transport phenomena and their effects on the weld pool dynamics and surface rippling in moving gas tungsten arc welding (GTAW) under pulsed currents are studied by using a 3D transient numerical model. The distributions of the melt-flow velocity and temperature, and weld bead formation are simulated. The effects of welding conditions, including welding current waveform, pulse frequency and welding speed, on the weld penetration, formation and final appearance of ripples are discussed. It is found that surface ripples are formed under pulsed current due to the up-and-down weld pool motion, caused mainly by the periodically varied current and solidification rate of weld pool. The results show that for the cases with the same average current, the pulsed current leads to the deeper weld penetration than continuous current, and the higher peak current corresponds to the higher ripples and deeper penetration. The larger pulse frequency results in the more uniform thermal energy distributions on the workpiece and tends to decrease the solidification rate, leading to the more uniform penetration depths, the smaller pitch and height of the ripples. A slow travel speed is helpful to reduce pitch of the ripples but also at the risk of the reduced effective penetration. Finally, a GTAW experiment for the case of continuous current is conducted to validate the modeling predictions in terms of weld width, penetration depth and the formation of ripples.

1. Introduction

The welding current (continuous or pulsed current) employed to gas tungsten arc welding (GTAW) has significant effects on the welding results [1]. In pulsed GTAW, the magnitude of the pulsed current that alternates between peak (high) current I_p and base (low) current I_b periodically varies at a certain frequency, as shown in Fig. 1. In each pulse, the peak current heats and melts the workpiece to form a point-like weld pool, and the base current maintains the arc burning and less heat is generated to impose on the weld pool as compared to the peak current. As a result, the pulsed GTAW combines the favorable arc characteristics of high current with the low heat input of low current [1], which, in turn, is widely used in various industrial applications for its excellent weld quality. The weld bead is formed on the workpiece after the weld pool is solidified. The surface ripples with arc shaped topographic features are always observed on the solidified weld bead in the pulsed GTAW. Surface rippling is more than a surface phenomenon and is generally associated with segregation, solute distribution, interdendritic pattern and other micro-structural features [2].

Up to date, a few studies on the arc welding have been focused on the fundamental understanding of possible mechanisms that lead to the formation of surface ripples [3–7]. It has been found that the formation of ripples is complex and probably involves more than one mechanism, depending on the process variables. In general, the ripple formation is attributed to the weld pool dynamics with the periodic oscillations during solidification. For GTAW, arc plasma exerts a sufficient pressure on the weld pool surface to produce pool oscillations when the arc pressure either fluctuates or is released. For GMAW (gas metal arc welding), in addition to the impact of the arc pressure, the ripple formation is mainly caused by the interplay between the periodic droplet impingements and the weld pool solidification [6,7].

Many researchers studied the weld pool dynamics and weld bead formation with experimental [8–12] or numerical [13–24] methods. However, it is rather difficult to experimentally measure the parameters such as temperature and velocity due to the non-transparency of base metal and the high-temperature arc plasma. Mathematical modeling provides an effective method to solve this problem. Many models have been developed for GTAW by

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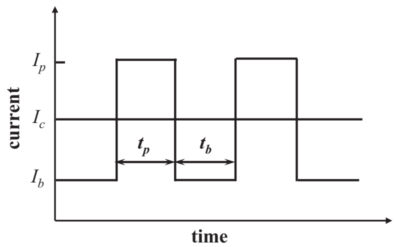

Fig. 1. Schematic sketch of continuous current (I_c) and pulsed current (I_p/I_b) waveform.

considering arc-plasma region, cathode and/or anode regions. Tanaka and Lowke [13] reviewed the recent models which can be used to predict the weld depths under the different process parameters. Fan et al. [14] numerically analyzed fluid flow driven by a combination of electromagnetic force, buoyancy force, arc drag force, and surface tension gradient for a partially or fully penetrated weld pool in a stationary GTAW. Lu et al. [15,16] simulated the behavior of weld pool and welding arc in GTAW including fluid flow and heat transfer by using ANSYS, in which the effects of a few forces on weld pool shape and the interaction between welding arc and weld pool were studied. Wu and Gao [17] developed the correlation of the heat flux on the anode surface with the plasma properties at the free-fall edge, and it was found the energy carried by the electrons constituted most of the heat on the anode surface. Recently, Liu et al. [18,19] calculated the weld pool dynamics during laser welding of aluminum alloy using a 2D model by considering the segregation and solute distribution. Most of these models only considered the stationary welding process under the continuous current. A few studies [20–23] focused on the modeling of weld pool dynamics during the pulsed GTAW. Kim and Na [20] numerically studied the transport phenomena in the weld pool of pulsed GTAW including the melt flow, heat transfer and phase change. Wu et al. [21] developed a 3D model to simulate the pulsed GTAW process, and analyzed the cyclic variation of fluid flow and heat transfer in weld pool under periodic arc heat input. Traidia et al. [22,23] numerically studied the spot pulsed GTAW with partially and fully penetrated weld pools, and analyzed the effects of pulsed welding parameters on the weld pool shape and size. Fan et al. [24] introduced a 2D transient model to study the arc temperature and arc pressure at the anode center under pulsed current GTAW, but the weld pool behavior was not considered. Rao et al. [25] developed a 3D model to simulate the arc characteristic of CMT (cold metal transfer) process with the periodically varied current and voltage. Few of the above models focused on the moving GTAW under pulsed current, especially the weld pool behavior and their effects on the surface rippling. Hu et al. [6] and Rao et al. [7] developed 3D transient models to study the formation of ripples in the moving GMAW under various welding conditions, but the prediction of ripple formation for pulsed GTAW were not involved. From the above review, it is found that the effects of the welding parameters, such as welding current waveform, pulse frequency and welding speed, on the weld bead formation and surface ripples during pulsed GTAW have not received much attention, and the underlying mechanisms have not been understood well.

In this paper, a 3D transient GTAW model employing the volume of fluid (VOF) technique [26] and the continuum formulation [27] is developed to simulate the transient distributions of the melt flow velocity and temperature in the weld pool, weld pool motion, and the formation of ripples for a moving GTAW process under pulsed currents. This work provides a better understanding to the effects of welding parameters on the weld pool and surface rippling in pulsed GTAW, and helps to identify the underlying physics and critical parameters.

2. Mathematical formulation

2.1. Governing equations

Fig. 2 is a schematic sketch of a bead-on-plate GTAW process. The 3D x–y–z coordinate system is fixed to the stationary base metal, while a 2D r–z cylindrical coordinate system is moving with the arc center. The electrode is assumed to move at the same velocity as the arc travels along the x-direction. In this study, the arc generation process is not included to avoid the excessive computational time; instead, the arc heating and arc pressure are assumed to have Gaussian distributions on the workpiece surface. The partial differential equations governing the conservation of mass, momentum, and energy developed by Diao and Tsai [27] are modified and employed in the present study and are given below.

(1) Continuity

$$\frac{\partial}{\partial t}(\rho) + \nabla\cdot(\rho\vec{V}) = 0 \tag{1}$$

(2) Momentum

$$\begin{aligned}\frac{\partial}{\partial t}(\rho u) + \nabla\cdot(\rho\vec{V}u) &= \nabla\cdot\left(\mu_l\frac{\rho}{\rho_l}\nabla u\right) - \frac{\partial p}{\partial x} - \frac{\mu_l}{K}\frac{\rho}{\rho_l}(u-u_s)\\ &\quad - \frac{C\rho^2}{K^{1/2}\rho_l}|u-u_s|(u-u_s)\\ &\quad - \nabla\cdot(\rho f_s f_l \vec{V}_r u_r)\\ &\quad + \nabla\cdot\left(\mu_l u\nabla\left(\frac{\rho}{\rho_l}\right)\right) + \vec{J}\times\vec{B}\Big|_x\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial}{\partial t}(\rho v) + \nabla\cdot(\rho\vec{V}v) &= \nabla\cdot(\mu_l\frac{\rho}{\rho_l}\nabla v) - \frac{\partial p}{\partial y} - \frac{\mu_l}{K}\frac{\rho}{\rho_l}(v-v_s)\\ &\quad - \frac{C\rho^2}{K^{1/2}\rho_l}|v-v_s|(v-v_s)\\ &\quad - \nabla\cdot(\rho f_s f_l \vec{V}_r v_r) + \nabla\cdot\left(\mu_l v\nabla\left(\frac{\rho}{\rho_l}\right)\right)\\ &\quad + \vec{J}\times\vec{B}\Big|_y\end{aligned} \tag{3}$$

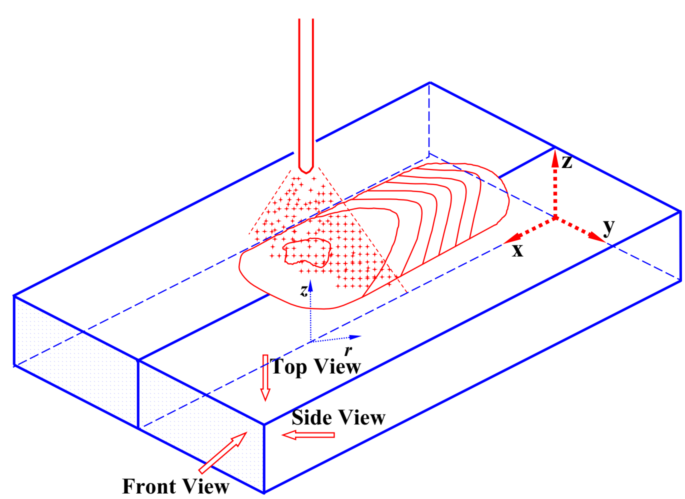

Fig. 2. Schematic sketch of a 3D moving GTAW system; x–y–z is a fixed coordinate system and r–z is a local coordinate system moving along with the arc center.