Application of Atmospheric-pressure Non-equilibrium Plasma Jet Technology

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1. Introduction

In 1986, M. Kogoma et al. succeeded in stable development under atmospheric pressure using helium gas [1]. Thereafter, it was made possible to produce atmospheric-pressure glow discharge (APGD) [2-5], which is a groundbreaking mean in the area of plasma technology. The establishment of this plasma generation technology under atmospheric pressure has raised expectations for atmospheric-pressure plasma in the plasma-related industry.

Recently, plasma processing technologies for various materials are investigated corresponding to different patterns and characteristics of plasma: surface modification technology with dielectric-barrier discharge developed by M. Eichler et al.[6], decontamination technology for radionuclide with ICP plasma reported by A. B. Antonlazzi et al.[7], surface modification technology for high-molecular polymer with AC 60[Hz] plasma torch developed by Y.-H. Choi et al. [8] and coating technology for aluminum and titania with APS plasma developed by S. R. Wylie et al. [9], for instance in plastic surface processing.

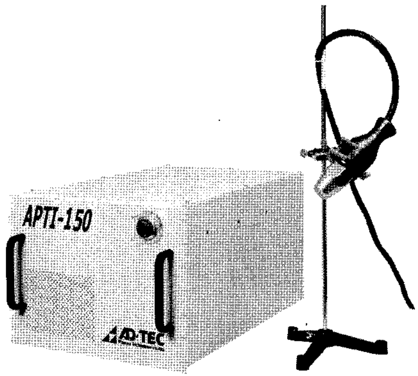


Fig. 1. Picture of the atmospheric-pressure non-equilibrium plasma jet equipment for skin canter treatment as an application to the area of medicine

Fig. 1 shows the atmospheric-pressure non-equilibrium plasma jet equipment for skin canter treatment as an application to the area of medicine [10]. As this instance indicates, a number of research and development are actually being conducted in new industries.

However, a typical technique of material surface processing technology with atmospheric-pressure discharge plasma is to generate plasma by using glow discharge, streamer discharge, corona discharge and arc discharge under atmospheric pressure for surface processing [11-15].

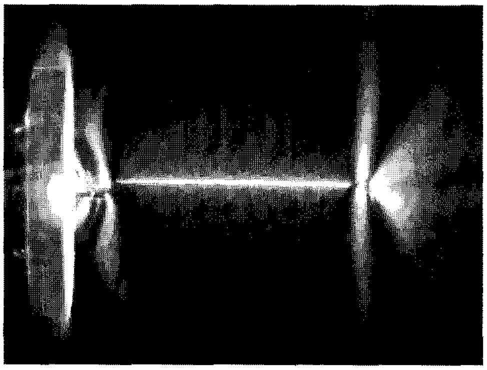


Fig. 2. Images of streamer discharge within atmospheric-pressure plasma

Fig. 2 shows images of streamer discharge within atmospheric-pressure plasma taken by Takagi et al., IwateUniversity.

Fig. 3 introduces the circuit developed and proposed by Takagi et al., IwateUniversity, to generate glow discharge under atmospheric pressure[16].

Processing effects of these techniques were firmly verified by previous researches. With plasma surface processing technologies, surface boundary is typically processed by

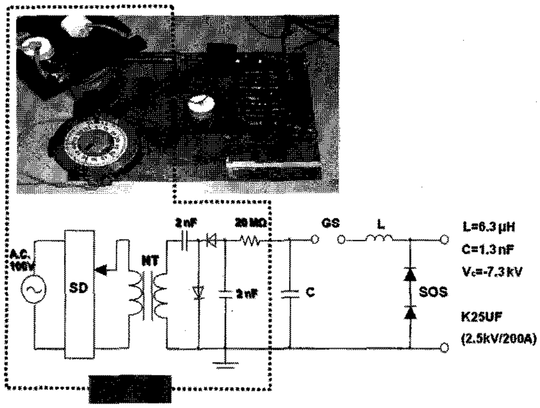


Fig. 3. The circuit of Introduced by atmospheric-pressure plasma

gas-phase reaction which cannot occur in gas-phase chemical reaction at normal temperature and pressure [17-20].

Basically, the mechanisms regarding plasma-phase and the relation between material surface and plasma are not fully clarified; they are only in the early stage of consideration by means such as simulation etc. [21] Therefore, the practical value for industrial use of this technology is still low.

Specifically, one of the closely-watched forms of plasma equipments in the area of atmospheric-pressure plasma is atmospheric-pressure non-equilibrium plasma jet. The term "plasma jet" is widely used and this may be broadly defined as a plasma flow jetted from a nozzle. However, the definition of plasma jet varies depending upon generating procedures and applications of plasma.

There are two prominent classifications of plasma jet: thermal equilibrium (thermal plasma) and non-equilibrium plasma. Descriptively, the thermal equilibrium plasma is a plasma source at pressure higher than atmospheric pressure; the non-equilibrium plasma is a plasma source at pressure lower than atmospheric pressure. However, these definitions may not be deemed precise. A nozzle-jetted capacitive-coupling plasma generation system is generally used for the fundamental system of plasma jet. As a plasma source, the atmospheric-pressure glow discharge shall be placed at the equivalent level to these sources. The two prominent types of physical classifications of plasma jet are thermal plasma and equilibrium plasma. An equipment to generate arc discharge stabilized by atmospheric plasma jet and/or gas flow is called as a plasma torch and is classified into two types depending upon electric connection method: transitional and non-transitional. The transitional plasma torch supposes the connection method that heats one electrode; the non-transitional plasma torch supposes the connection method that does not heat electrode but uses a plasma torch nozzle as one electrode. Generally, "plasma jet" refers to non-transitional arc plasma.

There are different types of plasma torch that generates plasma jet, ranging from those used for sources of driving force in large-scale aerospace industry and fusion of waste products etc. to those used as a torch part for plasma spraying. Research and development of torch part for plasma spraying started several decades ago, and in the recent years developments of new types of plasma jet are being put on stream: for example, the development of microwave plasma jet equipment by T. Yokoyama et al. [22] and the development of water-vapor plasma torch by B. Glocker et al.[23].

Therefore, technologies for industrial applications and future prospects of atmospheric-plasma non-equilibrium jet are introduced hereon.

2. Application of Atmospheric-pressure Non- equilibrium Plasma Jet

The basic procedure to generate atmospheric-pressure plasma jet is as follows: insert dielectric substance between electrodes to let electric charge moved by gaseous discharge rest on the surface of dielectric substance so that the electric field in the direction opposite to the electric current is produced. With short-time discharge, this field reversing can prevent thermalization of plasma and generation of arc discharge, as well as damage of counter electrodes due to development of streamer. Further, it is made possible to maintain discharge with extremely high voltage of several dozens of kV applied. Plasma torches currently in practical use are introduced below:

First of all, "Aiplasma" developed by Matsushita Electric Works Co., Ltd. is an atmospheric-pressure plasma cleaning equipment intended for precision cleaning of liquid crystal panels and electronic components. Aiplasma can eject dense plasma generated under atmospheric pressure in jets by using plasma gas primarily composed of argon, and direct it to processing object without annihilating active radical. Since Aiplasma allows for removal of organic contaminants by using enzyme in reaction gas in surface processing of object, and allows for reductive removal of oxidative products by using hydrogen as well, it is used widely in areas such as plasma cleaning of surface of ITO electrodes for LCD panels and surface cleaning of electronic components in semiconductor packaging. Further, Aiplasma can also be used for different applications by selecting reaction gas that meets concerned purpose; therefore, it is also used for purposes other than surface cleaning including improvement of adhesiveness of liquid crystal substrate and improvement of wettability of resin materials including polyimide.

Next, a dry-cleaning equipment with atmospheric plasma "AP-C03" is currently under development by Sekisui Chemical Co., Ltd., to improve reducibility in the area of semiconductor packaging and manufacturing where densification and pitch narrowing are progressing. Its essential structure is developed from the array of several plasma nozzles.

Fig. 4 shows the external appearance of AP-series equipment as an industrial application sample. This equipment is designed to widen the processing range to several meters and is used for cleaning of

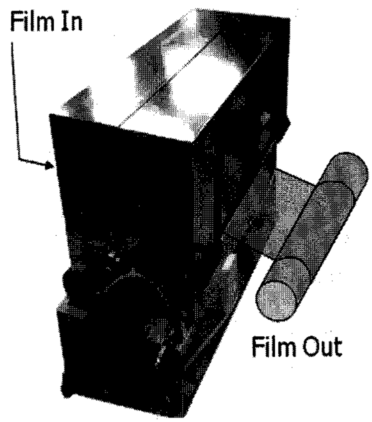


Fig. 4. The external appearance of AP-series equipment as an industrial application samples

lead frame and wiring on substrate in atmospheric-open system. In addition, using fluorocarbon gas as plasma gas allows for application of this product to metal-oxide reductive etching and resist ashing (photoresists shall be ashed and eliminated by oxygen plasma or equivalent to eliminate unneeded photoresists after being utilized as an etching mask through steps "coating -> exposure -> image development" in the lithographic process to transcribe patterns to wafers in manufacturing of IC). "AP-C03" is already made available to the market. Details of typical products are as follows:

Fig. 5 shows a still photograph of plasma jet with high-frequency DC pulsed power supply for plasma generation. It is one of the prominent features of this plasma jet that it mitigates overheat of electrodes by applying voltage with fast pulse waveform to prevent plasma from transition to equilibrium arc discharge and therefore no ark is generated

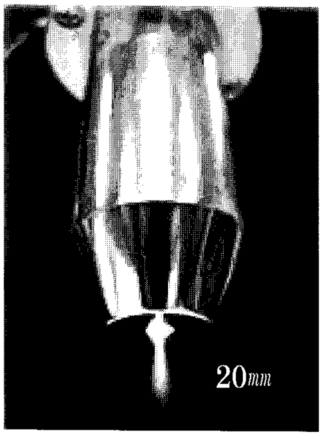


Fig. 5. Photograph of plasma jet with high-frequency DC pulsed power supply for plasma generation

on any metal surface allowing for cleaning and modification of sample surface.The plasma torch consisted of a titanium rod (OD: 4[mm], length: 10[mm]) at the center and an SUS pipe (OD: 36[mm], ID: 30[mm], length: 87[mm]) surrounding the rod. In the upper part of the torch, a quartz tube (OD: 26[mm], ID: 24[mm], length: 87[mm]) was placed between the titanium rod and the SUS pipe, generating dielectric barrier discharges to produce reactive species. The ID and length of the plasma torch nozzle were 10 and 20[mm], respectively. In the lower part of the torch where no dielectrics were introduced, arc discharges were generated. By using the electromagnetic pumping effect, the reactive species generated in the upper part of the torch were effectively emitted from the nozzle [24].

Fig. 6 shows the electrode construction of a plasma jet torch. These are the fundamental

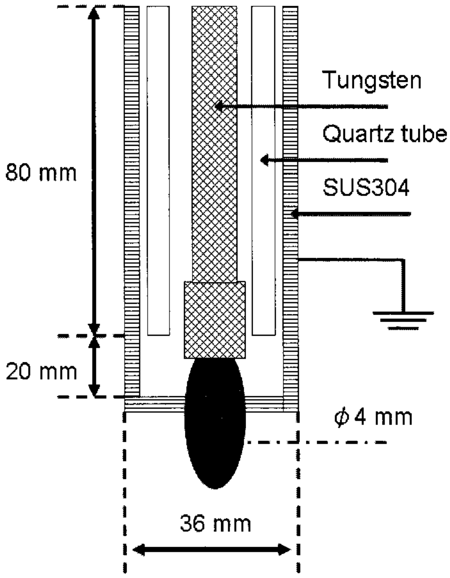


Fig. 6. Picture of the electrode construction of a plasma jet torch

principles in plasma generation with plasma jet torch electrodes. Then, atmospheric-pressure non-equilibrium microwave discharge plasma jet is introduced below:

Fig. 7 shows the still image of atmospheric-pressure non-equilibrium microwave discharge plasma jet. As for the essential structure of proposed atmospheric-pressure non-equilibrium microwave discharge plasma jet, two established methods are currently available: coaxial tube method and wave guide tube method. In the main structure of the atmospheric-pressure non-equilibrium microwave plasma jet introduced herein (manufactured by ADTEC Plasma Technology), the whole torch preserves the coaxial structure and the basic material of this structure is aluminum.

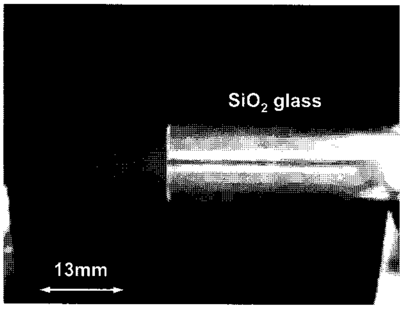


Fig. 7. Image of atmospheric-pressure non-equilibrium microwave discharge plasma jet

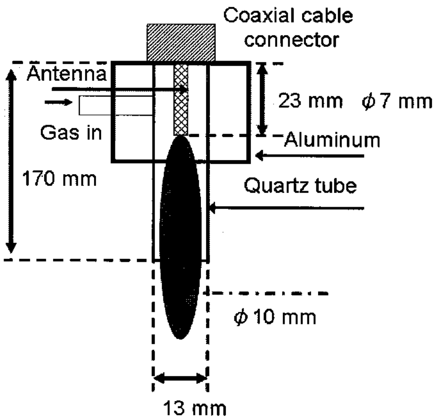


Fig. 8. Schematic diagram of atmospheric-pressure non-equilibrium microwave discharge plasma jet torch

Fig. 8 shows a schematic diagram of atmospheric-pressure non-equilibrium microwave discharge plasma jet torch that uses a microwave power source. The subject is the atmospheric-pressure non-equilibrium microwave discharge plasma jet equipment used in this study. This equipment has higher energy efficiency than conventional atmospheric-pressure non-equilibrium microwave discharge plasma jet despite its small body, and is characterized by a feature to easily generate plasma at low temperature and atmospheric pressure.

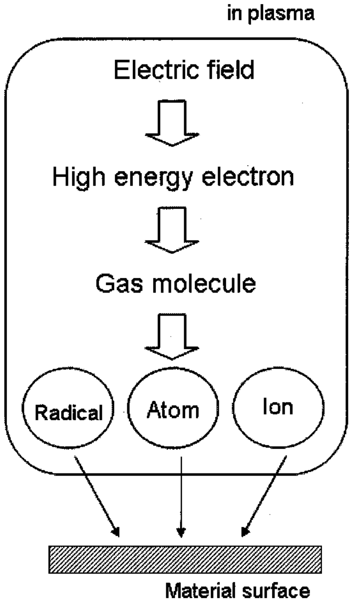
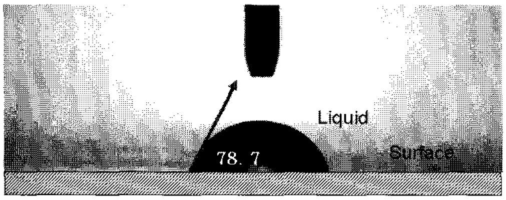


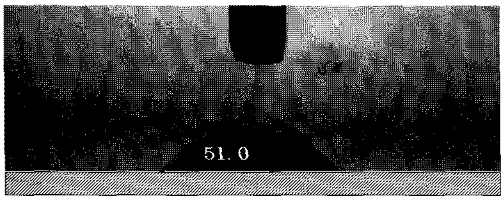
Fig. 9. The material surface processing mechanism by means of atmospheric-pressure non-equilibrium discharge plasma

Fig. 9 shows a material surface processing mechanism by means of atmospheric-pressure discharge plasma. Difference in discharge format of atmospheric-pressure discharge plasma from that shown in the figure depends on differences in frequency of ionization and excitation effect and spatial extension that are made due to differences in special condition under which plasma is generated and electric field. When discharge progresses, glow discharge occurs and a plasma state is made. In this state, voltage required for maintaining discharge is smaller than the sparkover voltage. When ions produced by ionization start emitting electrons as they collide with cathodes, the glow discharge progresses to the state of arc discharge and then the self-sustaining discharge voltage drops and generates plasma of higher degree of ionization. With either technique, it is difficult to ionize all atomic elements and molecules within the gas and to realize fully-ionized plasma; therefore, partially-ionized plasma that contains a small quantity of neutral particles is generated.

Fig. 10 shows results of material surface processing of poly(ethylene naptharate) film by means of atmospheric-pressure non-equilibrium discharge microwave plasma jet. In this figure, behavior of water drops on the poly(ethylene naptharate) film surface is observed. It clearly indicates that after plasma surface processing, surface tensity of the water drops differs from that observed previously. Basically, PET film surface processing is typically used to confirm generation of plasma by atmospheric-pressure non-equilibrium plasma jet [25].



(a) Non-treated



(b) Plasma treatment

Fig. 10. The material surface processing of PET film by means of atmospheric-pressure non-equilibrium discharge microwave plasma jet

3. New-type of Atmospheric-pressure Non-equilibrium Plasma Jet

Though a number of studies identify problems in plasma generation technologies of plasma surface processing technologies for different materials using atmospheric-pressure non-equilibrium plasma jet, these technologies have an advantage; they can generate plasma under atmospheric pressure at low cost and relatively easily. Recent new applications of atmospheric-pressure non-equilibrium plasma jet are introduced below:

For instance, Kanazawa et al., Oita-University,reportedcoronaradicalshowerthatp roducesdischargebyplacingtwonozzleelectrode

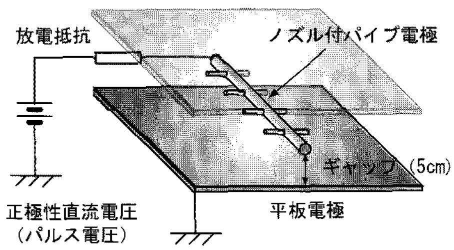
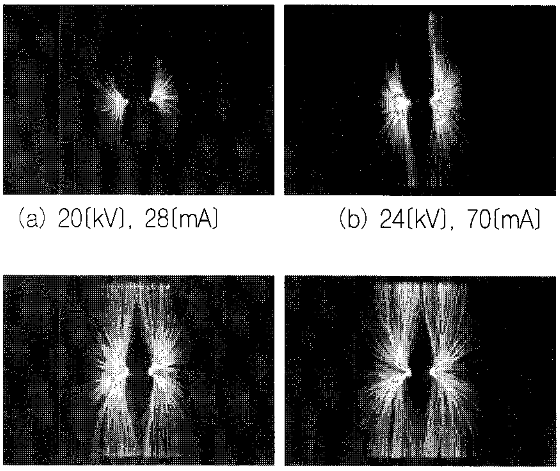


Fig. 11. Picture of the electrode construction of the corona radical shower

satthecenterofparallel-plateelectrodeinparall elwiththeplate[26].

Fig. 11 shows the electrode construction of the corona radical shower.



(a) 20[kV], 28[mA] (b) 24[kV], 70[mA]

(c) 28[kV], 110[mA] (d) 32[kV], 160[mA]

Fig. 12. The appearance of streamer used in the corona radical shower system

Fig. 12 shows the appearance of streamer used in the corona radical shower system.

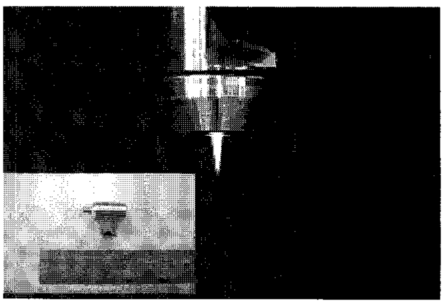


Fig. 13 indicates the form of miniature atmospheric-pressure non-equilibrium plasma jet. As seen in this figure, the electrode construction is small and diameter of generated plasma itself is as small as 1-3 millimeters. Therefore, this is expected to be applied to the areas such as dentistry and cosmetic surgery. As described above, new forms of atmospheric-pressure non-equilibrium plasma jet are proposed at the same time and expectations for applications of these technologies to new industries are raised.

4. Conclusion

Finally, a demand for industrial applications of atmospheric plasma jet is low at the present time. However, it can be concluded that the needs for the technologies will glow as more characteristics of atmospheric-pressure plasma jet are revealed and the number of applications increases in the future. Primarily, it has a number of advantages over conventional equipments such as vacuum plasma equipments. Since only short time has passed since the establishment of atmospheric-pressure plasma jet technologies, these technologies contain plenty of possibilities of industrial developments. Therefore, a number of researchers in the area of atmospheric-pressure plasma jet and businesses aiming for industrial applications of atmospheric-pressure plasma jet are highly expected to commit to this area of research across the globe.

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