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Numerical simulation of arc plasma and weld pool in double electrodes tungsten inert gas welding

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ABSTRACT

Based on a unified three dimension mathematical model developed in previous studies, arc plasma and weld pool in double electrodes tungsten inert gas welding are numerically investigated with emphasizes on electrode separation. The effects of small amounts of oxygen (4%) added to shielding gas on the weld pool dynamics are studied by neglecting its effect on the arc plasma reasonably. The distributions of current density, heat flux and shear stress at the anode are analyzed for various electrode separations. It is found that the electrode separation has a significant influence on the flow and temperature fields of arc plasma while has insignificant effect on the maximum temperature of it. With increase in the electrode separation, the distributions of current density, heat flux and temperature at the anode range from one peak profiles to two-peak profiles, while total heat input to the anode changes little. As the electrode separation increases, the extension of the weld pool alters from the direction vertical to the line through the two electrodes to that parallel to the line. The constriction of the weld pool width and increase of the weld pool depth are induced by the reversed heat convection in the weld pool due to small amounts addition of the oxygen. With a certain electrode separation, there exist two peak temperatures at the anode and local inward flow in the weld pool with argon shielding, while local outward flow appears with oxygen addition.

1. Introduction

Electrical arc welding is probably the most widely used welding process in commercial manufacturing. Various novel welding methods were developed to improve welding efficiency and/or quality with relatively low cost, such as activated flux tungsten inert gas (A-TIG) welding [1], advanced activating TIG welding (AA-TIG) [2], arc assisted activating TIG welding [3], dual-bypass gas metal arc welding (DB-GMAW) [4], twin-arc TIG (T-TIG) welding [5], tandem gas metal arc welding [6] and so on. In these welding processes, electric, heat, mass and momentum associated with arc plasma and electrodes are redistributed to obtain desired weld bead in practical welding production, and thus the transport phenomena tend to be more complicated than those in conventional arc welding.

For the DB-GMAW, the total heat input to the work piece was reduced through bypass arc [4]. Quite the contrary, in T-TIG, or double electrodes TIG welding, the welding current can be higher since the same current is carried by two electrodes, which means an increased total heat input to the work piece. On the other hand, the undercutting and hump defects presenting in high velocity TIG welding with large current can be avoided, which means an improved welding efficiency [5]. A-TIG welding is well kwon thanks to its significant improvement in weld penetration, and the mechanisms giving increased weld depth were clarified in principle in past decades [2,3,6–10]. It is essentially the combination of the heat conducted and that convected in the weld pool for different materials that determines the resulting weld geometry. By combining double electrodes TIG welding with arc assisted activating TIG welding, we developed double electrodes activating TIG (DA-TIG) welding process, which can obtain increased weld depth without appearance of weld defect such as undercut and hump in relatively high speed welding [11].

There have been several researchers devoted to studying the physical phenomena related to double electrodes TIG welding. They investigated the pressure of the coupled arc generated by double electrodes [12,13] and the spacial temperature profiles [14,15]. However, the experimental methods are limited by the fact that measurements of double-TIG arcs are more difficult because of the lack of rotational symmetry. Also, it is rather difficult to identify the importance of each parameter including

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current, arc length, welding speed, gas flow rate and electrode separation and so on in optimizing process parameters and weld quality. Numerical models provide a useful way to understand the complicated transport phenomena and to optimize parameters involved in the welding process.

Traditionally, the mathematical models focused on either the arc plasma [16–22] or weld pool [6–8,23–27]. Choo et al. [28,29] represented a semi-coupled 2-D model, and the weld pool impact on the arc was not included. Tanaka et al. [31,32] further developed the models of Lowke et al. [19] and Sansonnens et al. [30] so as to include the weld pool formation in TIG welding. The interaction of weld pool and arc plasma were investigated by Tanaka et al. [31,32], Murphy et al. [33] and Mougenot et al. [34] and other new results were presented by Traidia and Roger [35] and Yin et al. [36]. For the multi-electrode welding, the studies are relatively rare. Ogino et al. studied the heat source characteristics of the two TIG arc with different electrode separation [37] and arc plasma and weld pool formation in tandem TIG welding [38] by using numerical modeling. Nevertheless, the work piece was not melted and the weld pool does not form in the study of [37]. For the study of tandem TIG welding, the shielding gas in their model is pure argon and thus the influence of oxygen on the weld pool was not taken into account [38].

In a previous paper, we have developed a unified mathematical model including tungsten, arc plasma and weld pool for double electrodes TIG welding [39], in which electrode separation is a characteristic parameter, and shielding gas has a vital role in weld pool dynamics and ultimate shape and size. In this study, the transport phenomena in arc plasma and weld pool of double electrodes TIG welding are investigated and discussed accordingly with focuses on the electrode separation and the active gas, i.e. Ar + O_2. In Section 3.1, we present the calculated temperature and velocity of arc plasma and weld pool for different electrode separation with Ar shielding, and the variation of weld pool geometry are examined. In addition, the shear stresses acting on the weld pool are investigated. In Section 3.2, the combination effects of oxygen and the electrode separation on the weld pool dynamics are underlined and the shear stresses acting on the weld pool are presented. The heat input to the anode is presented for different electrode separation with Ar shielding and Ar + O_2 as well. The study provides a better understanding of transport phenomena and desired help for parameter optimization involved in double electrodes TIG welding and DA-TIG welding.

2. Mathematical models and numerical computation

The schematic of double electrodes TIG welding was presented in previous paper [39]. We designed a welding torch with a spacer which divided the torch cavity into two parts and thus keep shielding gas for each tungsten electrode flowing independently, so that the oxygen is added to the argon from one cavity and flow into the plasma. Oxygen is transferred by the arc plasma to the weld pool surface and alters the surface tension to plays a role to increase weld penetration. The welding effects on the weld dimension are similar to A-TIG welding and we named this process as DA-TIG welding [39]. According to the study of Jönsson et al. [40], small amounts of oxygen (<5%) has little effect on the arc thermal physical and transport properties, thus the effect of oxygen on the arc plasma is neglected reasonably, also its impact on the cathodes are not taken into account for its insignificant role in electrodes erosion and the resulting welding arc. The effect of oxygen on the surface tension of weld pool is included only.

The details of the mathematical model was presented previously [39], here we summarize it briefly. Arc plasma is treated as continuum medium and in local thermodynamic equilibrium (LTE). The argon arc is burning steadily in atmospheric pressure and the moving of the welding torch is not considered. The free surface of the weld pool is no deformable since the arc pressure at the anode is much lower than the TIG arc in the similar conditions [12,13]. The metal vapor from the anode surface is neglected since the concentration of the metal vapor in argon shielding is significantly lower than that in helium shielding [32], and exclusion of its influence cannot results in considerable discrepancy [31,33]. The anode is SUS 304 stainless steel. Energy equation and Maxwell's equations are solved in the whole domain while the Navier–Stokes equation is solved in the fluid domain, e.g. arc plasma and weld pool.

Buoyance is calculated by Boussinesq approximation and Lorentz force is calculated by solving Maxwell's equations. Shear stresses acting on the anode surface including plasma drag force τ_p and Marangoni stress τ_M,

$$\tau = \tau_M + \tau_P = \frac{\partial\gamma}{\partial T}\frac{\partial T}{\partial x_i} + \mu_P\frac{\partial v_i}{\partial z} \quad (1)$$

where v_i is the velocity component in x_i direction, and x_i represents x and y directions. γ is the surface tension and T is the temperature. μ_p is the plasma viscosity adjacent to the anode. In this paper, surface tension of the weld pool was measured at different temperatures with pure argon and with 1.0 L/min O_2 added to the shielding gas, respectively. The value of $d\gamma/dT$ can be calculated to get $3.64\times10^{-3}\ \mathrm{N\cdot m^{-1}K^{-1}}$ for the case of oxygen mixed and $-0.143\times10^{-4}\ \mathrm{N\cdot m^{-1}K^{-1}}$ for the case of pure argon [43–45].

In this paper, the surface tension of the weld pool was measured indirectly. The molten pool formed with pure argon shielding and with 1.0 l min^{-1} O_2 added were fast cooled and the specimens were prepared. By remelting and heating the specimens gradually, the surface tensions were obtained at different temperatures by sessile drop method. The surface tension temperature coefficient was deduced from the fitted liner correlation between surface tension and temperature. Since the oxygen solubility in the weld pool drops rapidly with the weld pool cooling, if we employ the oxygen content in the cold weld bead rather than in hot weld pool to calculate Marangoni force, Marangoni effect may be underestimated. On the other hand, only the oxygen on the weld pool surface rather than in the weld pool can plays a role of surfactant to alter the surface tension. For the content of sulfur in the SUS 304 stainless steel [46], it is much lower than the oxygen content and its effect on the surface tension is neglected reasonably. Therefore, we use a constant temperature dependence of surface tension obtained by experiment.

The melting of anode is treated by using enthalpy–porosity method, where a mushy zone exists between solid and fluid and a momentum source $\boldsymbol{S}_u$ and an energy source relate to latent heat are added to account for the phase change [41–42].

According to the research of Choo et al. [24] and Hong et al. [26], we consider the turbulent flow in the weld pool [39] and the standard two-equation K–ε model [47] is employed.

As presented in previous study [39], the electrode sheaths are neglected. We adjust the grid size adjacent to the electrodes and electrical conductivity and thermal conductivity to accordance the calculated arc temperature with the experimental ones. The suitable cell thickness adjacent to the electrodes is about 0.15 mm [39]. At the surface of the tungsten electrodes, non-slip condition is used. At the anode surface, heat flux to the anode is expressed as follows [35,38].

$$q_a = q_c + q_e + q_r = -k_{eff}\frac{T_{aw} - T_{ap}}{\delta} + |j_z|\Phi_a - \varepsilon_r\sigma T^4. \quad (2)$$

where k_{eff} is efficient conductivity thermal, T_{aw} and T_{ap} are, respectively, temperature of the anode surface and that of the plasma vicinity to the anode, δ is the thickness of the anode sheath and set as 0.15 mm. j_z is the component of the current density in z direction,