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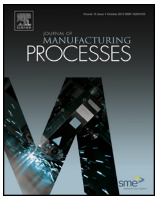

Modeling and simulation of arc: Laser and hybrid welding process

Dae-Won Cho, Won-Ik Cho, Suck-Joo Na*

Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea

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ABSTRACT

Welding is a fabrication process to join two different materials. Among the many welding processes, the arc and laser welding processes are the most widely used. Great effort is required to understand the physical phenomena of arc and laser welding due to the complex behaviors which include liquid phase, solid phase and, gas phase. So it is necessary to conduct numerical simulation to understand the detailed procedures of welding. This paper will present the various numerical simulation methods of the arc welding processes such as arc plasma, gas tungsten arc welding, gas metal arc welding, laser welding, and laser–arc hybrid welding. These simulations are conducted by the finite element method, finite differential method and volume of fluid method to describe and analyze the various welding processes.

1. Arc welding

1.1. Arc plasma

The arc plasma simulations normally describe the process to form arc plasma from welding parameters such as current, voltage, arc length, shielding gas, and tip angle. So these simulations can provide the distributions of temperature, velocity, and pressure in the arc plasma. Many studies have adopted FDM to analyze the arc plasma and boundary-fitted coordinate to describe the complex region, which includes the electrode surface configuration.

Fig. 1 shows a schematic diagram of GTAW with straight polarity. In the stable arc established after arc starting, the supplied shielding gas is continuously ionized and maintains the path for the welding current. The ionized gas has a much higher electrical conductivity than the gas before ionization, which allows the welding current to flow continuously. This flow of current also causes joule heating in the welding arc, which maintains its ionized state. Therefore, the ionized and high temperature welding arc gives rise to a highly concentrated heat source at the anode plate for welding. This self-maintained welding arc also generates a magnetic field and force. Additionally, the current density near the electrode is high and gradually decreases toward the anode plate. This gradual decrease of current density from cathode (electrode) to anode causes the axial pressure gradient, which acts as a driving force of the arc plasma for an additional convective heat flux into the base plate. From the outlet of the shielding nozzle, the shielding gas is continuously supplied and maintains mass continuity. At the anode plate, the electrons are condensed, producing energy proportional to the work functions of the anode material. To establish a numerical model for the complex welding arc from the standpoint of magneto hydrodynamics (MHD) type flow, some assumptions must be made in the arc domain and the boundaries.

a. The domain will satisfy the stationary and steady state conditions.
b. Although the real welding process includes the movement of the electrode and time-varying arc, it was assumed to be a stationary condition. Therefore, the arc can be treated as an axisymmetric problem, and the solution domain was represented in terms of the cylindrical coordinates. Additionally, the temperature of the cathode and anode were assumed to be constant and the anode plate was assumed to be flat.
c. At atmospheric pressure and normal welding conditions, the arc plasma can be assumed to be a laminar flow [2].
d. Regarding the body force inside the welding arc plasma, only EMF was considered. The buoyancy from gravity was neglected.
e. The fluid was considered to be incompressible.
f. The heating effect due to viscous dissipation was neglected.
g. The arc plasma was assumed to be in the LTE state [2–5].
h. With the above-mentioned assumption, the governing equations such as mass continuity, momentum, energy conservation and current continuity equations were used as follows [1].

Abbreviations: FDM, finite differential method; TIG, tungsten inert gas; EMF, electromagnetic force; LTE, local thermodynamic equilibrium; CCD, charge-coupled device; GTAW, gas tungsten arc welding; GHTAW, gas hollow tungsten arc welding; HAZ, heat affected zone; FEM, finite element method; VOF, volume of fluid; BOP, bead on plate; GMAW, gas metal arc welding; LIP, laser induced plasma; EPMA, electron prove micro analyzer.

* Corresponding author. Tel.: +82 42 350 3216; fax: +82 42 350 3210.
E-mail address: sjoona@kaist.ac.kr (S.-J. Na).

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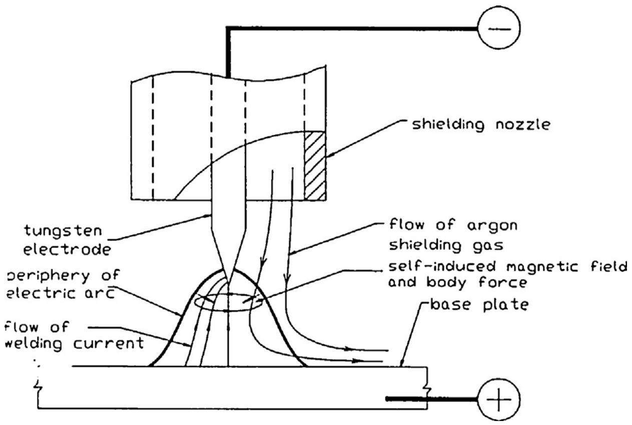

Fig. 1. Schematic diagram of the tungsten inert gas (TIG) welding arc [1].

(a) Mass continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho r u)+\frac{\partial}{\partial z}(\rho w)=0 \tag{1}$$

(b) Momentum equation:

$$r\text{-component}\quad \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho uu-r\mu\frac{\partial u}{\partial r}\right)+\frac{\partial}{\partial z}\left(\rho wu-\mu\frac{\partial u}{\partial z}\right)=0 \tag{2}$$

$$z\text{-component}\quad \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho uw-r\mu\frac{\partial w}{\partial r}\right)+\frac{\partial}{\partial z}\left(\rho ww-\mu\frac{\partial w}{\partial z}\right)=0 \tag{3}$$

(c) Current continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(rj_r)+\frac{\partial}{\partial z}(j_z)=0 \tag{4}$$

(d) Energy conservation equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho uh-r\frac{k}{C_p}\frac{\partial h}{\partial r}\right)+\frac{\partial}{\partial z}\left(\rho wh-\frac{k}{C_p}\frac{\partial h}{\partial z}\right)$$
$$=\frac{j_r^2+j_z^2}{\sigma}-S_r+\frac{5}{2}\frac{k_s}{e}\left(\frac{j_r}{C_p}\frac{\partial u}{\partial z}+\frac{j_z}{C_p}\frac{\partial h}{\partial z}\right) \tag{5}$$

where ρ is the density, u is the r-directional velocity, w is the r-directional velocity, μ is the dynamic viscosity, j_r is the radial current density, j_z is the axial current density, h is the enthalpy, k is the thermal conductivity, C_p is the specific heat at a constant pressure, S_r is the radiation loss term per unit volume for the argon arc plasma, k_B is Boltzmann constant and e is the electron charge.

From the arc plasma simulation, variable distributions could be obtained such as, current density, magnetic force, gas flow patterns, heat flux, current flux, temperature, arc pressure and shear stress. The resultant distributions for heat flux, current density, gas shear stress and arc pressure above the 0.1 mm from the anode plate in Fig. 2 can be used as boundary conditions in the molten pool simulations afterward.

In pulsing the welding arc, both the welding current and arc voltage are simultaneously switched between high and low levels at a given frequency and duration. Fig. 3 is a schematic representation of an ideal pulsed current rectangular waveform. However, the actual waveform in the experiment shows a different shape, which means that the rectangular waveform cannot be sustained in higher frequency in Fig. 4 [7,8].

In high frequency control over 100 Hz, Fig. 4(d) shows saw-toothed form rather than rectangular form. This practical aspect has to be taken into consideration in the analysis of the pulsed current arc. For the analysis of a high frequency pulsed current, the current must be calculated along the slope from the peak current to the base current. Numerical analyses for pulsed current processes can be performed. In the numerical analysis, performing a one-time step analysis of an unsteady problem shows no fundamental difference compared to solving a steady state problem. In a steady state problem, a large value is considered to be set to the time step, namely, $\Delta t\to\infty$. Fig. 5 shows the results of isothermal lines (11,000 K), which represent the progress of rapid convergence to a final state with iteration numbers. The third or the fourth iterations nearly reach a final value. From this method, it is possible to expect numerical analyses for an unsteady welding process of pulsed current in Fig. 5.

1.2. *Arc characteristics on workpiece*

Arc heat flux, current density and arc pressure should be described properly to simulate the arc welding processes accurately. There are several arc heat flux models proposed and applied for simulations of heat and mass transfer in arc welding, such as Gaussian surface flux distribution, hemispherical power density distribution and double ellipsoidal power density distribution. The arc heat flux distribution could also be measured by using a special type of calorimeter or thermocouples. The same arc characteristic of heat flux distribution can be adopted for arc pressure and current density. The irradiance distribution of welding arc next above the anode workpiece is obtained by applying Abel inversion algorithm to the CCD arc image, and then used to determine the distribution of arc heat flux, arc pressure and current density from the physical relations of arc irradiance, temperature and current density in GTAW [9].

1.2.1. *Arc characteristics in GTAW*

Gas tungsten arc plasma contains three regions; anode drop, arc column, and cathode drop. The arc column region is electrically neutral and in LTE, where the temperature of electron, ion, neutron and particle are the same. As the arc column is LTE, Saha equation and Boltzmann equation [10] use the same temperature and can be expressed as follows:

$$T_k=T_{exc}=T_i \tag{6}$$

where T_k is the kinetic temperature of arc plasma, T_{exc} is the excitation temperature of arc plasma and T_i is the ionization temperature of arc plasma. The temperature of arc plasma is qualitatively proportional to the radiation energy of particles which are excited and emitted in the arc plasma. With a CCD camera, it is possible to measure the 2D intensity of the arc plasma which can be then used to obtain the 3D arc irradiance by Abel inversion method [11].

1.2.1.1. Physical relation of arc irradiance, temperature and current density. To form the arc heat flux model, it is necessary to understand the energy transfer mechanism from arc plasma to anode. The arc heat flux can be described as follows:

$$Q_a(r)=\frac{5}{2}k_B(T_{a,g}-T_{an})\frac{J}{e}+J\varphi_a+J\varphi_f+k_g\frac{T_{a,g}-T_{an}}{\delta} \tag{7}$$

where k_B is the Boltzmann constant, J_a is the current density on the anode, φ_a and φ_f are the work functions of the anode metal and anode fall. $T_{a,g}$ is the temperature in gas, 0.1 mm above the anode, T_{an} is the temperature of the anode, k_g denotes the thermal conductivity, and δ is the anode fall region distance (about 0.1 mm).

The physics of the anode fall region is rather complex, where Dinulescu and Pfender [12] summarized and used the simple anode heat transfer equation, expressed in Eq. (7) which many researches [13,14] widely adopted in the welding physics area. The first term