

# Laminar/Turbulent Plasma Jets Generated at Reduced Pressure

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**Abstract**—Laminar dc plasma jets are attractive for precisely controlled plasma-material processing. The design of a novel non-transferred plasma torch enabled the switching between turbulent and laminar plasma flows by simply changing the plasma generation parameters. Images of the plasma flows generated at different conditions are presented.

**Index Terms**—DC plasma, high speed video camera, plasma stability.

**T**URBULENT dc plasma jets with high temperature, high velocity, and high enthalpy are very useful thermal sources for material processing in many industrial applications [1]. However, turbulent plasma jets are always accompanied by the extensive fluctuation in plasma flow, large entrainment of surrounding gas, and steep gradients in plasma properties (temperature, velocity, etc.), which accordingly restrict its further application in material processing, particularly in the future coating industry, where precise controllability and repeatability are of great importance. Efforts have been made to improve the stability of turbulent plasma with the optimization of the torch design. Through the use of splined inserts and microjets, Outcalt *et al.* reported that the properties of the plasma jet and the injected particles were markedly improved [2]. On the other hand, compared with the conventional turbulent plasma, laminar dc plasma is more attractive, owing to its good uniformity, flexibility, and relative higher thermal efficiency. However, it is more difficult to stably generate laminar plasma, and the characteristics of which are seldom reported. We have developed a novel nontransferred dc plasma torch that is capable of generating both turbulent and laminar plasma flows at reduced pressure [3]. The images of such plasma flows are presented in this paper.

Turbulent/laminar plasma was generated at various conditions. Argon was used as the primary plasma gas, and the gas flow rate was regulated to be 4.4, 6.6, 8.8, 13.2, and 17.6 slm by a calibrated mass flowmeter. The arc current was kept at

80 A for all the cases, whereas the arc voltage varied from 55 to 78 V, depending on the working conditions. The chamber pressure was controlled to range from 500 to 10 000 Pa. The images of the plasma jets were taken by a high-speed video camera (MotionBLITZ Cube36C, Germany) equipped with a Navitar 50-mm F0.95 TV lens. The camera speed was set to be 2500 frame/s, and the exposure time of each frame was set to be  $10^{-5}$  s. The recording time for each plasma condition was 1 s, which means that 2500 images were attained for one plasma condition. No gain was applied, and the lens aperture was kept constant at the brightest end of 0.95.

Fig. 1 summarizes the images of the plasma jets generated at the conditions previously described. The torch exit is at the left side of the image, and the vertical line depicted in Fig. 1(j) represents the size and position of the torch exit. For each condition, random sampling of the image was taken from the 2500 frames of each video clip. The laminar plasma flow is distinguished by the homogeneous plume, whereas the turbulent plasma jet has a twisted plume. Thus, the plasma in Fig. 1(d), (e), (h), (i), and (j) is in laminar state, and the plasma in Fig. 1(a), (b), (c), (f), and (g) is in turbulent form. When the Ar gas flow rate is constant at 17.6 slm, the plasma transformed from laminar to turbulent flows at an elevated chamber pressure. When the chamber pressure is 500 and 1000 Pa [Fig. 1(e) and (d)], the overall uniformity of the plasma plume can be confirmed, even when the exposure time is as short as  $10^{-5}$  s and significant gradient in neither axial nor radius direction can be observed. With the increase in chamber pressure, the plasma plume becomes intensively twisted and changes to a fully developed turbulent state. At the same time, the length, together with the volume, of the plasma contracts at higher chamber pressures. At higher pressures, with the change in the arcing conditions, the temperature of the plasma increases, which leads to brighter zones in the high-temperature area. When the chamber pressure is kept constant, the decrease in gas flow rates also promotes the laminar flow. Fig. 1(f)–(j) shows this tendency. Measurements of the velocity of the laminar plasma flow show that the typical central velocity at the torch exit is 1200 m/s. The axial gradient of velocity is  $6.4 \text{ m/s} \cdot \text{mm}$  from 0 to 70 mm off the torch exit, whereas the radial gradient of velocity is  $28.4 \text{ m/s} \cdot \text{mm}$  from 0 to 20 mm off the central axis. The electron temperature at the torch exit is 14 000 K.

In conclusion, high-speed video camera images have been presented, showing the evolution of turbulent plasma to laminar plasma at lower chamber pressures and gas flow rates in a dc nontransferred plasma torch.

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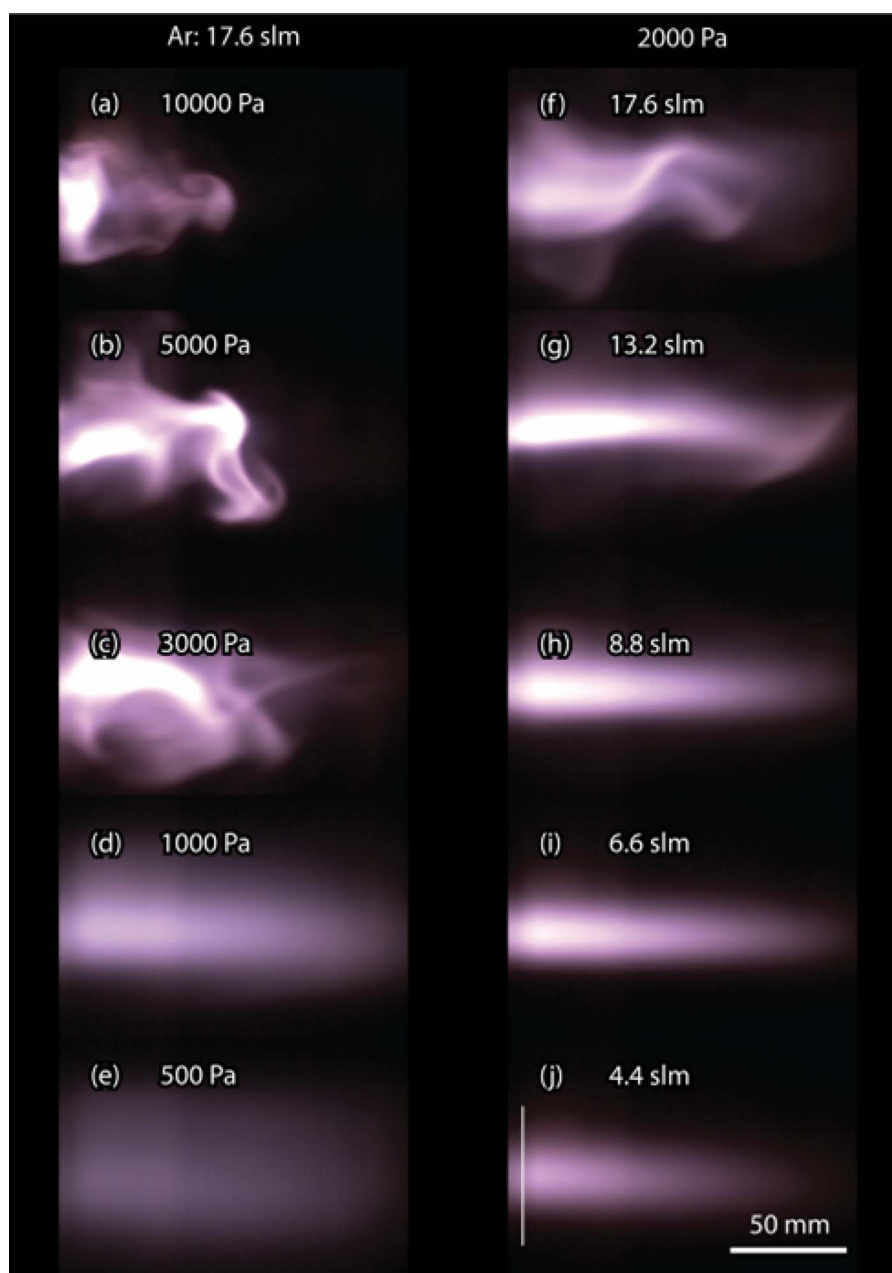


Fig. 1. High-speed video camera images of laminar and turbulent argon plasma generated with the same dc nontransferred plasma torch at reduced pressure. The exposure time is  $10\ \mu\text{s}$ , and the camera speed is 2500 frame/s. The vertical line in (j) represents the size and position of the torch exit.

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