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Measurement and calculation of plasma drag force in arc welding based on high-speed photography technology and particle dynamics

Ke Li *, Zhisheng Wu, Cuirong Liu

College of Materials Science and Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, PR China

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ABSTRACT

To investigate the plasma drag force acting on the droplet in gas metal arc welding (GMAW), we used a high-speed photography system to image the metal transfer process, and proposed a method employing particle dynamics to measure the plasma drag force. Experimental results of the droplet diameter, mass, acceleration, plasma drag force and gravity acting on the droplet are presented. The results indicate that, with the increase of welding current, the droplet diameter, mass and gravity decrease, the droplet acceleration and plasma pressure increase, while the plasma drag force and the gravity acting on the droplet decrease. Moreover, we find that the plasma drag force is 10 and near 100 times the gravity acting on the droplet. The experimental values of plasma drag force and plasma pressure show good agreement with the theoretical value by fluid theory; their order of magnitudes are 10^{-4} N and 10^{3} Pa, respectively, which demonstrates that it is an effective method to analyze the plasma drag force of welding arc.

1. Introduction

In arc welding process, the electric arc is a heat source as well as a force source, it produces three mechanical forces including electromagnetic force, plasma drag force and spot pressure acting on the molten drop. The plasma drag force is derived from the fast flow of gas around the liquid drop at the tip of the wire; it urges the molten droplet to detach from the electrode tip as soon as possible and to accelerate toward the melt pool; finally, it becomes a pressure on the melt pool surface. From previous research [1], we know that the plasma drag force affects the metal transfer behavior greatly, which influences the arc stability, melt pool formation, weld appearance and the joint performance. Therefore, an analysis of the plasma drag force in arc welding is important for a better understanding of the metal transfer process and improvements in the quality and productivity of welding.

The magnitude and distribution of the plasma drag force can be obtained by simulation and experimental methods. In many previous literatures [2–7], the mathematical model of the arc was constructed by the theory of magnetic fluid dynamics; the plasma drag force in gas shielded arc welding was calculated by finite element method. But all these simulation results lacked sufficient experimental verification. In literature [8,9], the arc pressure and its distribution on the upper surface of the workpiece were measured using static pressure measurement with a hole. In literature [10–12], the plasma drag force was measured using precise pressure sensors. However, the distribution of the plasma drag force is not uniform, which is the strongest at the end of the wire, and becomes weaker with the arc extending to the workpiece. Hence one can see that previous experimental methods measured only the force of the arc end on the workpiece surface, but not the plasma drag force at the end of a wire.

In the present paper we use a high-speed video camera system combined with laser shadowing technique to investigate the plasma drag force acting on the detached droplet from the electrode tip. The droplet diameter is defined by ellipsoid-sphere conversion method, the droplet mass and gravity are calculated, and the droplet acceleration is measured using particle kinematics. After obtaining the mass and acceleration of the droplet, the plasma drag force acting on the detaching droplet is calculated by Newton's second law. The theoretical value of plasma drag force based on fluid mechanics is also shown in Section 4. The experimental values are compared with the theoretical calculation value in Section 5.

2. Experimental system

In the experiment, a mild steel welding wire with a diameter of 1.2 mm was used to perform weld bead on a 6-mm thick mild steel plate, a direct current welding power source was employed, the wire was connected at the positive polarity, and the electrode extension was 14 mm. The workpiece travel speed was held constant at 600 mm/min. A pure argon shielding gas was used in the welding process and its flow rate was set to 15 l/min. The welding voltage was set to 21 V and the welding current was changed from 120 A to 280 A.

In order to observe the metal transfer process in detail, a high-speed video camera was used in this test, whose capable maximum frame rate is 10,000 frames per second (fps), and it was set to 5000 fps with each

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* Corresponding author. Tel.: +86 13994278092.
E-mail address: codylee@163.com (K. Li).

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frame time at 0.2 ms in this test. The exposure time was set at 4 μs. The optical system consists of a 300 mW semiconductor laser with a wavelength of 650 nm, a beam expander, a band-pass filter centered at 650 nm, an all-pass filter with 2% transmission and two pieces of protected glasses. The laser beam crosses through the welding arc while droplets are falling; a shadow image of wire and droplet is created on the camera screen. The optical filters are used to block the intense light from the welding arc. To capture clearer images, a 90-mm macro lens was configured on the camera. A schematic of the experimental system is shown in Fig. 1.

3. Experimental measurement of plasma drag force

Forces acting on the droplet before detachment include gravity, surface tension, electromagnetic force, plasma drag force and spot pressure [13]. However, after the molten droplet detached from the electrode tip, the arc jumps to the wire end again and the separated droplets flytoward the melt pool; there only remains gravity and plasma drag force acting on the droplet [14]. According to Newton's second law, the total force acting on the droplet after detachment is:

$$F = F_g + F_p = ma \tag{1}$$

where F_g and F_p are the gravity and the plasma drag force acting on the drop, respectively, m is the mass and a the acceleration of the droplet. The gravity acting on the droplet is given by:

$$F_g = mg \tag{2}$$

where g is the gravitational acceleration (9.8 $\mathrm{m/s^2}$). Thus, the plasma drag force acting on the droplet can be written as:

$$F_p = ma - mg. \tag{3}$$

The droplet mass can be calculated as:

$$m = \rho_d \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 \tag{4}$$

where ρ_d is the density of the molten droplet, whose value is about 7000 $\mathrm{kg/m^3}$, and D is the droplet diameter.

To measure the droplet diameter should be the primary task of this study. The droplet size can be measured from the still images captured by the high-speed video camera. From experimental results, it can be found that the shape of the detached drop is not a standard sphere but rather an approximate ellipsoid, as shown in Fig. 2a. If the ellipsoidal drop is converted into a spherical drop with the same volume, the droplet size can be expressed using the sphere's diameter. Accordingly, the molten droplet seemed to be an ellipsoid rotating around the long axis, whose volume is:

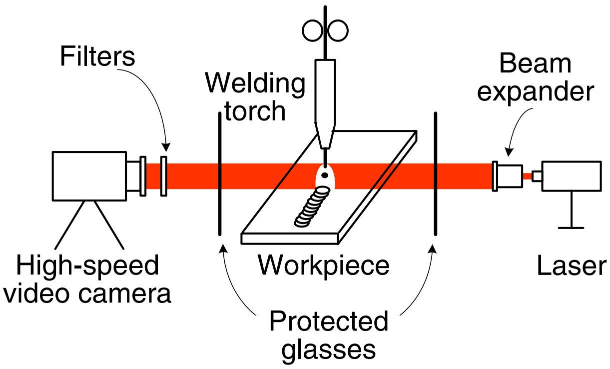

Fig. 1. Schematic diagram of high-speed photography system.

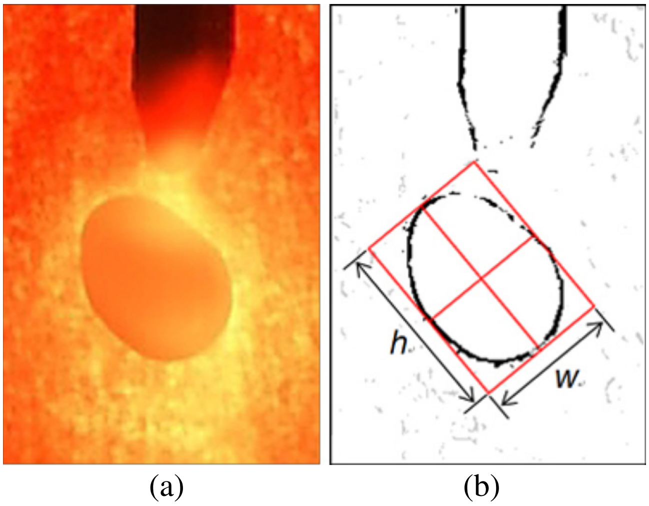

Fig. 2. Still image captured by high-speed video camera. (21 V/170 A with pure argon shielding gas). (a) Original image, (b) image processed by edge detection.

$$V = \frac{4\pi}{3}\frac{h}{2}\left(\frac{w}{2}\right)^2 \tag{5}$$

where h and w are the long axis and the short axis of the ellipsoid, respectively, which can be measured from the still images by edge detection, as shown in Fig. 2b. The volume of the sphere with diameter D is:

$$V = \frac{4\pi}{3}\left(\frac{D}{2}\right)^3. \tag{6}$$

When an ellipsoid is converted to a sphere with the same volume, the sphere's diameter is:

$$D = \sqrt{hw^2}. \tag{7}$$

Thus the droplet size can be expressed as the average diameter of hundreds of drops.

During the drop's falling process, if we ignore the variety of a drop's shape, the molten drop can be treated as a mass point. Therefore, we can use the bottom point of the drop to describe the drop's movement. The droplet acceleration can be measured according to the droplet's moving track after detachment. Taking the wire diameter of 1.2 mm for a reference, the droplet's real displacement between two adjacent frames within 1 ms after detachment can be measured from the still images. The diagram of the displacement is shown in Fig. 3. According to the particle kinematics theory, the droplet acceleration can be calculated as follows:

$$a = \frac{\Delta s_4 + \Delta s_3 - \Delta s_2 - \Delta s_1}{4t^2} \tag{8}$$

where t is each frame time (0.2 ms).

4. Theoretical calculation of plasma drag force

According to the theory of fluid mechanics, the plasma drag force on the liquid drop can be estimated by considering the drag force on a sphere immersed in a fluid [15]; it can be carried out by:

$$F_p' = C_d A \frac{\rho_f v_f^2}{2} \tag{9}$$