Cold arc-plasma jet under atmospheric pressure for surface modification

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Abstract

A relatively cold arc-plasma jet under atmospheric pressure was developed using a pulse power supply, called a Plasma Energized (PEN)-Jet. A needle electrode was placed in a glass tube, and a cap electrode with a center-hole (3 mm diameter) was placed at the tube end. The electric arc was discharged between the electrodes by applying intermittent bipolar pulse power. By introducing dry air, nitrogen, or oxygen gas into the tube from the other end, the plasma gas of the arc was spewed out from the center-holed cap electrode, and a plasma jet was formed. The length and temperature of this plasma jet was measured as a function of pulse frequency (10–30 kHz). Both were found to increase with the increase in pulse frequency, not being very dependent on the type of gas under present experimental conditions. Maximum jet length was approximately 15 mm at 30 kHz, and maximum temperature at 5 mm from the cap electrode was 250 °C. Various metals and polymers were treated by PEN-Jet. The water contact-angle of these materials was found to decrease.

Keywords: Pulsed arc; Atmospheric pressure; PEN-Jet; Jet length; Temperature; Metal treatment; Hydrophilic property

1. Introduction

Plasmas under atmospheric pressure using electric discharges have shown great promise when applied to change the superficial properties of materials: friction, wettability, adhesion, gas and fluid permeability, biocompatibility, corrosion/wear/scratch resistance, and dye-affinity [1]. Treatment under atmospheric pressure is simpler to set-up, easier and economical to operate, and more productive, compared to traditional vacuum treatment. Atmospheric pressure plasmas can be generated by various methods: corona, glow, arc, dielectric barrier discharge, RF discharge, and microwave discharges, as reviewed in several articles [1–3].

A gliding arc is one of the plasmas with relatively low temperature operated under atmospheric pressure. The gliding arc is usually generated between two diverging electrodes in a submerged gas flow [4,5]. The arc starts at the shortest upstream electrode gap and is then dragged toward a wider electrode gap by an external forcible gas flow [4,5]. Even when the arc reaches the widest electrode gap, the arc column is pushed farther away if the power supply provides enough voltage. The arc is instantly extinguished when the arc voltage exceeds the voltage of the power supply. Immediately thereafter, a new arc starts at the shortest electrode gap. This series of behavior is repeated, usually producing a flat plasma jet. The gliding arc has been used for chemical [6], gas conversion and decomposition processes [4,7,8], gas pollution control [9], and wool surface treatment [10]. Recently, a gliding arc with simultaneous bipolar pulse power has been commercialized for the superficial treatment of hydrophilicity or adherability, irradiating the plasma to the material surface. Such gliding arc treatment is available for polymers. However, for conductive materials such as metals, gliding arc irradiation causes treated surface to suffer serious damage due to the appearance of aggressive arcs-spots.

In the present study, using the power supply for a pulse gliding arc, an arc-plasma torch-jet (Plasma ENer-gized (PEN)-Jet) with relatively low temperature was generated under atmospheric pressure to treat especially conductive materials without any damage. The jet length and temperature were first measured as a function of the pulse frequency, gas flow rate, and gas species. Various metals as well as polymers were treated with the PEN-Jet and the hydrophilicity of the treated surface was examined.
2. Experimental set-up

Fig. 1 depicts the PEN-Jet experimental set-up. A copper (Cu) needle electrode (1 mm diameter) was placed inside a glass tube (5 mm inner diameter, 7 mm outer diameter, 50 mm long). At one end of the tube, a cap electrode (Cu; 0.2 mm thick) with a 3-mm hole was placed. A ceramic tube (3 mm inner diameter, 5 mm outer diameter, 10 mm long) was also inserted to protect the glass tube from thermal shock. The gap distance between electrodes was 3 mm. The electrodes were connected to the burst-pulse generator (Haiden Laboratory, PHF-2K-T2) and the pulse-boosting transformer (Haiden Laboratory, PT-2K). As shown in the left inset of Fig. 1 (no load, 30 kHz), the burst pulse (≈200 V peak to peak) was the input to the primary transformer. Pulse frequency in this system means the reciprocal period between the bursts. The right two insets of Fig. 1 show the typical waveforms of voltage between each electrode and ground when the arc is discharged. An approximately 1 kV pulse was applied to each electrode so that approximately 2 kV of pulse was applied between the electrodes.

In the present work, in order to obtain the preliminary macroscopic characteristics of the PEN-Jet, the jet length and temperature were measured as a function of the pulse frequency, gas types, and gas flow rate. The gas flow rate was regulated with a rotameter. Experimental conditions and parameters were as follows: electric input power, less than 50 W (below the readable level of the power supply indicator, the power increases as the pulse frequency increases due to the own characteristics of power supply, approximately 40, 45 and 50 W at 10, 20 and 30 kHz, respectively); pulse frequency, 10–30 kHz; intermittent frequency, 67 Hz; energized periodical duty ratio, 50%; gas type, air, nitrogen (N₂), and oxygen (O₂); flow rate, 0.5–3 l/min.

The PEN-Jet was irradiated onto the metals (aluminum (Al), copper (Cu), and stainless steel (SUS; SUS304)) and polymers (polyamide (PA; nylon), polyethylene terephthalate (PET), and polymethylmethacrylate (PMMA)). The water contact-angle on the treated surface was measured with a face contact-angle meter (Kyowa Interface Science Co., Ltd; CA-DT type (CA-QI Series)). The volume of water droplet was 8 μl.

For comparison, a gliding arc generated between two tungsten wire electrodes (2 mm diameter) with a diverging configuration, was also irradiated onto the metals and polymers. The shortest and longest gaps were 11 and 49 mm, respectively. The gas exit window was rectangular (7×51 mm²). The gliding arc operated under the following conditions: electric input power, 200 W; pulse frequency, 10 kHz; intermittent frequency, 67 Hz; energized periodical duty ratio, 50%; gas type, air; flow rate, approximately 500 l/min.

3. Results and discussion

Prior to the development of the PEN-Jet, the gliding arc-plasma was irradiated onto PA and SUS substrates. The plasma appearance was recorded with a hand-held digital camera (SONY, DSC-F505K). When the gliding arc was irradiated onto SUS as shown in Fig. 2b, micro arc-spots appeared at two positions corresponding to the two electrodes on the SUS substrate, unlike the appearance on PA as shown in Fig. 2a. This indicates that when the gliding arc is irradiated onto the metal surface, the arc current passes completely through the metal.
Therefore, the arc-spots appear at the interface between the plasma and the conductive solid. In other words, when the metal is inserted to the electric arc-plasma, the arc is split into two serial arcs, and the arc-spot inflicts serious damage on the substrate. When polymer-painted metals are treated, the paint may peel off.

Fig. 3 shows the photographs of PEN-Jets taken with the hand-held digital camera. Fig. 3a shows the free burning arc jet, and Fig. 3b shows the irradiation of PEN-Jet onto the SUS substrate. In contrast to the gliding arc irradiation, the arc-spots did not appear on the substrate in PEN-Jet irradiation. The arc column itself did not extend to the substrate, but only the plasma extruded by the gas flow irradiated onto the substrate.

The jet length was measured with the unaided eye in a dark room. The visible jet length is shown in Figs. 4 and 5 as a function of the gas flow rate. Fig. 4 shows the effect of pulse frequency and Fig. 5 the effect of gas species. When no gas flowed into the tube, the arc-plasma discharged only in the tube and no jet was formed. When the gas flowed into the tube, plasma was extruded from the hole in the cap electrode. In the case of air as shown in Fig. 4, the jet length increased almost proportionally to the gas flow rate. The jet length also increased when the pulse frequency rose. Similar results were obtained for N₂ and O₂ gas, indicating that a higher flow rate and higher pulse frequency can provide a longer jet. The higher gas flow effectively forces the plasma gas to come out of the exit. This mechanism is considered to be essentially similar to the gliding arc as described in Section 1. The reason why the higher pulse frequency brings the longer jet is that the electric input power into the plasma increases with the pulse frequency as mentioned in Section 2.

The temperature of the PEN-Jet along the jet axis was measured with an isolation thermocouple. The results are shown in Fig. 6. The plasma temperature has a maximum in the vicinity of the cap electrode or the exit of the plasma, and gradually decreased with the distance from the cap electrode. For example, in the case of air and 10 kHz, the temperature near the cap electrode was approximately 150 °C, and that 80 mm from the cap electrode was approximately 80 °C. This indicates that in the outer visible plasma jet region, the gas still exceeded the room temperature. The temperature was found to increase as the frequency increased. In the case of 30 kHz with air flow, the temperatures near the cap electrode and 20 mm distant were approximately 400 and 170 °C, respectively. There was no
significant difference in the type of gas used. The temperature of the PEN-Jet is relatively high compared to that of other atmospheric pressure plasmas based on corona or glow discharges (\(<100 \, ^\circ C\)), but is very much lower compared to that of general arc discharges (\(>1000 \, ^\circ C\)).

The PEN-Jet was irradiated onto the metals and polymers. As an example, water-droplet (50 \(\mu\)l) on treated and untreated SUS surfaces are shown in Fig. 7. Droplet on the untreated SUS surface took a semi-spherical form, whereas that on the treated SUS surface spread out almost even. This shows that the PEN-Jet can modify the hydrophilic property of the material surface. Fig. 8 shows the results of the contact-angle of an 8-\(\mu\)l water droplet immediately after treatment compared with the results of a gliding arc. A moving substrate surface (1.5 mm/s) was treated by a fixed PEN-Jet and a gliding arc. For the gliding arc, the substrate was set at 15 mm from the top of the electrode. The PEN-Jet was operated with air flow and a 30-kHz pulse frequency. The distance between the cap electrode and the substrate in the PEN-Jet treatment was 8 mm for all materials except PET, which was set at a 13-mm distance to avoid deformation due to the heat of the PEN-Jet. As shown in Fig. 8, the water contact-angle was dramatically decreased for metals and polymers by both the PEN-jet treatment as well as the gliding arc treatment. There is no significant difference in relative merit between both treatments. There was no obvious damage or deformation under those conditions, except for metals treated by the gliding arc. Damage spots were clearly observed on metal surfaces from the gliding arc treatment.

4. Conclusions

To avoid serious damage to a substrate during a gliding arc treatment, the pen type plasma jet (PEN-Jet)
er and sharper PEN-Jets which are suitable for tiny areas, high-aspect holes or grooves, or pinpoint accuracy, can easily be designed and manufactured. On the other hand, multiple or matrix PEN-Jets with low power consumption could also be designed for treating large areas.

Acknowledgments

This work was partly supported by Itoh Optical Industrial Co., Ltd and by a grant for outstanding research projects of the Research Center for Future Technology, Toyohashi University of Technology. The authors would like to thank Mr Koichi Matsunaga of Haiden Laboratory Inc. for his helpful discussions.

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