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Spectroscopic diagnostics of plasma jet in micro-detonation of striking arc machining of engineering ceramics

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ABSTRACT

Micro-detonation of striking arc machining (MDSAM) is a newly developed energetic beam machining technology for engineering ceramics. During machining process, its energy exports with the micro-detonation plasma jet. In this paper, spectroscopic diagnostics is performed to analyze the internal physical state of the micro-detonation plasma jet and an experimental test is employed to study the effect of plasma jet on the silicon nitride ceramics. The Stark broadening method was used to get the electron density and the electron temperature was measured by line intensity method. The results showed that the electron density of plasma is in the range of 10^{16}–10^{17} cm^{-3} and meets local thermal equilibrium (LTE). During measuring the electron temperature, the emission line of N element was observed and the line intensity method was used. With the fixed machining parameters of MDSAM, the temperature of the plasma is 11,986 K. The machining test showed that the machined surface of the silicon nitride ceramics was covered with a loose recast layer. The study provides an important reference to reveal the machining mechanism for MDSAM.

1. Introduction

Micro-detonation of striking arc machining (MDSAM) is a newly developed energetic beam machining technology for engineering ceramics [1]. Comparing with other ceramics machining technology, MDSAM has shown obvious advantages such as low original equipment cost, decreased operation cost, higher material removal rate and more flexible process [2]. During MDSAM process, the machining energy is exported by the micro-detonation plasma jet. The shape and temperature of the micro-detonation plasma jet can directly affect the machining efficiency and quality. Therefore, to study the interior physical condition of the micro-detonation plasma jet is of important value for MDSAM process.

For plasma jet, the electron density and electron temperature are the key parameters of plasma to gain some insight in its microscopic as well as macroscopic behaviors [3]. Electron density and temperature measurements have been made using both probe [4] and spectroscopic methods [5]. Emission spectroscopy, which is characterized by simple and accurate, is the effective methods and has been developed to be very powerful for the diagnostics of plasma. Many plasma parameters, such as the density and temperature of the plasmas can be obtained quantitatively via the measurement of spectra.

Among various techniques for electron density measurement estimation used in plasma spectrometry, Stark broadening is the most popular approach for its independence from local thermal equilibrium (LTE) and the availability of theoretical stark broadening line profiles for emission lines of hydrogen, helium, and argon [6,7]. The most popular spectroscopic technique for electron temperature determination is absolute or relative spectral line intensity method. Joshi measured the electron density in a DC plasma spray torch using Stark broadening of H_β and Ar I (430 nm) lines [8]. Förster derived the electron temperature of an atmospheric pressure plasma jet by Boltzmann plot method [9]. Torres determined both the electron density and temperature in discharges produced by microwaves by Stark broadening of lines spontaneously emitted by atmospheric pressure plasma [10].

In this paper, after assembly of the experiment setup for diagnostics of the micro-detonation plasma jet, the electron number density and electron temperature of the micro-detonation plasma jet were determined. The electron density of the micro-detonation plasma jet was calculated from the stark broadening of H_α spectral line and the condition of local thermodynamic equilibrium of the micro-detonation plasma jet was analyzed. The spectral line intensity method has been used to determine the electron temperature of the micro-detonation plasma jet. The temperature was correlated to electron density values. The machined Si_3N_4 ceramics was characterized by scanning electron microscope (SEM).

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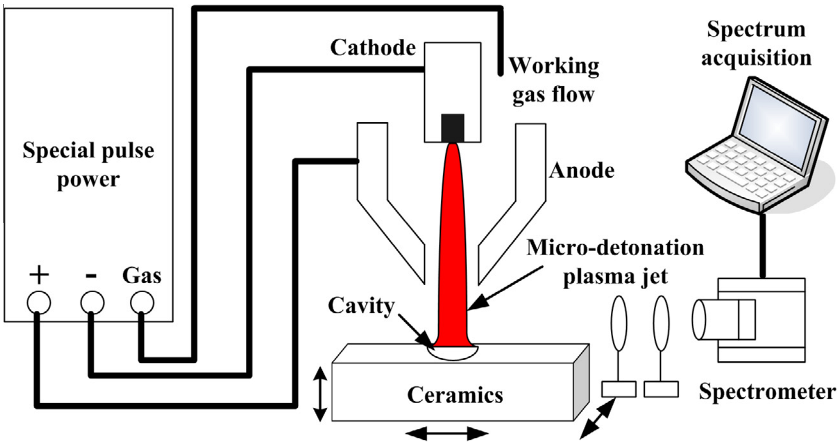

Fig. 1. Schematic diagram of the experimental setup.

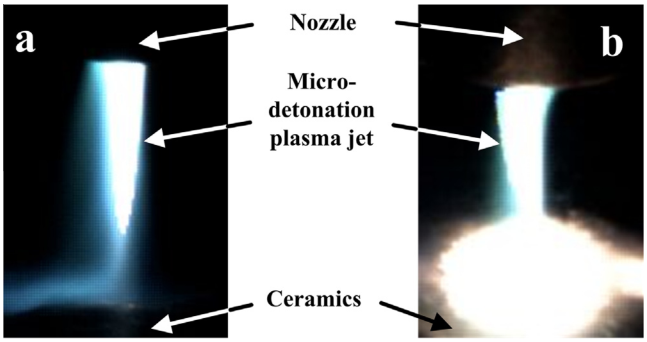

Fig. 2. Photo of (a) micro-detonation plasma jet, and (b) interaction process of micro-detonation plasma jet and ceramics.

2. Experiment and methodology

2.1. Experimental setup

Fig. 1 shows a schematic of the experimental system consisting of MDSAM system and a spectrometer (Acton SpectraPro2750i, 2400 grooves/mm, bandwidth 0.04 nm, 25 μm slits) with higher resolution. The MDSAM system comprises four main components, namely, the gas supply, special pulse power, three-dimensional digital control work bench, and micro-detonation generator.

In the MDSAM system, the hafnium electrode of the micro-detonation generator serves as the cathode, whereas the nozzle acts as the anode. When the special pulse power is in operation, a high-frequency pulse voltage is supplied between the two electrodes, causing a spark discharge and electric arc ignition. The current increases rapidly with increasing gas ionization, thus generating a plasma jet. The high density electrons and ions of the plasma jet achieve kinetic energy in the electric field and collide with each other at high speed, producing a lot of heat. The plasma jet expands in diameter due to the high temperature. At the same time, the electromagnetic field and the cooling airflow apply a compression effect on the plasma jet. While the plasma jet passes the nozzle, the narrow nozzle wall applies a mechanical constraint on it. Under the combined compression, the pressure of the plasma jet increases rapidly to a critical value. When the plasma jet bursts through from the nozzle, the plasma jet with high temperature and high pressure breaks the restraints and expands in volume, generating a micro-detonation. The micro-detonation plasma jet generated by MDSAM is shown in Fig. 2(a). When it is applied to the workpiece surface, the high temperature melts or vaporizes the ceramic surface material and the high pressure throws out the removed materials. The interaction process of micro-detonation plasma jet with ceramics is shown in Fig. 2(b). After single pulse machining, a round cavity is formed. With the three-dimensional feed movement of the work bench, the cavity spreads gradually, and surface removal is realized.

In MDSAM, five parameters affect the process. The parameters are working current (I), nozzle diameter of micro-detonation generator (R), pulse width (t), working gas pressure (P), the distance between the nozzle and the workpiece surface (D). The parameters in the experiment are fixed as follows: $I = 70$ A, $t = 100$ ms, $P = 0.14$ MPa, $D = 4$ mm, and $R = 1$ mm. 99% N_2 serves as working gas and 1% H_2 is used as tracing element. The reaction-sintered Si_3N_4 ceramics serves as the experimental materials.

2.2. Electron density measurement

Stark broadening method is used to calculate the electron density. This technique does not require any assumptions about thermodynamic equilibrium. The line profile of the H_β line at 486.5 nm and H_α line at 656.3 nm are measured. The H_β line is shown in Fig. 3(a). Although the broadening effect is obvious, the signal-to-noise ratio and profile symmetry are worse. In addition, there are interferences by other lines at both sides. So it is difficult to get the accurate full width at half height (FWHH). The H_α line is shown in Fig. 3(b), which has a clear profile and a high signal-to-noise. Therefore, H_α line is selected in the electron density measurement.

The Stark width is related to electron density by Eq. (1) [11]:

$$\Delta\lambda_{1/2} = C(N_e, T_e)N_e^{2/3} \tag{1}$$

where $\Delta\lambda_{1/2}$ is the measured Stark width, N_e is the electron density and T_e is the electron temperature. $C(N_e, T_e)$ is the coefficient whose value is given by Griem [11], for H_α line, $C(N_e, T_e) = 3.75 \times 10^{-14}$.

For the measured broadening width include Doppler and an instrumental component, Stark width is calculated as follows:

$$\Delta\lambda_{1/2} = \Delta\lambda_0 - \Delta\lambda_I - \Delta\lambda_D \tag{2}$$

where $\Delta\lambda_0$ is the measured broadening width, $\Delta\lambda_I$ is the instrumental broadening and $\Delta\lambda_D$ is the Doppler broadening.

2.3. Electron temperature measurement

The electron temperature of the micro-detonation plasma jet can be determined by the line intensity method. Two emission lines of the same kinds of atoms or ions are used to calculate the electron temperature T_e via the following equation: