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Mathematical Modeling of Heat Flux Distribution of Plasma Arc by Transverse Alternating Magnetic Field

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Abstract: A theoretical analysis was carried out to investigate the characteristics of plasma arc injected transverse to a transverse-alternating magnetic field. Two mathematical models were developed to describe both the oscillating amplitude of the plasma arc root and the heat flux density distribution of plasma arc on the workpiece surface. The characteristic of plasma arc under the external transverse-alternating magnetic field imposed perpendicular to the plasma current was discussed. The effect of process parameters, such as working gas flux, arc current, magnetic flux density and the standoff from the nozzle to the workpiece, on the oscillation and heat flux distribution of plasma arc were also analyzed. The analytical results show that it is feasible to adjust the shape and heat flux density of the plasma arc by the transverse- alternating magnetic field, which expands the region of plasma arc thermal treatment and uniforms the heat flux density upon the workpiece. Furthermore, the oscillating amplitude of plasma arc decreases, and the heat flux density gradient upon the workpiece increases with decrease of the magnetic flux density. Under the same magnetic flux density, more gas flux, more arc current, and less standoff cause the oscillating amplitude to decrease.

Keywords: Plasma arc, transverse magnetic field, heat flux, mathematical modeling.

1. INTRODUCTION

Plasma arc has generally been applied to material processing such as welding, cutting, spraying, etc. Its characteristics have a crucial and direct influence on above processing quality. Usually, the energy distribution of plasma arc is limited in a smaller region and the temperature gradient of plasma arc exerts more variation in the arc column owing to the avalanche effect of gas discharge and the constraint of plasma arc by its own magnetic field. For the above features of plasma arc, plasma welding and plasma cutting are better than other corresponding processes. However, some material processes, including surface cleaning [1] and surface modification of large areas [2], don't desire the heat source to be concentrated, but require soft and broad controllable plasma arcs. Therefore, conventional plasma arc is not a convenient tool for heating over a wide area because of the concentrated heat flux in a small arc root.

In order to obtain a shape-controlled soft plasma arc, some researchers attempted to introduce an external transverse magnetic field to expand the cross section of arc column and flatten the distributions of arc current and temperature, considering the electromagnetic property of the plasma arc. J. Awrejcewicz combined analytical and numerical analyses of oscillations in a string-type generator [3]. Meanwhile, they found that the form of plasma arc in the electromechanical system showed some interesting nonlinear phenomena [4, 5]. D.B. Sobyanin *et al.* carried out laboratory experiments to investigate the evolution of plasma jet injected transverse to the magnetic field and observed that the plasma jet propagation existed in two stages [6]. In the first stage, the magnetic field expulsion was detected. At the second stage, deceleration and deflection of the plasma jet due to field-aligned currents were investigated. A. Zhainakov *et al.* performed a numerical simulation of an open electric arc in an external transverse magnetic field within the three-dimensional mathematical model. Furthermore, the effect of external controlled discharge parameters and the magnetic field of the electrodes on the characteristics of plasma arc were also revealed [7]. The results showed that the angle of deviation of an arc in space was directly proportional to the interelectrode spacing and inversely proportional to the current strength.

Up to now, many studies on the characteristics of plasma arc under an external transverse DC magnetic field have been published. However, little attentions are given to the investigations on the oscillating motion and heat flux distribution of plasma arc under an external transverse alternating magnetic field. In previous studies, W.J. Xu *et al*. carried out some experiments in flexible forming of sheet metal using plasma arc under an external transverse AC magnetic field [8]. Meanwhile, the effects of the plasma arc in the external transverse AC magnetic field on the metal surface quality and efficiency of flexible forming were analyzed. The experimental results show that it is feasible to improve the flexible forming of sheet metal using the plasma arc with the external transverse AC magnetic field. However, the heat flux distribution of plasma arc is to vary and the conventional Gauss model on the heat flux density of plasma arc is inappropriate owing to the effect of external transverse

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alternating magnetic field. Consequently, it has to depend on experimental measurement to obtain the heat flux distributions of plasma arc, which limits the application of the plasma arc with external transverse alternating magnetic field.

In this paper, an external transverse triangular wave alternating magnetic field is applied to a plasma arc to heat a larger area on metal surface. By analyzing the principle of the external transverse AC magnetic field driving the plasma arc, two mathematical models are developed to describe the oscillating amplitude of the plasma arc root along the metal surface and the heat flux density distribution of plasma arc on the metal surface, respectively. Moreover, the influence of processing parameters, such as magnetic flux density, working current, argon flow rate and the distance from the nozzle outlet to the workpiece anode on the oscillating amplitude and heat flux density distribution of the plasma arc are also investigated. As well as, the theoretical values of oscillating amplitude are compared with the measured values by video camera and the model values of heat flux density distribution are also compared with the calculated values by Gauss model when the magnetic flux density is zero.

2. FOUNDATIONAL PRINCIPLE

A schematic illustration to expand the plasma arc using an external transverse alternating magnetic field (ETAMF) is shown in Fig. (**1**). The device consists of a transferred arc torch with a tungsten cathode and a nozzle, an anode workpiece, a DC power supply to generate a plasma arc, a gas feeding system for the torch, a support frame to fix the torch, a excitation device including two excitation coils and two magnetic irons to perpendicularly introduce the magnetic field into the plasma arc, an AC power supply for the magnetic field, which is connected to the excitation coils, can supply various types of alternating current such as sinusoidal and triangular ones. In this paper, the type and the frequency of AC power supply is triangular wave and 50Hz, respectively.

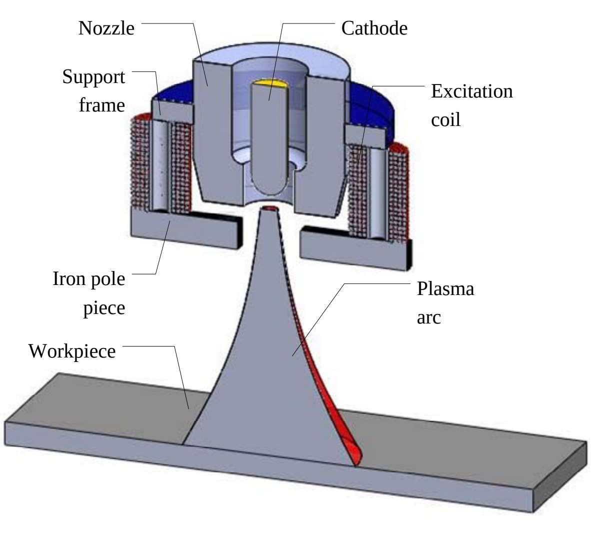

Fig. (1). Generator device of plasma arc with an ETAMF.

When the DC power supply is applied between the cathode and anode, the gas is to be ignited and the plasma arc is to be generated. Then the AC power supply is applied between two excitation coils, the alternating magnetic field is to be generated, which is perpendicularly introduced into the above transferred arc. As a result, the plasma arc oscillates on the metal surface at the frequency of alternating electromagnetic force. It is well known that plasma arc consists of a lot of charged particles and each charged particle is driven by the Lorentz force under the external transverse magnetic field. Consequently, charged particles are in gyroscopic motion neglecting the interaction and the self-induced magnetic field of these particles. The gyration radius of charged particles can be expressed as

$$r = \frac{mv}{qB} \tag{1}$$

where, m, v, q is the mass (kg), velocity (m/s), electric quantity (C), respectively. B (T) is the magnetic flux density of external transverse alternating magnetic field.

The transferred arc is also in the oscillatory motion along the transverse direction, since plasma being made up of all charged particles. Furthermore, the form of the arc column is like a bell for the cause of excitation frequency and thermal inertia of the transferred arc.

3. MODELLING APPROCH

3.1. Oscillated Amplitude of Plasma Arc Under ETAMF

In Fig. (**2**), the external alternating magnetic field runs parallel to "Y" coordinate axis, which drives all charged particles to gyroscopic motions and compels the plasma arc to oscillate along the direction paralleled to "X" coordinate axis. Supposing that T is the time how long charged particles pass through the external transverse alternating magnetic field, if the excitation frequency f is less than $1/2T$, it can be considered that the oscillating amplitude of plasma arc be independent of the excitation frequency of external alternating magnetic field.

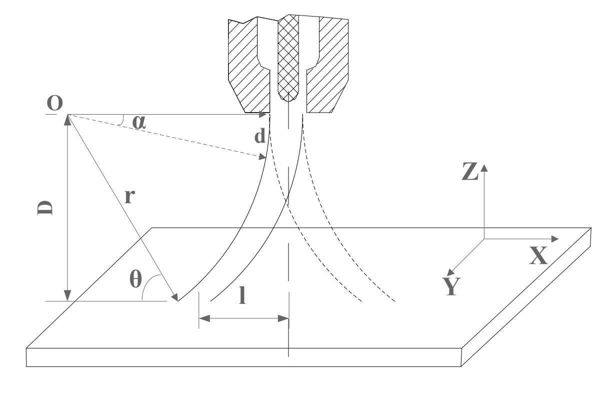

Fig. (2). Movement of the plasma arc in an ETAMF.

Thus, the electromagnetic force of any little section of plasma arc can be expressed as

$$F = BId \tag{2}$$

where, I is the current of plasma arc (A), d is the length of any little section of plasma arc (m). The relationship between the section length of plasma arc and the gyration radius can be expressed as

$$d = r\alpha \tag{3}$$

where, α is the central angle of corresponding little section of plasma arc (rad).

Furthermore, the Lorentz force of any little section of plasma arc can be also expressed as

$$F = m_d a \sin\alpha \tag{4}$$

where, m_d and a is the mass (kg) and acceleration (m/s^2) of little section plasma arc, respectively. m_d can be written as

$$m_d = \frac{\rho Q t}{60} \tag{5}$$

where, ρ is the gas density (kg/m^3), Q is the gas flow rate (L/min), t is the time of charged particles leaving the nozzle outlet (s). With the simultaneous solution of above five equations, the gyration radius r can be written as

$$r = \frac{m_d a \sin\alpha}{BI\alpha} = \frac{\rho Q t a}{60BI} = \frac{\rho Q v}{60BI} \tag{6}$$

As shown in Fig. (**2**), the oscillating amplitude of plasma arc driven by the external transverse alternating magnetic field can be expressed as

$$l = r - \sqrt{r^2 - D^2} \tag{7}$$

where, D (m) is the distance from the nozzle outlet to the anode workpiece. From Eq. (6) and Eq. (7), it can be seen that the gyration radius r decreases with the increase of magnetic flux density B. Once the gyration radius r is less than the distance D, it means that the magnetic flux density B oversteps a critical value and the arc is to be unstable. To remain the plasma arc stable, the gyration radius should be more than the distance from the nozzle outlet to the anode, meaning tg$\theta \approx \sin\theta$.

$$\frac{l}{D} \approx \frac{D}{r} \tag{8}$$

Combined Eq. (6), Eq. (7) with Eq. (8), the maximum oscillating amplitude of plasma arc under the external transverse alternating magnetic field can be transformed as

$$l_0 = \frac{60IBD^2}{\rho Q v} \tag{9}$$

3.2. Heat Flux Density of Plasma Arc Under ETAMF

In order to establish the mathematical model of arc heat flux distribution upon the anode, the assumptions are summarized as follows:

i. The total heat flux W (W) of plasma arc is transferred to the anode, neglecting the heating effect of viscous dissipation.

ii. Without the external alternating magnetic field, the arc root on the anode can be regarded as a round area heat source with the radius of R_0.

iii. Under the external transverse alternating magnetic field, the arc root on the anode can be considered as an elliptic area heat source with the shorter axis of R_0 and the longer axis of (R_0+l_0), as shown in Fig. (**3**).

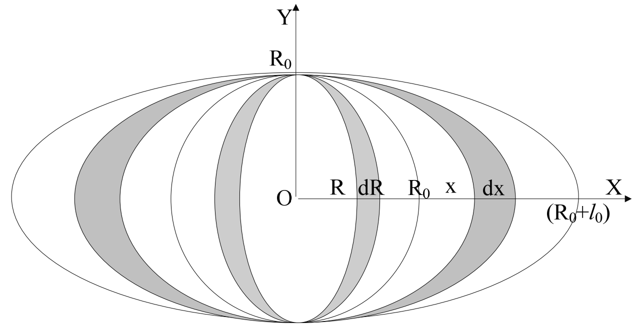

Fig. (3). Form distribution of plasma arc on anode surface.

Driven by the external transverse alternating magnetic field, the heat flux density h (W/m^2) of plasma arc can be written as

$$h = \frac{W}{\pi R_0^2} \tag{10}$$

Supposing that the distance from any point in the arc root to the center of plasma arc is R, heat input into the small element of the arc root (dS) for the time (dt) can be expressed as

$$dQ = h\left[\pi R_0 \left(R + dR\right) - \pi R_0 R\right]dt \tag{11}$$

The applied alternating field is assumed in the form of

$$B(t) = \begin{cases} \dfrac{2B_0}{T}t & 0 \le t < \dfrac{T}{2} \\ 2B_0\left(1 - \dfrac{t}{T}\right) & \dfrac{T}{2} \le t \le T \end{cases} \tag{12}$$

where, B_0 is the maximum magnetic flux density (T), T is the time for the half cycle (s).

The displacement of any point R in the plasma arc root can be expressed as

$$x = \begin{cases} \dfrac{2l_0}{T}t \\ 2l_0\left(1 - \dfrac{t}{T}\right) \end{cases} \tag{13}$$

where, with the simultaneous solution of Eq. (9) and Eq. (12), l_0 can be written as

$$l_0 = \frac{60IB_0D^2}{\rho Q v} \tag{14}$$

Combined Eq. (10) with Eq. (11) and the derivative of Eq. (13) with respect to t, the total heat input the anode can be expressed as

$$Q_{in} = \iint \frac{T \cdot W}{2l_0 R_0} dR \cdot dx \tag{15}$$

During the half period of arc oscillatory motion, W' is defined as the heat input into the anode workpiece in unit time, which can be written as

$$W' = \frac{1}{T} Q_{in} \tag{16}$$

The heat flux density H can be expressed as

$$H = \frac{W'}{S} = \frac{dW'}{\pi R_0 (x + dx) - \pi R_0 x} \tag{17}$$

With the simultaneous solution of Eq. (15), Eq. (16) and Eq. (17), the heat flux density H can be written as

$$H = \int \frac{W}{2\pi R_0^2} \cdot \frac{1}{l_0} dR \tag{18}$$

During a half cycle of the magnetic field, the arc root centre moves from $-l_0$ to l_0 on the anode. For $-l_0+R_0 \le x \le l_0-R_0$, the whole arc root passes point x. However, for $x < l_0+R_0$ or $x > l_0-R_0$, a part of the arc root passes the point. Therefore, the heat flux density can be transferred as

$$H(x) = \begin{cases} \dfrac{W}{2\pi R_0^2} \cdot \dfrac{l_0 + x + R_0}{l_0} & (-l_0 - R_0 < x < -l_0 + R_0) \\ \dfrac{W}{2\pi R_0^2} \cdot \dfrac{2R_0}{l_0} & (-l_0 + R_0 \le x \le l_0 - R_0) \\ \dfrac{W}{2\pi R_0^2} \cdot \dfrac{l_0 - x + R_0}{l_0} & (l_0 - R_0 < x < l_0 + R_0) \end{cases} \tag{19}$$

4. CALCULATIONS AND DISCUSSIONS

As shown in Fig. (**1**), the whole system can be divided into the part generating the plasma arc and another part generating the external transverse triangular wave alternating magnetic field. The working parameters in each part are shown in Tables **1** and **2**, respectively. In the Table **2**, I_0, N, Φ, L and f are the excitation current, coil turn, coil diameter, coil length and excitation frequency, respectively. With above working parameters and measured variables, the models on the oscillating amplitude and the heat flux density distribution of plasma arc are solved. As a result, the effect of process parameters, such as the gas flow rate Q, the arc current I and the overhang from the nozzle outlet to the anode workpiece D on above two models are obtained.

Table 1. Parameters of the Generator Device of Plasma Arc

Parameters of Plasma Arc							
I(A)	15	20	25	15	15	15	15
Q(L/min)	5	5	5	4	6	5	5
D(mm)	7	7	7	7	7	6	8
v(m/s)	12.5	25.8	36.3	8.95	13.3	11.9	13.2

Table 2. Parameters of the External Transverse Alternating Magnetic Field

Parameters of ETAMF				
I_0(A)	N	Φ(mm)	L(mm)	f(Hz)
0~1.2	200	44	38	50

4.1. Effect of Process Parameters on the Oscillating Amplitude

4.1.1. Effects of the Gas Flow Rate on the Oscillating Amplitude

Under typical operation conditions (I=15A, D=7mm), the oscillating amplitude of plasma arc in the external alternating magnetic field are calculated in this section by inputting three different argon gas flow rates: 4, 5, 6L/min. As shown in Fig. (**4a**), the oscillating amplitude increases with the enhancement of external magnetic flux density until the magnetic flux density reaches its critical value. For above three different gas flow rates, the critical values of external magnetic density are 10.1, 17.4 and 22.5mT, respectively. However, in an overly magnetic flux density, the oscillating amplitude becomes unclear owing to the arc movement being unstable. From Fig. (**4a**) and Fig. (**4b**), it can be seen that the oscillating amplitude of plasma arc decreases with the increase of argon gas flow rate at the same magnetic flux density (B=10mT). The reason is that increasing the gas flow rate is to raise the velocity of plasma jet on the nozzle outlet and to shorten the time of plasma passing through the external transverse magnetic field. As a result, in a shorter time, the same electromagnetic force drives the plasma arc to oscillate with less amplitude.

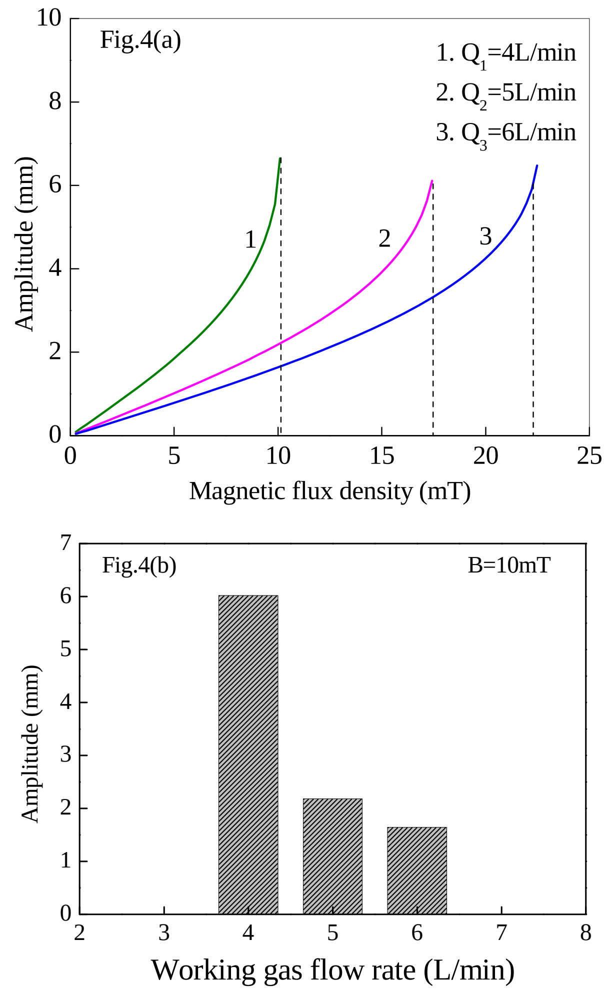

Fig. (4). Effect of the magnetic flux density on the oscillating amplitude under different gas flow rate.

4.1.2. Effects of the Arc Current on the Oscillating Amplitude

Under typical operation conditions (Q=5L/min, D=7mm), the oscillating amplitude of plasma arc in the external alternating magnetic field are calculated in this section by inputting three different arc currents: 15, 20 and 25A. As shown in Fig. (**5a**), the oscillating amplitude increases with the enhancement of external magnetic flux density until the magnetic flux density reaches its critical value. For above three different gas flow rates, the critical values of external magnetic density are 17.3, 27.2 and 30.4mT, respectively. However, in an overly magnetic flux density, the oscillating amplitude becomes unclear owing to the arc movement being unstable. From Fig. (**5a**, **b**), it can be seen that the oscillating amplitude of plasma arc decreases with the increase of arc current at the same magnetic flux density (B=15mT). The reason is that increasing the arc current is to increase the electromagnetic force and to improve the oscillating amplitude of the plasma arc. On the other hand, the ascension of plasma velocity on the nozzle outlet arising from the increase of arc current leads to the oscillating amplitude having a sharply decreasing tendency. Completely considered above two effects of arc current, it can be concluded that the oscillating amplitude increases with the enhancement of arc current for the decreasing tendency playing a more significant role than the increasing tendency.

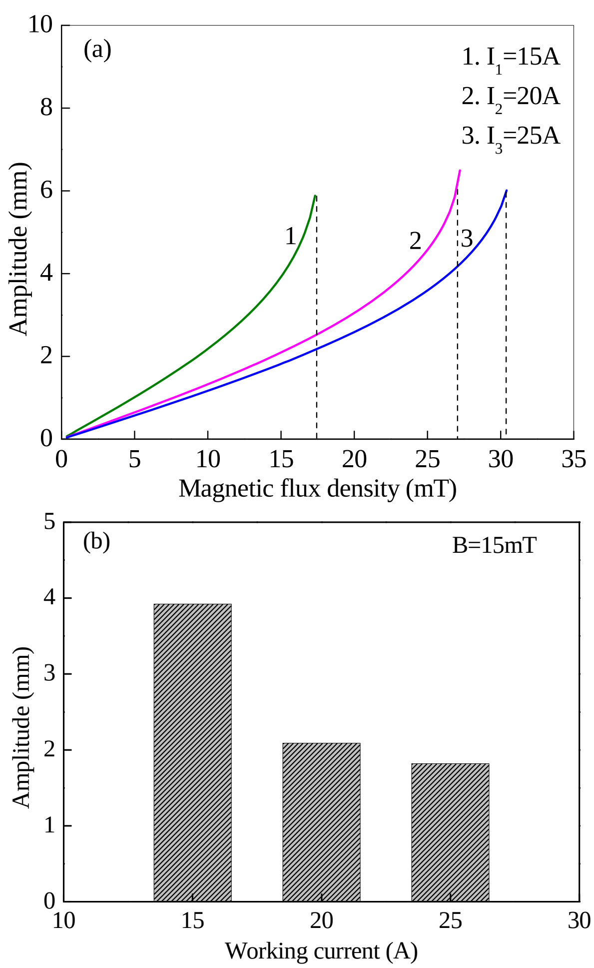

Fig. (5). Effect of the magnetic flux density on the oscillating amplitude under different arc currents.

4.1.3. Effects of the Nozzle Overhang on the Oscillating Amplitude

Under typical operation conditions (I=15A, Q=5L/min), the oscillating amplitude of plasma arc in the external alternating magnetic field is calculated in this section by inputting three different overhangs: 6, 7 and 8mm. As shown in Fig. (**6a**), the oscillating amplitude increases with the enhancement of external magnetic flux density until the magnetic flux density reaches its critical value. For above three different overhangs, the critical values of external magnetic density are 16.2, 17.6 and 19.6mT, respectively. However, in an overly magnetic flux density, the oscillating amplitude becomes unclear owing to the arc movement being unstable. From Fig. (**6a**, **b**), it can be seen that the oscillating amplitude increases with the expansion of overhang from the nozzle outlet to the anode workpiece at the same magnetic flux density (B=15mT). The reason is that increasing the overhang is to elongate plasma arc. On the one hand, it has a little influence on the plasma velocity on the nozzle outlet. On the other hand, it causes the plasma to prolong the passing time and to increase the path length of plasma. Consequently, it can be concluded that the oscillating amplitude is to increase with the increase of projection displacement on the workpiece surface, ascending from the expansion of overhang from the nozzle outlet to the anode workpiece.

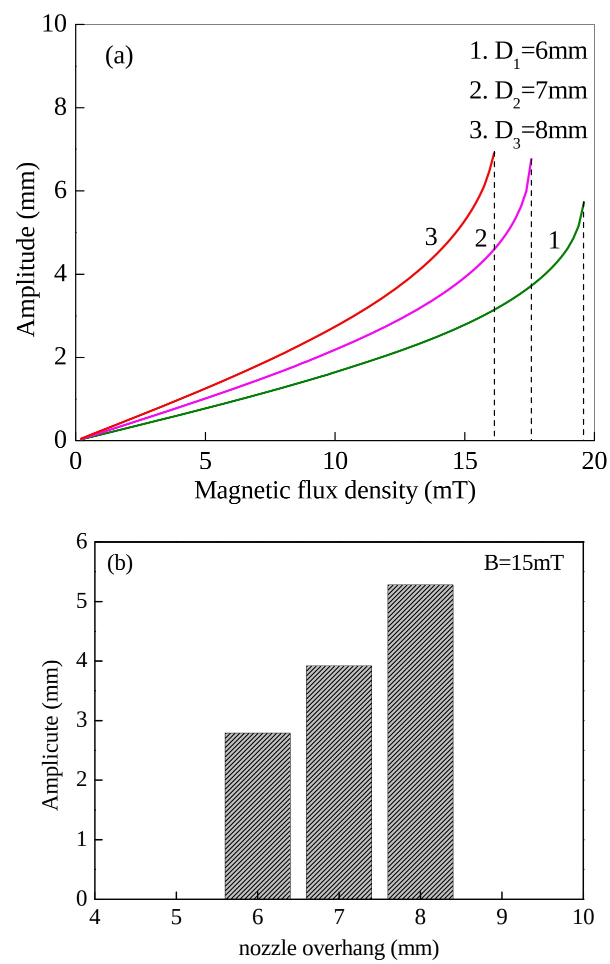

Fig. (6). Effect of the magnetic flux density on the oscillating amplitude under different nozzle overhangs.

4.2. Effects of Process Parameters on the Heat Flux Density Distribution

4.2.1. Effects of the Gas Flow Rate on the Heat Flux Density Distribution

Under typical operation conditions (I=15A, D=7mm, B=15mT), the heat flux density distributions of plasma arc on the anode workpiece surface are calculated in this section by inputting three different argon gas flow rates: 4, 5, 6L/min. As shown in Fig. (**7**), the radius of heat flux distribution decreases with the increase of gas flow rate. It also can be seen that the heat flux density on the center of arc root ascends and the gradient of heat flux density near the center of arc root increases with the increase of gas flow rate. The reason is that increasing the gas flow rate is to accelerate the velocity of plasma on the nozzle outlet and to reduce the oscillating amplitude of plasma on the anode workpiece. On the other hand, due to the effect of stabilizing arc arising from the increase of plasma velocity, it is difficult to flatten the heat flux density of plasma arc. As a result, it can be concluded that the heat flux of plasma arc on the workpiece surface is more concentrated with the increase of gas flow rate.

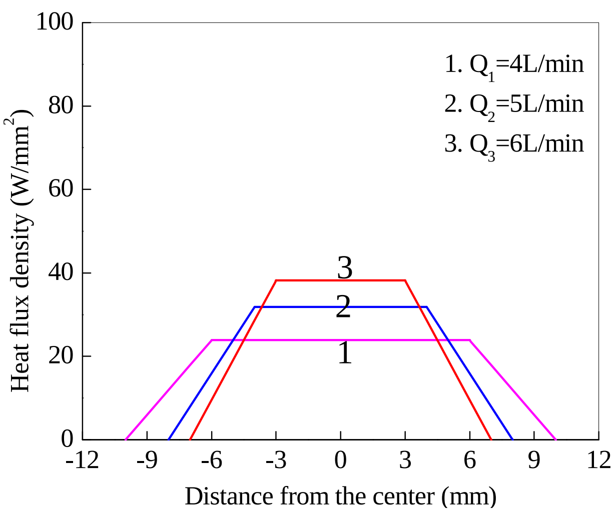

Fig. (7). Effect of the gas flow rate on the heat flux density distribution.

4.2.2. Effects of the Arc Current on the Heat Flux Density Distribution

Under typical operation conditions (Q=5L/min, D=7mm, B=15mT), the heat flux density distributions of plasma arc on the anode workpiece surface are calculated in this section by inputting three different arc currents: 15, 20 and 25A. As shown in Fig. (**8**), the radius of heat flux distribution decreases with the increase of arc current. It can be also seen that the heat flux density on the center of arc root ascends and the gradient of heat flux density near the center of arc root increases with the increase of arc current. The reason is that increasing the arc current is to decrease the oscillating amplitude of plasma arc in the external transverse alternating magnetic field, which leads to the shrink of heat flux density distribution. On the other hand, the constraint by arc own magnetic field is strengthened and the heat flux of plasma arc is more concentrated with the increase of arc current. Consequently, it can be concluded that it is more difficult to expand the distribution region and to flatten the heat flux density of plasma arc on the anode workpiece surface.

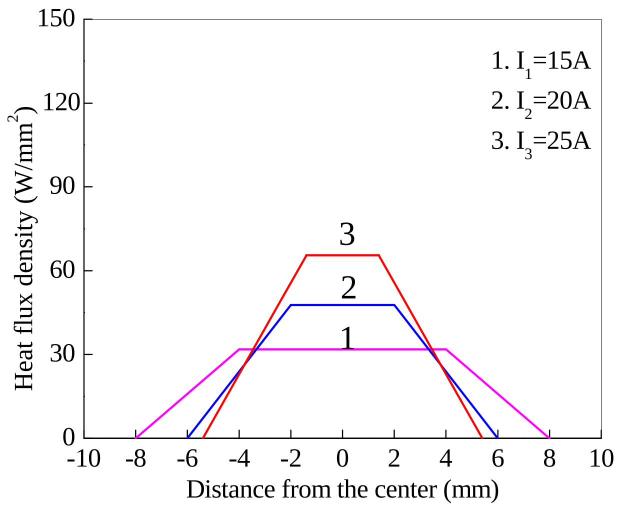

Fig. (8). Effect of the arc current on the heat flux density distribution.

4.2.3. Effects of the Nozzle Overhang on the Heat Flux Density Distribution

Under typical operation conditions (I=15A, Q=5L/min, B=15mT), the heat flux density distributions of plasma arc on the anode workpiece surface are calculated in this section by importing three different overhangs: 6, 7 and 8mm. As shown in Fig. (**9**), the radius of heat flux distribution increases with the expansion of overhang. It also can be seen that the heat flux density at the center of arc root descend and the gradient of heat flux density near the center of arc root reduces with the increase of the overhang from the nozzle outlet to the anode workpiece. The reason is that increasing the overhang means to expand the oscillating amplitude and to improve the heat flux distribution radius. Meanwhile, with the expansion of the heating area, the heat flux on the center of arc root is dispersed into the whole heating region. As a result, it is much easier to flatten the heat flux density of plasma arc on the workpiece surface with the increase of the overhang from the nozzle outlet to the anode workpiece.

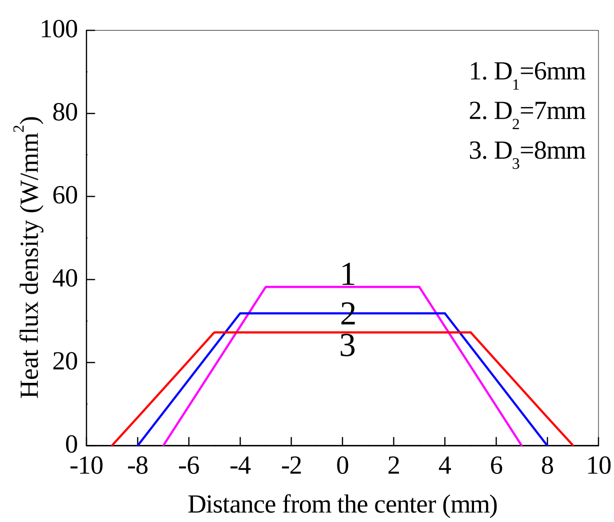

Fig. (9). Effect of the nozzle overhang on the heat flux density distribution.

4.2.4. Effects of the Magnetic Flux Density on the Heat Flux Density Distribution

Under typical operation conditions (I=15A, Q=5L/min, D=7mm), the heat flux density distributions of plasma arc on the anode workpiece surface are calculated in this section by importing three different magnetic flux density: 10, 12.5 and 15mT. As shown in Fig. (**10**), the radius of heat flux distribution increases with the enhancement of magnetic flux density. It also can be seen that increasing the magnetic flux density is to decrease the heat flux density at the center of the arc root. Furthermore, the gradient of heat flux density near the center of arc root is descended with the increase of magnetic flux density. The reason is that increasing magnetic flux density is to increase the oscillating amplitude of the plasma arc. Moreover, the extension of the heat flux distribution radius means more heat flux on the center of arc root is transferred into the whole heating area. Consequently, the heat flux density of plasma arc on the anode workpiece is easier flattened for the increase of magnetic flux density.

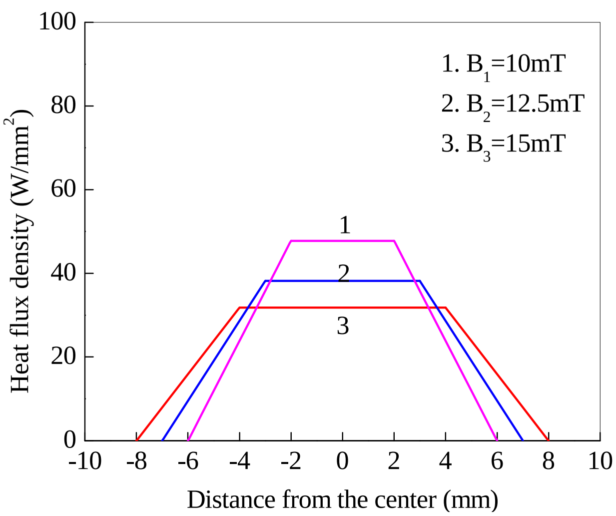

Fig. (10). Effect of the magnetic flux density on the heat flux density distribution.

4.3. Experimental Verification

In this experiment, the applied magnetic flux density is a triangular wave, the process parameters such as the argon gas flow rate, the arc current and the overhang from the nozzle to the anode workpiece are 5L/min, 15A and 6mm, respectively. Fig. (**11a**) show the shape of the oscillating plasma arc without magnetic field. From Fig. (**11a**), it can be seen that the radius of heat flux distribution is 2mm. With an external transverse alternating magnetic field (B=15mT), the plasma arc is driven to oscillate on the anode workpiece. As shown in Fig. (**11b**), the radius of heat flux distribution is 5mm. From Fig. (**11a**, **b**), the oscillating amplitude of plasma arc can be measured (l=3mm). Consequently, it can be concluded that the calculated value (l=2.8mm) from the model of oscillating amplitude coincides with its measured value and the agreement between them is more than 93%.

Fig. (**12**) shows the distributions of heat flux density in no magnetic field, in triangular wave alternating magnetic field (B=15mT), respectively. As shown in Fig. (**12**), without no magnetic field (B=0), the heat flux density on the center of arc root from the model developed in this paper (H=95.5W/mm^2) accords with the value calculated from Gauss model (H=101.6W/mm^2). The error between them is less than 6%. It also can be seen that with an external magnetic field (B=15mT), the heat flux density and its distribution radius from the model developed in this paper are more than calculated values of heat flux density from Gauss model and the model in this paper with no external magnetic field, respectively.

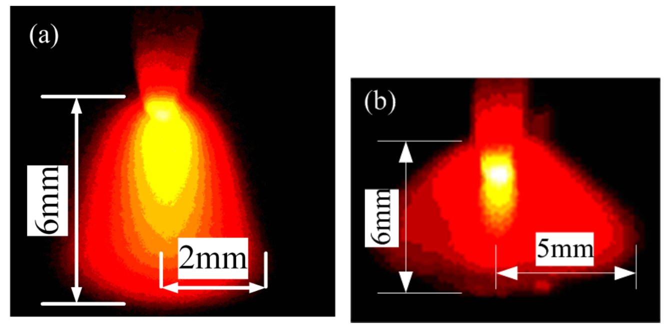

Fig. (11). Distributions of plasma arc forms with or without an external transverse alternating magnetic field.

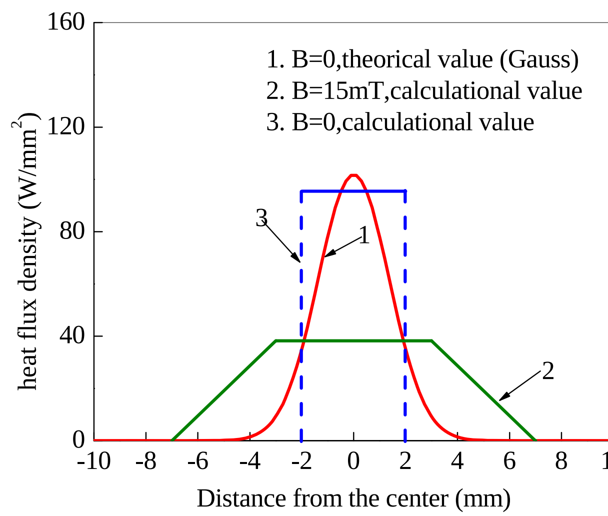

Fig. (12). Distributions of heat flux densities with or without an external transverse alternating magnetic field.

The distribution of the heat flux density on the workpiece surface is measured using a specially designed copper anode. It is 400mm long and 200mm wide. The anode is divided into several sections through which a cooling-water channel passes. Thermocouples are inserted into the water channel ate the inlet and outlet of each section. Heat flow from the arc root into each section is evaluated from the temperature increase of the cooling water through the channel. In Fig. (**13**), solid circles show experimental results of heat flux density, and solid lines represent the predicted relations. The experimental heat flux distributions agree fairly well with the theoretical ones.

5. CONCLUSIONS

This work has presented a new method to investigate the characteristics of plasma arc under an external transverse triangular wave magnetic field. With two models on the oscillating amplitude and the heat flux density distribution of plasma arc, the effects of process parameters such as the gas flow rate, arc current and overhang from the nozzle outlet to the anode workpiece on the characteristics of plasma arc are revealed. It is feasible to predict the forms and the heat flux density distributions of plasma arc under different operation conditions and to control the heating area and the heat flux density of plasma arc on the workpiece surface. Obtained results are summarized as follows:

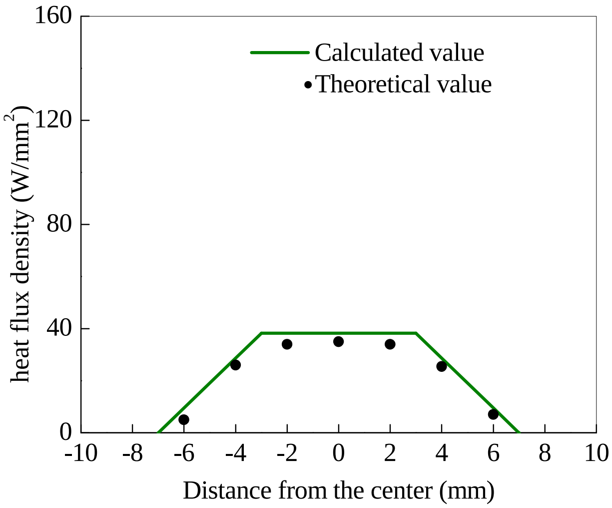

Fig. (13). Comparison of experimental results with theoretical ones of heat flux density.

It is effective to control the heating area and to flatten the heat flux density distribution of plasma arc with an external transverse alternating magnetic field. Increasing the external magnetic flux density is to cause the oscillating amplitude and the radius of heat flux density distribution to increase, which results in the heat flux density on the center of arc root and its gradient near the center to decrease. However, an overly strong magnetic field makes the arc motion unstable.

Under the same external magnetic flux density, the oscillating amplitude and heat flux density distribution of plasma arc vary with the change of process parameters. Increasing the arc current or gas flow rate is to decrease the oscillating amplitude of plasma arc. Accordingly, the radius of heat flux distribution descends and the heat flux density on the center of arc root increase. Meanwhile, the heat flux density of whole heating region is easier flattened with the increase of arc current or gas flow rate.

Increasing the overhang from the nozzle outlet to the anode workpiece is to the extension of oscillating amplitude, which causes the radius of heat flux distribution to increase. Moreover, increasing the overhang, the heat flux density on the center of arc root and its gradient near the center is to decrease. Consequently, it means the heat flux density on the whole heating area is easier flattened with the expansion of overhang from the nozzle outlet to the workpiece surface.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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REFERENCES

[1] J.B. Meng, W.J. Xu, and W.Q. Song, “Modelling of reactive kinetics in the metal surface contaminant cleaning using atmospheric pressure plasma arc”, *Appl. Surf. Sci.*, vol. 254, pp. 6826-6830, 2008.

[2] A.L. Lei, G.H. Li, L.J. Feng, and N. Dong, “Structure and abradability Cu-Al2O3 gradient coatings fabricated by plasma spraying”, *Trans. Chin. Weld. Inst.*, vol. 29, pp. 65-68, 2008.

[3] J. Awrejcewicz, “Combined analytical and numerical analysis of oscillations in the string-type generator”, *J. Appl. Math. Mech.*, vol. 74, pp. 432-434, September 1994.

[4] J. Awrejcewicz, “Nonlinear oscillations of a string caused by the electromagnetic field”, *J. Tech. Phys.*, vol. 35, pp. 5-12, 1994.

[5] J. Awrejcewicz and Z. Koruba, Classical Mechanics. In: *Applied Mechanics and Mechatronics*. Springer: New York, 2012.

[6] D.B. Sobyanin, B.G. Gavrilov, and I.M. Podgorny, “Laboratory investigation of plasma jet interaction with transverse magnetic field”, *Adv. Space Res.*, vol. 29, pp. 1345-1349, 2002.

[7] A. Zhainakov, R.M. Urusov, and T.E. Urusova, “Numerical simulation of gas dynamic flows formed by an electric arc in external transverse magnetic field”, *High Temp.,* vol. 40, pp. 199-203, 2002.

[8] W.J. Xu, Y.X. Guo, W.Q. Song, J.B. Meng, and Z.G. Li, “Experimental study of flexible formation using plasma arc controlled by alternate magnetic field”, *Mech. Sci. Technol.,* vol. 26, pp.387-390, 2007.

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