

Research Article

Heat Flux of a Transferred Arc Driven by a Transverse Magnetic Field

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Received 12 August 2009; Accepted 21 September 2009

Recommended by Jainagesh Sekhar

Theoretical consideration of a magnetically driven arc was performed to elucidate the variation of heat flux with an imposed DC magnetic field. Experiments were conducted to confirm the validity of the theoretical model. The heat flux decreased concomitantly with increased imposed magnetic flux density. Theoretical predictions agreed with experimental results.

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1. Introduction

Because of intense energy concentration to a small arc-root, transferred arcs have been widely used for cutting and welding of metals. However, conventional arcs remain inconvenient for heating and melting over a wide area. Many attempts have been made to expand arc profiles using external magnetic fields [1]. Takeda developed a magnetically driven arc by imposing an alternating magnetic field perpendicular to a transferred arc [2, 3]. In the oscillatory motion of such a magnetically driven arc, the amplitude increases with the increase of the imposed magnetic flux density. The oscillating arc can be regarded as a broad heat source with oscillation amplitude width, as presented in Figure 1. The heat flux distribution is known to be nonuniform along the oscillatory motion of the arc [4]. For practical applications of such magnetically driven arcs, a clear understanding of the nonuniformity in the heat flux is necessary.

In this work, the variation of the heat flux in the arc root was studied under a DC magnetic field imposed perpendicularly to the arc.

2. Theoretical Considerations

2.1. Displacement of an Arc-Root with Imposed Magnetic Flux Density. A schematic arrangement of the magnetically driven arc and a coordinate system used in the present work are presented in Figure 2.

The plasma torch is located on the z -axis. The anode expands in the x - y plane. An external DC magnetic field is imposed in the direction of x . Without an imposed magnetic field, the arc-root center position is located at the origin $(0, 0, 0)$. The arc is assumed to be cylindrically symmetric to the z -axis. The interaction of the arc current and the external magnetic field engenders arc movement in the y direction. Displacement of the arc-root center position $(0, Y, 0)$ increases with increased the imposed magnetic flux density.

The following relation was reported in a previous work [3]:

$$\frac{Y}{L} = R - \sqrt{R^2 - 1}. \quad (1)$$

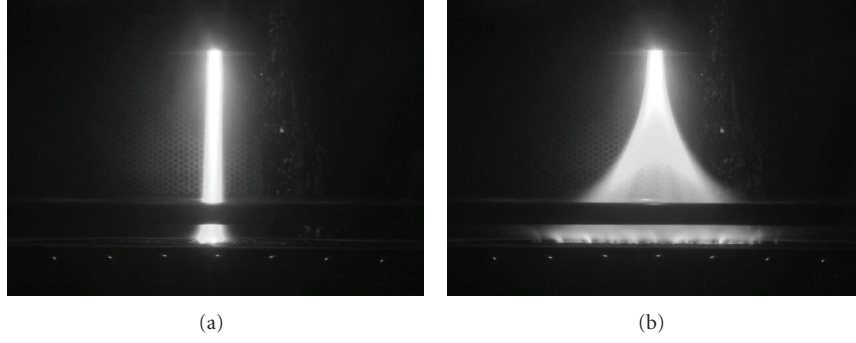


FIGURE 1: Typical plasma arc without magnetic field (a), and magnetically driven arc in an alternating magnetic field (b).

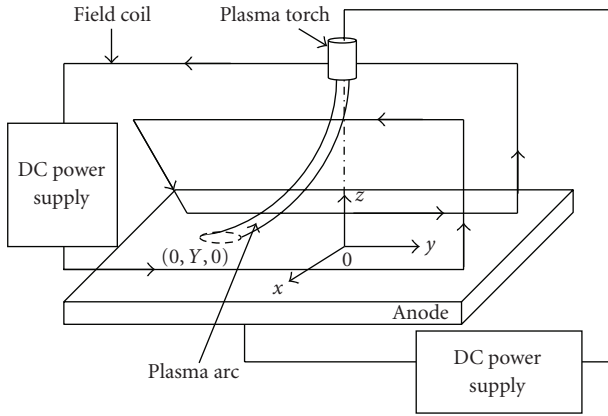


FIGURE 2: Experimental setup for a magnetically driven arc.

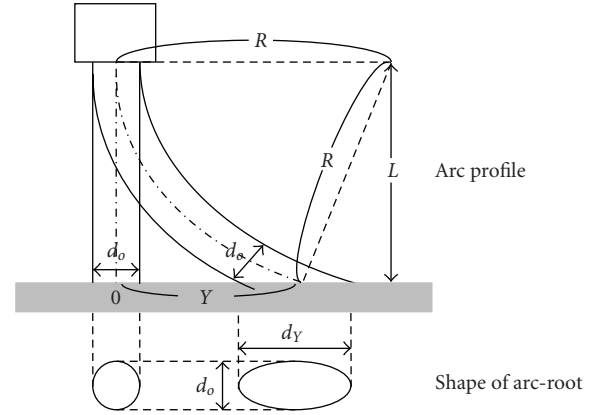


FIGURE 3: Schematic illustration on the arc root deformation.

Therein, Y , L , and R , respectively, represent the arc-root center position, the standoff distance between the torch and the anode, and the radius of curvature, which varied inversely with magnetic flux density.

2.2. Arc-Root Deformation Caused by the Imposed Magnetic Field. As portrayed in Figure 3, the arc-root profile under no magnetic field is assumed as a circle of diameter d_o . When the magnetic field is imposed, the arc-root shape deforms from a circle to an ellipse with major diameter d_Y and minor diameter d_o .

Considering the relation of (1), the ratio of the major diameter to the minor diameter in the arc-root is expressed as

$$\frac{d_Y}{d_o} = \frac{1 + (Y/L)^2}{1 - (Y/L)^2}. \quad (2)$$

Here, we introduce $h_Y(x, y)$ as the heat flux distribution function in the arc-root centered at Y . As described in the experimental results, the heat flow from the arc to the anode remains constant, independent of the imposed magnetic flux density. Therefore, the following ratio of the heat flux is assumed:

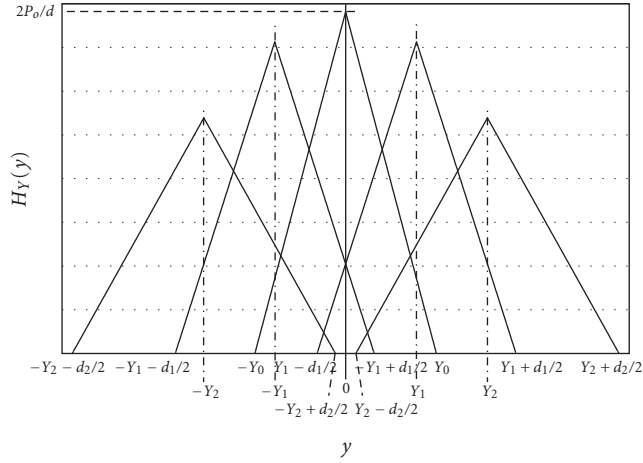
$$\frac{h_Y(0, Y)}{h_0(0, 0)} = \frac{1 - (Y/L)^2}{1 + (Y/L)^2}. \quad (3)$$

In that equation, $h_0(0, 0)$ and $h_Y(0, Y)$, respectively, represent the heat flux of the arc-root center at $Y = 0$ and that at Y , according to the definition of $h_Y(x, y)$.

2.3. Assumption of the One-Dimensional Heat Flux Distribution Function. To simplify the consideration, the two-dimensional heat source of the arc is transformed into a one-dimensional heat source; the arc-root is assumed as a line heat source with length d_Y , instead of an elliptic heat source with major diameter d_Y and minor diameter d_o . The one-dimensional heat flux is expected to be satisfied by the following condition:

$$H_Y(y) = \int_{-\infty}^{\infty} h_Y(x, y) dx. \quad (4)$$

The one-dimensional distribution function of the heat flux under no magnetic field is expressed as $H_0(y)$ because the arc-root center is located at $Y = 0$. Considering the experimental observation that the heat flux of the arc has a maximum value at the center of the arc-root and decreases its value with distance from the center [5], the following


 FIGURE 4: Variation of $H(y)$ with Y .

assumption is adopted in the present work for the one-dimensional distribution function:

$$H_0(y) = \frac{2P_o}{d_o} \left\{ 1 - \left| \frac{2y}{d_o} \right| \right\} \quad \text{for } 0 \leq |y| < \frac{d_Y}{2}, \quad (5)$$

$$H_Y(y) = 0 \quad \text{for } |y| \geq \frac{d_Y}{2}.$$

Therein, P_o represents the total power transferred from the arc to the anode. Under the imposed magnetic field, the distribution function for the heat flux centered on $y = Y$ is expressed as shown below:

$$H_Y(y) = \frac{2P_o}{d_Y} \left\{ 1 - \left| \frac{2(y-Y)}{d_Y} \right| \right\} \quad \text{for } 0 \leq |y-Y| < \frac{d_Y}{2}, \quad (6)$$

$$H_Y(y) = 0 \quad \text{for } |y-Y| \geq \frac{d_Y}{2}. \quad (7)$$

In those equations, d_Y denotes the one-dimensional heat source length, which varies with Y according to the relation of (2). Schematic distributions of the heat flux for various Y are depicted in Figure 4. As clarified there, the peak value of the heat flux decreases and the arc-root length increases concomitantly with increased Y (or increased B). The validity of the rough simplification is examined through comparison of theoretical predictions with experimental results.

2.4. Heat Flow to a Calorimeter. To estimate the heat flux, a calorimetric measurement is often used, as described in the next section. The heat flux is not measured directly using the calorimeter. According to a schematic illustration of a calorimeter depicted in Figure 5, the heat flow to the calorimeter, $W_Y(y^*)$ should be given as the following relation:

$$W_Y(y^*) = \int_{y^*-l}^{y^*+l} H_Y(y) dy. \quad (8)$$

Therein, in Figure 5, the center of the calorimeter with width of $2l$ is at $y = y^*$. Furthermore, subscript Y in (8) signifies the center position of the arc-root.

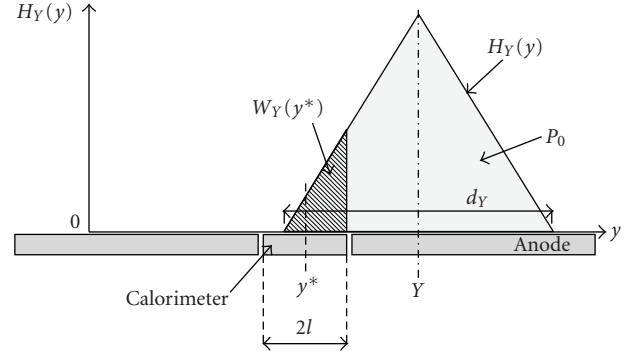


FIGURE 5: Schematic illustration of the heat flow from the arc to a calorimeter.

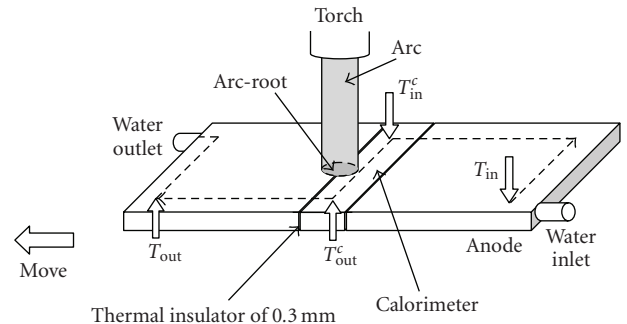


FIGURE 6: Anode assembly and calorimeter to measure the heat flow.

At $y^* = 0$ and $Y = 0$,

$$W_0(0) = \frac{4l(d_o - l)}{d_o^2} P_o. \quad (9)$$

The diameter of the arc-root under no magnetic field is determined using (9), as

$$d_o = \frac{2P_o l + \sqrt{4P_o^2 l^2 - 4P_o W_0(0)}}{W_0(0)}. \quad (10)$$

Then, using d_0 , $H_Y(y)$ is obtainable from (6) and (2). Finally, $W_Y(y^*)$ is calculable theoretically from (8) using $H_Y(y)$.

3. Experiments

Experiments were conducted to confirm the validity of the theoretical consideration. A schematic depiction of the experimental arrangement is presented in Figure 2. Experimental conditions are similar to those described by Yamamoto et al. [4]. A transferred arc was produced between a plasma torch with a tungsten cathode and a water-cooled copper anode. The standoff distance between the torch orifice and the anode was fixed at 70 mm. A power supply connected to the torch and the anode was operated in a constant current mode. The arc current was fixed at 130 A. Argon gas was fed to the torch as a plasma-forming gas at the flow rate of 4.5×10^{-4} kg/s. An external magnetic field perpendicular to the arc was generated using DC

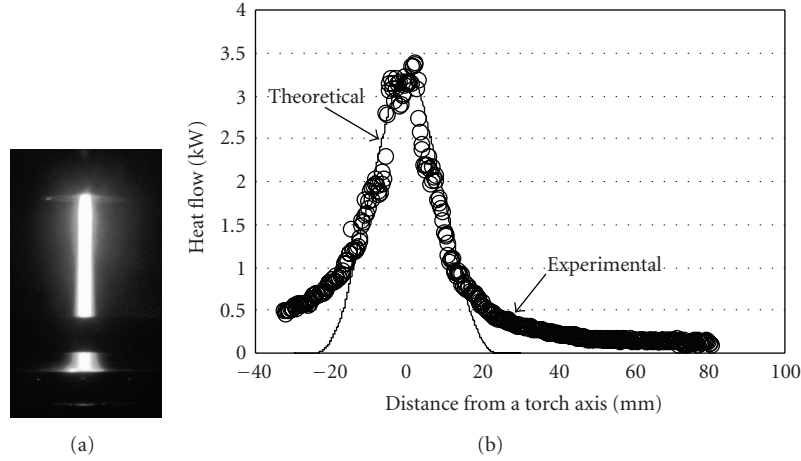


FIGURE 7: Comparison of experimental variation of heat flow to the calorimeter with the theoretical one under no magnetic field ($Y = 0$).

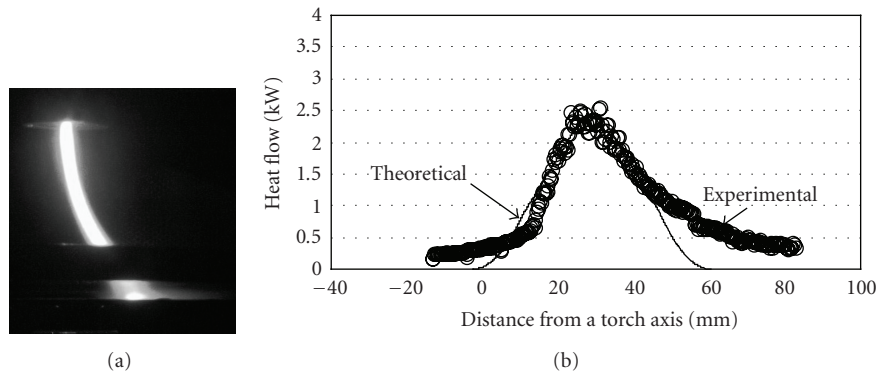


FIGURE 8: Comparison of the experimental variation of heat flow from a magnetically driven arc to the calorimeter with the theoretical variation of heat flow at $Y = 2.9$.

electric current through a two-turn rectangular field coil. The maximum magnetic flux density in the coil center was 2.22 mT at the coil current of 300 A.

In this study, instead of the heat flux distribution, we measured the variation of the heat flow using an assembly of a specially designed water-cooled copper anode block, as depicted in Figure 6. Designated as a calorimeter hereinafter, it was 10 mm wide, 10 mm thick, and 100 mm long. The calorimeter moved in the direction of the arc movement at 0.33 mm/s using its motor drive mechanism. The heat flow from the arc to the calorimeter was estimated according to the temperature increase of the cooling water through this block.

4. Comparison of Theoretical Predictions with Experimental Results

4.1. Determination of P_o and d_o . For numerical calculations, it is necessary to determine unknown parameters P_o and d_o . From the measurement of temperature difference between input temperature T_{in} and output temperature T_{out} , P_o was obtained as

$$P_o = 7.2 \text{ kW.} \quad (11)$$

It was confirmed that P_o was independent of the imposed magnetic flux density. The heat flow at $y^* = 0$ under no magnetic field was also measured and $W_0(0)$ of 3.3 kW was obtained. Substituting P_o , l , and $W_0(0)$ into (10), the arc diameter d_o was determined as

$$d_o = 38.4 \text{ mm.} \quad (12)$$

4.2. Comparison of Theoretical Predictions with Experimental Results. Variations of the heat flow from the arc were measured by changing the calorimeter position in two different cases. For the case of no imposed magnetic field, the arc profile and the variation of the heat flow transferred to the calorimeter with y^* are portrayed, respectively, in Figures 7(a) and 7(b).

In the other case, the arc was deformed by the imposed magnetic field generated by the field coil current of 160 A, as presented in Figure 8(a). The center position of the arc-root moved from $Y = 0$ to $Y = 29$ mm: the obtained variation of the heat flow to the calorimeter with y^* is presented in Figure 8(b). Using experimental values of P_o and d_o obtained in Section 4.1, numerical calculations of $W_Y(y^*)$ were conducted for the two cases of $Y = 0$ and $Y = 29$ mm. The theoretical variation for $Y = 0$ and that

for $Y = 29$ mm are shown, respectively, in Figures 7(b) and 8(b).

The agreement of theoretical predictions with experimental results is good despite the rough assumptions used for theoretical considerations.

5. Conclusions

The variation of heat flux from an arc with magnetic flux density was considered theoretically under a DC magnetic field imposed perpendicular to the arc. Two-dimensional heat flow was transformed into one-dimensional heat flow to simplify the theoretical model. The distribution function of the heat flux in the arc-root was assumed as triangular.

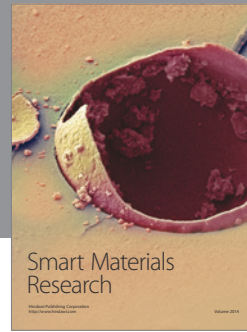
Theoretical considerations yielded these predictions.

- (1) The arc root on the anode expands with the increase of the imposed magnetic flux density.
- (2) The heat flux density decreases with increase of the magnetic flux density.

Experiments were conducted to measure the heat flux distribution using a specially designed calorimeter. The comparison of experimental results with theoretical predictions confirmed the validity of the assumptions used in the theoretical model.

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