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# Energy propagation in plasma arc welding with keyhole tracking

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ABSTRACT

A three dimensional mathematical model was developed to research the dynamic interaction between energy propagation and keyhole evolution in PAW (Plasma Arc Welding). Particularly, a keyhole-tracking heat source model was proposed to reflect the energy propagation in the wake of keyhole evolution, which was tracked by the VOF (Volume of Fluid) technique. The model consists of a Gaussian heat flux on top surface and a lower developing conical heat source related to the dynamic keyhole growth. In addition, a dynamic energy distribution coefficient was established, bound up with the keyholing process for the first time. The design of this heat transfer model introduces the analogy to actual energy propagation in experiment. Evolution of the dynamic energy density distribution concerning keyhole effect was analyzed in details, and the corresponding temperature field was calculated and displayed to reveal the mechanism of thermal process in the workpiece. Furthermore, the keyholing process and molten metal flow in the weld pool were investigated to exhibit how the keyhole promotes the deep penetration welding. Finally, the experiments were carried out on the stainless steel plate, and the measured weld bead geometry, keyhole size and time for workpiece completely penetrated through were all close to simulation results.

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## 1. Introduction

Welding is the process of permanently joining two or more metal parts by melting both materials. The molten materials quickly cool, and the two metals are permanently bonded. This process usually involves series of complex phenomena, mainly including heat transfer in material melting and solidification, molten metal flow, solid/liquid phase change and even vaporization. Most of the familiar objects in modern society, from buildings and bridges, to computers, vehicles, and turbines [1], could not be produced without the use of welding. Especially, with the rising development of advanced manufacturing industry, such as aircraft and aerospace industries, shipbuilding and marine industries and automotive industries, cost-effective high-efficiency high-quality welding processes are being progressively required for increased performance requirements and enhancements in product quality. Thus, the high energy density welding processes, featured by producing high-quality welds with a high-aspect-ratio, provide a means for these process demands by using a special heat source capable of offering extremely high-power-density energy input. Among the rest, the PAW (Plasma Arc Welding), owing to its cost effectiveness [2] and higher tolerance to joint gaps and misalignment than others [3], has attracted extensive attention in its research. In PAW, high-temperature ($1.0 \times 10^4$–$5.0 \times 10^4$ K) high-velocity (100–500 m/s) plasma arc penetrates into the weld pool, forming a vapor-filled cavity called as “keyhole”. As far as we know, the weld bead geometry and penetration determine the weld strength in almost all welding situations. While the keyhole is usually attributed to the most critical role in the weld shape [4]. Therefore, by appropriate control of the keyhole evolution, it is available to achieve a stable keyhole welding process and high-quality welds.

In fact, keyholes are also formed, and extensively analyzed in other high energy density welding processes. Tremendous researches on keyhole formation and heat transfer in the weld pool have been conducted for laser and electron beam welding [5–9]. However, the welding mechanism in these processes differs from that in PAW process. In PAW the keyhole is produced and maintained mainly by the pressure of plasma arc, significantly distinct from that by the recoil pressure of evaporating metal in laser and electron beam welding [2]. Although lots of experimental researches have been conducted on plasma system [4,10–14], theoretical studies on thermal and fluid mechanics aspects of the keyhole welding process remain scarce. With several simplifications, researchers have developed various numerical models to calculate weld pool shape, flow pattern in the pool and temperature

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**Nomenclature**

| | |
|---|---|
| $A_0$ | mushy zone constant in Eq. (14) |
| $A_v$ | constant in Eq. (25) |
| $b$ | parameter of energy distribution in Eq. (8) |
| $C_j$ | adjusting coefficient in Eq. (18) |
| $C_p$ | specific heat |
| $C_{pl}$ | specific heat of plasma arc |
| $C_m$ | specific heat of metal |
| $D$ | thickness of the workpiece in Eq. (7) |
| $f^\alpha$ | sulfur concentration in Eq. (20) |
| $f_l$, $f_s$ | liquid fraction and solid fraction |
| $F$ | volume of fluid function in Eq. (15) |
| $F_x$, $F_y$, $F_z$ | electromagnetic force in $x$, $y$ and $z$ direction |
| $g$ | acceleration of gravity |
| $h$ | sensible enthalpy of material |
| $h_{conv}$ | convective heat transfer coefficient |
| $h_{ref}$ | reference enthalpy |
| $H$ | enthalpy of material |
| $I$ | welding current |
| $k$ | thermal conductivity |
| $k_{pl}$ | thermal conductivity of plasma arc |
| $k_m$ | thermal conductivity of metal |
| $K$ | permeability |
| $L$ | dynamic height of heat source in Eq. (7) |
| $L_a$ | latent heat of fusion |
| $L_v$ | latent heat of vaporization |
| $\vec{n}$ | normal vector to the local free surface |
| $p$ | pressure |
| $q_{conv}$ | heat loss by convection |
| $q_{evap}$ | heat loss by evaporation |
| $q_{rad}$ | heat loss by radiation |
| $q(x, y, z, t)$ | heat source |
| $r$ | radius |
| $r_1$ | plasma arc radius on the workpiece |
| $r_2$ | plasma arc radius at nozzle |
| $r_e$, $r_i$ | radius of conical heat source ends in Eq. (7) |
| $r_g$ | radius of Gaussian heat flux in Eq. (6) |
| $R$ | ideal gas constant |
| $R_1$, $R_2$ | principal radii of curvature of free surface |
| $\vec{s}$ | tangential direction to the free surface |
| $t$ | time |
| $T_l$, $T_s$ | liquidus temperature and solidus temperature |
| $T_m$ | melting temperature of material |
| $T_{ref}$ | reference temperature |
| $T_\infty$ | ambient temperature |
| $u$, $v$, $w$ | velocity in the $x$, $y$ and $z$ direction |
| $U$ | welding voltage |
| $\mathbf{V}$ | velocity vector |
| $V_r$ | Darcy seepage velocity in Eq. (13) |
| $W$ | melt mass evaporation rate |
| $x$, $y$, $z$ | coordinate of $x$, $y$ and $z$ axis |
| $x_0$, $y_0$, $z_0$ | initial position of heat source |
| $z_e$, $z_i$ | $z$-coordinate of conical heat source ends |

*Greek symbols*

| | |
|---|---|
| $\beta$ | thermal expansion coefficient |
| $\varepsilon$ | radiation emissivity |
| $\eta$ | thermal efficiency of plasma arc welding |
| $\kappa$ | surface curvature in Eq. (19) |
| $\mu$ | dynamic viscosity |
| $\mu_0$ | magnetic permeability |
| $\mu_{pl}$ | dynamic viscosity of plasma arc |
| $\mu_m$ | dynamic viscosity of molten metal |
| $\rho$ | density |
| $\rho_{pl}$ | density of plasma arc |
| $\rho_m$ | density of metal |
| $\sigma$ | Stefan–Boltzmann constant |
| $\sigma_j$ | current distribution parameter in Eq. (17) |
| $\chi_1$, $\chi_2$ | energy distribution coefficients |
| $\gamma$ | surface tension |
| $\partial\gamma/\partial T$ | temperature gradient of surface tension |

history of workpiece by presupposing a keyhole shape [2,15,16]. Fan and Kovacevic [17] firstly employed the VOF (Volume of Fluid) technique to track the keyhole formation, growth and collapse in a two dimensional PAW simulation. Recently, Zhang et al. [18] and Wu et al. [19] established a three-dimensional model by VOF technique to investigate the transient evolution of keyhole geometry and weld pool in PAW process, respectively. In addition, the LS (Level Set) method [20,21] and force balance analysis [22,23] were also applied to compute the dynamic developments of keyhole geometry in PAW.

Different from above keyhole tracking methods, some researchers, from the viewpoint of engineering applications, pay more attention to energy utilization in the weld pool and have developed many types of effective heat source model which is able to reasonably reflect the energy propagation due to keyhole effect. Since these models leave out the cumbersome and time-consuming keyhole tracking, thereby offering great convenience in practical implement. And they are usually capable of making the prediction of weld geometry as accurate as that by experimental tests. In early welding analysis, Gaussian surface heat flux was generally adopted to represent the arc thermal energy [17,24,25]. Goldak et al. [26] proposed a double-ellipsoidal heat source model which is more suitable to analyze the thermal history of deep penetration welds. In order to describe the characteristics of high ratio of the weld penetration to width, TDC heat source (Three-dimensional Conical), MTDC heat source (Modified Three-dimensional Conical), QPAW heat source (Quasi-steady state Plasma Arc Welding) and TPAW (Transient thermal model for Plasma Arc Welding) were successively proposed and applied in PAW analysis [27,28]. Wu et al. [29] constructed a novel heat source model, which was a combination of a double-ellipsoidal heat source and a cylindrical heat source. Their model shows fairly accurate PAW weld shape and reveals the volumetric distribution characteristics of plasma heat intensity along the direction of thickness. Li et al. [30] developed an improved heat source model taking into account the influence of fluid flow in weld pool, thus predicting a more precise weld geometry as well as an obvious hump in the fusion line.

However, PAW researches above are either simplified by the effective heat source models or leave out the variation of heat flux due to the keyhole extension. Hence, a three dimensional model was developed in this paper to reveal the more actual dynamic interaction between energy propagation and keyhole evolution during the keyhole PAW process. In our model, the keyhole evolution affects the instantaneous energy propagation in the weld pool, which, in turn, affects the keyhole evolution. In fact, it is the dynamic interaction that profoundly determines every development of the weld pool. Theoretical basis is expected to be provided by our research for the keyhole control so as to produce high-quality welds. The continuum equations [31] and Volume of Fluid (VOF) [32] technique were integrated to model these complex

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