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Determining the heat flux distribution of laminar plasma jet impinging upon a flat surface: An indirect method using surface transformation hardening

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ABSTRACT

Laminar plasma jet (LPJ) is a promising high energy beam for various engineering applications. However, there lacks of a method for measuring the heat flux distribution of the LPJ impinging upon a flat surface ($q_H(r)$), with high accuracy, little limitations on the axial distance from the torch exit and the power of the LPJ. Therefore, this paper proposes an indirect method for determining $q_H(r)$ using surface transformation hardening. It makes use of the fact that when LPJ is used in the surface transformation hardening of a ferrous material, the size of the heat affected zone is directly correlated with the heat flux distribution. It combines the experiment and numerical simulation on the heat transfer process of the surface transformation hardening to indirectly obtain $q_H(r)$ at a certain axial distance from the torch exit. The proposed method was used to determine $q_H(r)$ of the nitrogen LPJ generated by a customized laminar plasma torch at different axial distance from the torch exit. It was found that the proposed method exhibits high accuracy through benchmarking with the results obtained by numerical simulation and by direct measurement using the double calorimetric technique reported in literature. Furthermore, the proposed indirect method has little limitations on the axial distance from the torch exit and the power level of the LPJ. In addition, it was found that that axial gradient of the LPJ's heat flux is low, with less than 50% drop after an axial distance of 100 mm from the torch exit. Finally, the determined $q_H(r)$ was directly verified by the numerical simulations and experimental observation on plasma surface transformation hardening of a different ferrous material.

1. Introduction

Atmospheric pressure plasma jet is promising in application to diverse fields. It can be roughly classified into non-thermal plasma jet and thermal plasma jet. The non-thermal plasma jet whose gas temperature is relatively low is used in the treatment of materials that is sensitive to high temperature, e.g. cancerous cells, polymer, etc. [1–4], while the thermal plasma jet has been mainly applied in high temperature treatment of materials [5–7]. The thermal plasma jet can be generated by DC arc plasma torch. If the plasma torch was elaborately designed and controlled [8–11], the status of the thermal plasma jet can be tuned to be laminar or quasi-laminar instead of the conventional turbulent. Such thermal plasma jet is named as laminar plasma jet (LPJ), which is characterized by high specific enthalpy and stability, favorable temperature and velocity distribution, low axial temperature gradient, etc. These prominent merits of the LPJ ensure better processing repeatability and controllability in many industrial applications [12,13], e.g. plasma spraying [14,15], plasma surface hardening [7,16], plasma cladding/re-melting [17], plasma wind tunnel [18], etc. The quality of these applications is greatly determined by the plasma jet characteristics, e.g. temperature profile, velocity profile, and heat flux distributions [19,20]. When the application involves the impingement of LPJ upon substrates [21–23], there exists an important physical variable, heat flux distribution of the LPJ at different axial distance from the plasma torch exit. If the heat flux distribution of the LPJ impinging on the flat surface can be quantitatively determined, the quality of the plasma processing could be precisely predicted and controlled.

Many methods, including numerical simulation or experimental measurement, have been attempted to determine the heat flux distribution of the plasma jets as a function of nozzle diameter, axial distance from the torch exit, power level or arc current, type of plasma working gas, etc. Wang et al. [24] carried out numerical modeling study on the characteristics of laminar and turbulent

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argon plasma jets impinging normally upon a flat surface in ambient air. It was found that the maximum heat flux of the LPJ reached 55 W/mm^2 at the axial distance of 10 mm, which is slightly higher than that of the turbulent plasma jet (TPJ). But the gradient of LPJ's heat flux is much smaller than that of the TPJ. The experimental measurement methods can be roughly classified into transient and steady-state methods. For the transient method, Meng et al. [25] used a small sensor of high thermal conductivity as a heat flux probe to measure the distribution of the heat flux. The heat flux probe was placed about 20 mm from the plasma torch exit and perpendicularly swept across the jet at a velocity of a 0.1 m/s. The temperature variation of the probe was recorded and used to derive the heat flux distribution. Such method is able to directly measure the heat flux distribution quickly. However, the obtained heat flux distribution was not symmetric, which is different from that obtained by the simulation method. In addition, as the heat flux probe cannot resist high temperature, it is difficult to be used to measure the heat flux close to the torch exit. For the steady-state methods, different types of heat flux sensors were used or designed. Tu et al. [26] used a commercial water-cooled heat flux meter to measure the stationary and non-stationary behavior of heat flux delivered by the argon plasma jet at an axial distance from 130 to 250 mm. Asmann et al. [27] used a commercial enthalpy probe (outside diameter of 3.17 mm, orifice diameter of 0.66 mm), TEKNA model ENTCS0, to determine the radial heat flux profile in a triple torch plasma system. Cheron et al. [28] designed an experimental device with four thermogauges (diameter 7.6 mm) to measure the parietal heat flux in a low pressure (1.5 mbar) nitrogen plasma wind tunnel. Ghorui et al. [29,30] used a double calorimetric technique to determine the heat flux profile of argon and nitrogen plasma jet at different power levels and axial distances. The inner calorimeter has a diameter of 25 mm, while the outer calorimeter has an inner diameter of 26 mm and an outer diameter of 150 mm. These steady-state methods used different sensors with a relatively large diameter to measure the heat flux of the plasma jet. The obtained heat flux is inherently the spatial-averaged value. Therefore, when it is used to derive the heat flux distribution, the obtained maximum heat fluxes may be much smaller than true ones. The larger size of the sensor, the larger the measurement error may it be. For example, the maximum heat flux for argon plasma jet with power of 10.8 kW and axial distance of 25 mm experimentally obtained by Meher et al. [29] is about 1 W/mm^2, while the maximum heat flux for argon plasma jet with power of 11 kW and axial distance of 20 mm numerically simulated by Wang et al. [24] is about 25 W/mm^2. In addition, as the sensors used usually cannot resist high temperature, the heat flux distribution close to the torch exit is difficult to be measured.

Therefore, it is desirable to establish a new method for determining the heat flux distribution of the LPJ impinging upon a flat surface, with high accuracy, little limitations on the axial distance from the torch exit and the power of the LPJ. In this paper, an indirect method for determining the heat flux distribution of the LPJ impinging upon a flat surface is proposed. It was inspired by the fact that when the LPJ is used in surface transformation hardening of the ferrous material [31], the size of the hardened layer is directly correlated with the heat flux distribution if other conditions are maintained the same. Therefore, combining the experiment and numerical simulation of the heat transfer process of the surface transformation hardening, the heat flux distribution may be indirectly obtained. To illustrate the proposed method, a laminar plasma torch (LPT) was specifically designed to produce the LPJ. Plasma surface hardening experiments on U75V steel with different axial distance from the torch exit were carried out. The sizes of the hardened layer were measured and used in the numerical simulation of the plasma surface hardening process to iteratively obtain the heat flux distribution. To verify the obtained heat flux distribution, numerical simulation and experiments on plasma surface hardening of 45 steel with three different axial distances were carried out.

2. Method for determining the heat flux distribution of the LPJ impinging on a flat surface

2.1. Laminar plasma jet

The LPT as shown in Fig. 1 was designed to produce the LPJ. Its design and characteristics have been studied by Cao et al. [10,32]. It is mainly constructed with a cathode, an anode and several inter-electrodes. The diameter of the anode nozzle is 7 mm. This structure provides an arc channel in which the arc root could be confined to a certain axial and circular range on the anode wall. The LPJ generated is shown in Fig. 2-(a) with a maximum jet length over 450 mm.

The prominent features of the LPJ are the uniform radial distribution and low axial gradient of the heat flux. The heat flux distribution at any section of the LPJ is assumed to obey the Gaussian distribution as described by Eq. (1).

$$q_J(r) = q_{Jm} e^{(-kr^2)} \tag{1}$$

where $q_J(r)$ is the heat flux distribution at any section of the LPJ, q_{Jm} the maximum heat flux at the specified section of the LPJ, r the distance from the center of the plasma jet, k a constant coefficient that determines the shape of the distribution. When the LPJ axially propagates, q_{Jm} is expected to decreases as shown in Fig. 2-(b) due to the energy dissipation to the air surrounding the LPJ.

2.2. An indirect method for determining the heat flux distribution by surface transformation hardening

When the LPJ impinges upon a flat surface, e.g. the plasma surface transformation hardening, it is desirable to quantitatively determine the heat flux distribution of the LPJ on the flat surface in order to precisely predict and control the quality of the plasma processing. When the LPT is set at a certain axial distance (d) from the substrate surface as shown in Fig. 3-(b), the LPJ impinges on the substrate and heats the substrate with a heated circle. The heat flux distribution within the heated circle ($q_H(r)$), which is a direct reflection of $q_J(r)$, is reasonably assumed to obey the Gaussian distribution as shown in Fig. 3-(a). It can be described by Eq. (2).

$$q_H(r) = q_{Hm} e^{-kr^2} \tag{2}$$

where q_{Hm} is the maximum heat flux. r is the distance to the center of the heated circle. The total heat energy (Q) of the heated circle is

$$Q = \int_0^\infty q_H(r) 2\pi r dr = q_{Hm} \int_0^\infty e^{-kr^2} 2\pi r dr = \frac{q_{Hm}}{-k} \int_0^\infty e^{-kr^2} d(-kr^2) = \frac{q_{Hm}\pi}{K}$$

Thus,

$$q_{Hm} = \frac{KQ}{\pi} \tag{3}$$

Based on Tekriwal and Mazumder [33], 95% of the total heat energy (Q) is concentrated in the heated circle of radius r_H. The relationship of Q and k can be expressed by Eq. (4).

$$0.95Q = \int_0^{r_H} \frac{Qk}{\pi} e^{(-kr^2)} 2\pi r dr = Q \int_{r_H}^0 e^{(-kr^2)} d(-kr^2) = Q[1 - e^{(-kr_H^2)}] \tag{4}$$

Simplifying Eq. (4), it follows: