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New model of body force in electromagnetic stirring gas tungsten-arc welding①

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[Abstract] After measuring arc electrical current density distribution in gas tungsten-arc welding(GTAW) with a probe method, the new expression of body force and model of LD10CS aluminum alloy weld pool are put forward for the first time in GTAW with additional longitudinal magnetic field controlling. The influence of additional longitudinal magnetic field on body force is discussed by electromagnetic principle. This study provides the basis to study fluid flow of the weld pools and arc welding technique with electromagnetic controlling.

[Key words] GTAW; body force; model; longitudinal magnetic field; weld pool
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1 INTRODUCTION

Electromagnetic stirring (EMS) welding technique is different from the common arc welding technique and has the following advantages[1~3]: 1) low costs for investment owing to simple additional equipment; 2) operational reliability which thanks to the use of high-performance coil; 3) better mechanical quality owing to the fine crystal grain; 4) minimized risk of cold cracking owing to low hydrogen content; 5) good-looking welding seams with clean weld surfaces; 6) better arc control and suitable for another welding process; 7) good environmental protection owing to the low power magnetic field.

The welding technique is used in the metallurgy, chemical engineering, pressure vessel, electric power, aviation and spaceflight or other fields[1~4]. However research of the gas tungsten-arc welding (GTAW) with additional longitudinal magnetic field controlling is lack[5~7]. The body force of the GTAW weld pool is the precondition of the numerical simulation of fluid flow in weld pool and heat transfer process and the base of understanding the effect of the additional longitudinal magnetic field on GTAW process. The purpose of this work is to define the body force so as to improve the heat transfer and fluid flow of the arc welding technique with magnetic field controlling.

2 BASIC THEORY

Electromagnetic force applying to weld pool fluid of LD10CS aluminum alloy in GTAW with longitudinal magnetic field is composed of two parts: 1) self-electromagnetic force, $\boldsymbol{F}_{zm}$, which is the electromagnetic force generated by interaction of divergent current with its self-magnetic field in weld pool; 2) body force of the incompressible fluid in GTAW weld pool, $\boldsymbol{F}_{wm}$, which is the additional electromagnetic force generated by interaction of divergent current with the additional longitudinal magnetic field in the weld pool[8].

So, electromagnetic force $\boldsymbol{F}_m$ of incompressible fluid in GTAW weld pool with longitudinal magnetic field controlling can be expressed as

$$\boldsymbol{F}_m = \boldsymbol{F}_{zm} + \boldsymbol{F}_{wm} \quad (1)$$

In order to calculate the body force of incompressible fluid in GTAW weld pool with longitudinal magnetic field controlling, the body force in weld pool of LD10CS aluminum alloy in the fixed spot GTAW with longitudinal magnetic field controlling is researched.

On the other hands, the additional longitudinal magnetic can be taken as uniform magnetic field. The force and magnetic induction are vectors and the body force meets Maxwell's equation:

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} \quad (2)$$

where magnetic permeability $\mu_0 = 4\pi \times 10^{-7}$ H/m.

3 CURRENT DISTRIBUTION

Because LD10CS aluminum alloy is non-magnetic and the additional longitudinal magnetic field is uniform. Obviously, the current flux distribution of incompressible fluid surface in the weld pool is the same as that of interface between the weld arc and the weld pool in GTAW with additional longitudinal magnetic field controlling. The probe method can be used to measure the current flux distribution of welding arc[1~3]. The measurement value of the weld arc current flux is shown in Fig. 1 at the condition of a small

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welding current (I= 100 A) and weak magnetic field (B< 0.1 T).

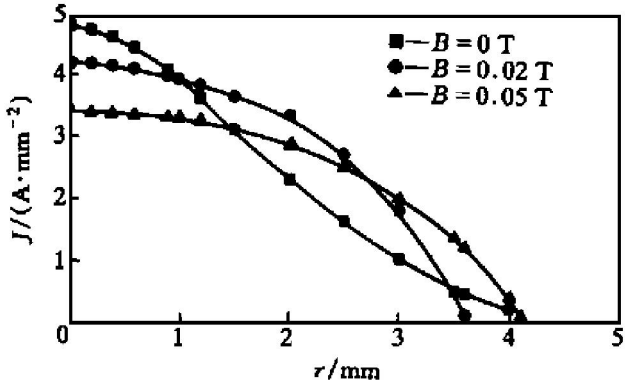

Fig. 1 Measurement value of welding electric current density distribution in EMS GTAW (I= 100 A; arc length L= 3 mm)

At the condition of small electric current ($I \leqslant$ 200 A) and weak magnetic field ($B \leqslant$0.1 T), Gaussian distribution model of welding arc current flux was put forward by the numerical regression analysis, and the equation is shown as follows.

$$J(r)_{arc} = J_0 \cdot \frac{KI}{\pi}\exp(-Kr^2) \tag{3}$$

where the lumped coefficient of current flux $K = a/2\sigma_j^2$; I is welding electric current, $J(r)_{arc}$ is electric current density distribution of welding arc; a is the constant of lumped coefficient (a= 0.5~2); J_0 is electric current density; σ_j is distribution parameter of welding arc current flux.

When welding electric current is 100 A and magnetic induction is 0.02 T, the regression curve of welding arc current flux is shown in Fig. 2.

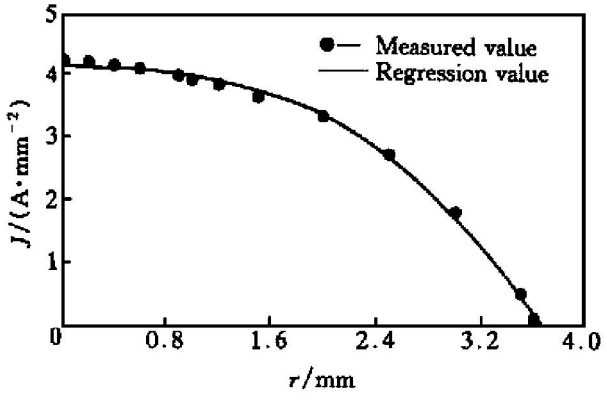

Fig. 2 Regression value of welding electric current density distribution in EMS GTAW

4 BODY FORCE EQUATION

The additional longitudinal magnetic is introduced along axial direction. Fig. 3 shows the schematic diagram of GTAW weld pool and the cylindrical coordinate system. The vectors (eg. force, current flux and magnetic induction) along the radial and axial directions are expressed as two partial vector (r, z) respectively and are symmetrical about the axis oz. So the magnetic induction $\boldsymbol{B}$ can be expressed as:

$$\boldsymbol{B} = [0,\ B_\theta(r,\ z),\ 0] \tag{4}$$

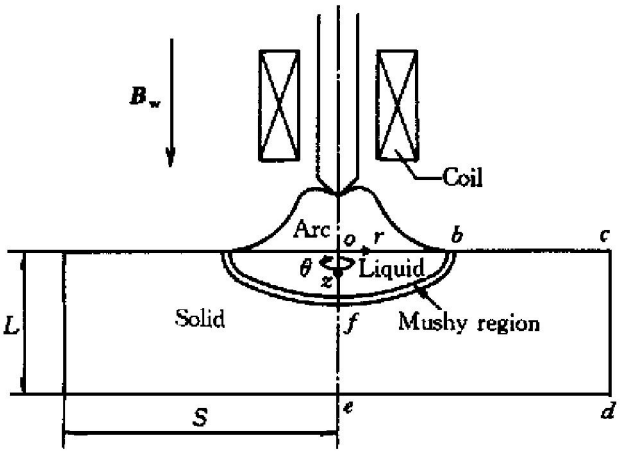

Fig. 3 Schematic diagram of GTAW with longitudinal magnetic field controlling

$$\nabla \times \boldsymbol{B} = \frac{1}{r}\begin{vmatrix} \boldsymbol{r} & \boldsymbol{r}_\theta & \boldsymbol{z} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial z} \\ 0 & rB_\theta & 0 \end{vmatrix} = \left[-\frac{\partial}{\partial z}B_\theta,\ 0,\ \frac{1}{r}\frac{\partial}{\partial r}(rB_\theta)\right] \tag{5}$$

The magnetic flow function $\Psi_e = rB_\theta$, so Eqn. (5) becomes

$$\nabla \times \boldsymbol{B} = \left(-\frac{1}{r}\frac{\partial \Psi_e}{\partial z},\ 0,\ \frac{1}{r}\frac{\partial \Psi_e}{\partial r}\right) \tag{6}$$

In Eqn. (2), the term $\mu_0\boldsymbol{J}$ takes the following form.

$$\mu_0\boldsymbol{J} = \mu_0(J_r,\ 0,\ J_z) \tag{7}$$

Substituting Eqn. (6) and (7) into Eqn. (2), the corresponding part of vector can be expressed as

$$\left.\begin{aligned} J_r &= -\frac{1}{\mu_0}\frac{1}{r}\frac{\partial \Psi_e}{\partial z} \\ J_z &= -\frac{1}{\mu_0}\frac{1}{r}\frac{\partial \Psi_e}{\partial r} \end{aligned}\right\} \tag{8}$$

On the other hands,

$$\boldsymbol{J} \times \boldsymbol{B} = \begin{vmatrix} \boldsymbol{r} & \boldsymbol{r}_\theta & \boldsymbol{z} \\ J_r & 0 & J_z \\ 0 & rB_\theta & 0 \end{vmatrix} = (-rB_\theta J_z,\ 0,\ J_r B_\theta) \tag{9}$$

or

$$\left.\begin{aligned} (\boldsymbol{J} \times \boldsymbol{B})_r &= -B_\theta J_z \\ (\boldsymbol{J} \times \boldsymbol{B})_z &= -B_\theta J_r \end{aligned}\right\} \tag{10}$$

According to Ref. [9], $\partial J_r/\partial z = 0$, so

$$\left.\begin{aligned} \frac{\partial J_r}{\partial z} &= \frac{\partial}{\partial z}\left(-\frac{1}{\mu_0 r}\frac{\partial \Psi_e}{\partial z}\right) = -\frac{1}{\mu_0 r}\frac{\partial^2 \Psi_e}{\partial z^2} = 0 \\ \Psi_e &= C_1 z + C_2 \end{aligned}\right\} \tag{11}$$

where Ψ_e satisfies the boundary condition.

When $z = L$, $\Psi_e = 0$;

when $z = 0$, $\Psi_e = \frac{\partial \Psi_e}{\partial r} = \mu_0 J_z r$.

L is defined as thickness of welding workpiece. So the magnetic flow function Ψ_e become

$$\Psi_e\Big|_{z=0} = \int \mu_0 J_z \Big|_{z=0} r\,dr \tag{12}$$

According to Fig. 1, Eqn. (3) and Eqn. (12), on the condition of the small current ($I = 100$ A) and weak magnetic field ($B < 0.1$ T), the constant of lumped coefficient a is 1, so the boundary condition is as follows.

$$\left.\begin{aligned} J_z\Big|_{z=0} &= \frac{I}{2\pi\sigma_J^2}\exp\left(-\frac{r^2}{2\sigma_J^2}\right) \\ \Psi_e\Big|_{z=0} &= \frac{\mu_0 I}{2\pi\sigma_J^2}\int_0^r \exp\left(-\frac{r^2}{2\sigma_J^2}\right) r\,dr \\ &= \frac{\mu_0 I}{2\pi}\left[1-\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\right] \end{aligned}\right\} \tag{13}$$

Through a solution of Eqns. (11) and (13), the magnetic flow function Ψ_e is

$$\Psi_e = \frac{\mu_0 I}{2\pi}\left[1-\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\right]\left(1-\frac{z}{L}\right) \tag{14}$$

The current density distribution of GTAW weld pool surface with longitudinal magnetc field controlling is decided by the experimental measurement. From Fig. 2 and Eqn. (3). B_θ can be expressed as

$$B_\theta = \frac{\Psi_e}{r} = \frac{\mu_0 I}{2\pi r}\left[1-\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\right]\left(1-\frac{z}{L}\right) \tag{15}$$

After substituting Eqn. (14) into Eqn. (8), the current density J of the LD10CS weld pool become

$$\left.\begin{aligned} J_z &= \frac{I}{2\pi\sigma_J^2}\exp\left(\frac{r^2}{2\sigma_J^2}\right)\left(1-\frac{z}{L}\right) \\ J_r &= \frac{I}{2\pi L r}\left[1-\exp\left(\frac{r^2}{2\sigma_J^2}\right)\right] \end{aligned}\right\} \tag{16}$$

After substituting Eqn. (15) into Eqn. (10), Eqn. (10) can be expressed as

$$\left.\begin{aligned} (\boldsymbol{J}\times\boldsymbol{B})_r &= -\frac{\mu_0 I^2}{4\pi^2\sigma_{Jr}^2}\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\times \\ &\quad \left[1-\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\right]\left(1-\frac{z}{L}\right)^2 \\ (\boldsymbol{J}\times\boldsymbol{B})_z &= -\frac{\mu_0 I^2}{4\pi^2 L r^2}\left[1-\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\right]^2\cdot \\ &\quad \left(1-\frac{z}{L}\right) \end{aligned}\right\} \tag{17}$$

The Self-electromagnetic force $\boldsymbol{F}_{zm}$ of LD10CS weld molten pool in GTAW with longitudinal magnetic field controlling is as follows.

$$\boldsymbol{F}_{zmr} = (\boldsymbol{J}\times\boldsymbol{B})_r = -\frac{\mu_0 I^2}{4\pi^2\sigma_{Jr}^2}\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\cdot \left[1-\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\right]\left(1-\frac{z}{L}\right)^2 \tag{18a}$$

$$\boldsymbol{F}_{zmz} = (\boldsymbol{J}\times\boldsymbol{B})_z = -\frac{\mu_0 I^2}{4\pi^2 L r^2}\left[1-\exp\left(-\frac{r^2}{2\sigma_J^2}\right)\right]^2\left(1-\frac{z}{L}\right) \tag{18b}$$

For the uniform additional longitudinal magnetic induction B_w and welding current axial directions J_z are parallel, body force F_{wm} of LD10CS weld pool in GTAW with longitudinal magnetic field controlling is

$$F_\theta = F_{wm} = \frac{IB_w}{2\pi L r}\left[1-\exp\left(-\frac{r^2}{2\sigma_J}\right)\right] \tag{19}$$

where B_w is the additional magnetic induction vector of LD10CS weld pool in GTAW with longitudinal magnetic field controlling. Body force F_{wm} is in the vertical plane of oz axis.

The above equations show that, electromagnetic force of weld pool coming into being in GTAW with longitudinal magnetic field controlling (including the body force generated by the additional magnetic field) is independent of welding polarity. The welding polarity only changes with the direction of body force.

5 MODEL OF FLUID FLOW

In Fig. 3, velocities along the radial(r), axial (z) and circle(θ) directions are expressed as v, u and w, respectively. A spatially distributed heat flux, $q(r)$, and current flux, σ_J, fall on the constant surface at $z = 0$, which is the surface of the workpiece. Because the energy exchanges between the welding arc and molten pool, and the additional electromagnetic driving force of liquid molten takes place in the weld pool, convection flows, electromagnetic effect and force are induced in r, z and θ direction in the molten pool. It is anticipated that the weld pool configuration is governed by the combined effects of the additional longitudinal magnetic field, self magnetic field, buoyant and surface tension forces. The transient nature of the developing liquid-solid boundary are also taken into consideration. Before introducing the equation of fluid flow in GTAW weld pool with longitudinal magnetic controlling, the welding pool surface is as constant plane surface. When the arc welding current is less than 200 A, the liquid metal is Newton Body and distribution model of welding arc heating density and current flux can be taken as the Gaussian distribution undoubtedly at the condition of a small welding current ($I < 200$ A) and weak magnetic field ($B < 0.1$ T)[10].

Let $u = u(r, z)$, $v = v(r, z)$ and $\omega = \omega(r, z)$ denote the velocity components in the axial z and radial r directions, respectively, the unsteady-state continuity, momentum and energy equations of the incompressible fluid in the molten pool are

$$\frac{1}{r}\frac{\partial(rv)}{\partial r} + \frac{\partial(u)}{\partial z} = 0 \tag{20a}$$

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r} + u\frac{\partial v}{\partial z} - \frac{w^2}{r}\right) = F_r - \frac{\partial p}{\partial r} + \mu\left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} - \frac{v}{r^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{20b}$$

$$\rho\left(\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial r}+u\frac{\partial u}{\partial z}\right)=F_z-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial z^2}\right) \quad (20c)$$

$$\rho\left(\frac{\partial w}{\partial t}+v\frac{\partial w}{\partial r}+u\frac{\partial w}{\partial z}+\frac{v\omega}{r}\right)=F_\theta+\mu\left(\frac{\partial \omega^2}{\partial r^2}+\frac{1}{r}\frac{\partial \omega}{\partial r}-\frac{\omega}{r^2}+2\frac{\partial \omega^2}{\partial z^2}\right) \quad (20d)$$

$$\rho c_p\left(\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial r}+u\frac{\partial T}{\partial z}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial r}\right) \quad (20e)$$

In arc welding with longitudinal magnetic controlling, the body force in Eqn. (20), including additional electromagnetic, self-electromagnetic and buoyant effects, can be expressed according to Eqns. (18) and (19) as follows.

$$\left.\begin{aligned} F_z&=-\frac{\mu_0 I^2}{4\pi^2 Lr^2}\left[1-\exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right]^2\left(1-\frac{z}{L}\right)-\rho g\beta(T-T_1)\\ F_r&=-\frac{\mu_0 I^2}{4\pi^2\sigma_{jr}^2}\exp\left(-\frac{r^2}{2\sigma_j^2}\right)\left[1-\exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right]\cdot\left(1-\frac{z}{L}\right)^2\\ F_\theta&=-\frac{IB_w}{2\pi Lr}\left[1-\exp\left(-\frac{r^2}{2\sigma_j}\right)\right] \end{aligned}\right| \quad (21)$$

where I, B_w, σ_j, β, k, T and ρ denote welding current, additional magnetic induction, distribution parameter of current density, coefficients of thermal expansion, thermal conductivity of molten metal, temperature and density of workpiece, respectively.

6 CONCLUSIONS

In GTAW with longitudinal magnetic field controlling, the welding characteristics is different from the common GTAW.

1) Electromagnetic force of weld pool includes self-electromagnetic force and body force generated by the additional magnetic field. The additional body force of LD10CS weld pool in GTAW with longitudinal magnetic field controlling is

$$F_\theta=F_{wm}=\frac{IB_w}{2\pi Lr}\left[1-\exp\left(-\frac{r^2}{2\sigma_j}\right)\right]$$

2) A mathematical model is developed to represent the additional electromagnetic force field, the velocity field and the thermal field in GTAW weld pool with additional longitudinal magnetic field controlling. The model considers the transient nature of the EMS system, surface tension forces and heating transfer between arc and weld pool, the combined effect of additional longitudinal magnetic and welding self-electromagnetic field. The model presented in this paper is quite comprehensive and correct.

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