Gas cylinder-free atmospheric steam plasma source for surface treatment/sterilization

Taiki Osawa[1], Kai Fukuchi[1], Akito Shirai[1], Akane Yaida[1], Akitoshi Okino[(*)1]

[1] *FIRST, Tokyo Institute of Technology, Yokohama, Japan*

[(*)] aokino@es.titech.ac.jp

Background

Currently, processing technologies for products with microstructures such as semiconductors are evolving year by year, and materials with various properties are used in products by bonding multiple materials like layers. To create this microstructure or as a pre-process for bonding materials, wet processes such as self-assembled organic monolayer formation[1] and dry processes such as plasma etching and chemical vapor deposition (CVD) are used. However, the wet process generates waste fluid, and the dry process needs large facility and complex process because it uses vacuum equipment.

In recent years, surface treatment technology using atmospheric plasma has been attracting attention. Atmospheric plasma does not require vacuum equipment and allows continuous treatment under atmospheric. In addition, since a large amount of chemically reactive species can be generated, hydrophilic treatment can be achieved in a short time[2]. As shown in Fig. 1, multi-gas plasma jet that can stably generate plasma at low temperatures below 50℃ under atmospheric pressure was developed our laboratory. And plasma generated by various gases has irradiated some materials such as fluoroplastic PFA sheets and heat-sensitive polyimide films. Even PFA sheets, which are considered difficult to hydrophilize, showed a high hydrophilic effect when irradiated with oxygen plasma for 10 seconds, reducing the contact angle of droplets from 85 degrees to 30 degrees. In oxygen plasma, hydroxyl radicals ($HO^{\cdot}$) can be generated by the reaction between oxygen plasma and surrounding air. I think that the fluoro group of PFA surface was replaced by hydroxy groups(-OH) as hydrophilic groups by reacting this $HO^{\cdot}$, resulting in hydrophilicity.

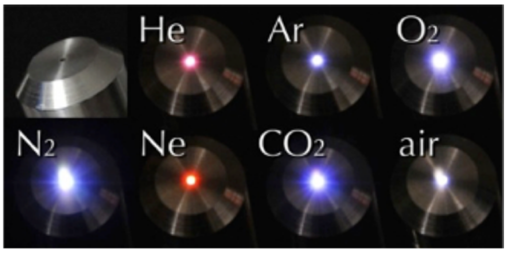

Fig. 1: Multi-gas plasma jet

Because of its high reactivity, $HO^{\cdot}$ is used not only for surface treatment but also in other fields. For example, $HO^{\cdot}$ also have high oxidizing power and contribute to bactericidal action. In particular, oxygen plasma has been shown to be highly effective in both the gas and liquid phases, and bactericidal effects can be achieved by the reaction of highly oxidizing reactive species with bacteria. Therefore, atmospheric plasma is also expected to be applied to the field of sterilization. However, multi-gas plasma jet use a various gases to generate plasma, and thus require gas cylinders. In recent years, the price of gas cylinders has skyrocketed, and since oxygen plasma generates a large amount of ozone, a simple and harmless plasma-generating medium is required. Therefore, the purpose of this study is to develop an atmospheric pressure plasma system using steam as a plasma generating gas in order to generate more hydroxyl radicals without using gas cylinders.

Steam plasma source

To generate more hydroxyl radicals, just steam was used as a plasma generation gas. As shown in Fig. 2, purified water was introduced at 10 mL/min using a peristaltic pump into a copper tube heated to about 200°C by a ribbon heater. When the purified water touched the heated copper tube, it was evaporated, generating 17 L/min of steam since the volume was increased more than 1,700 times. Steam plasma was generated by introducing the steam into the plasma jet, and applying an AC voltage of 9 $kV_{0\text{-}p}$ and 16 kHz to the electrodes in the plasma jet as shown right side of Fig. 2.

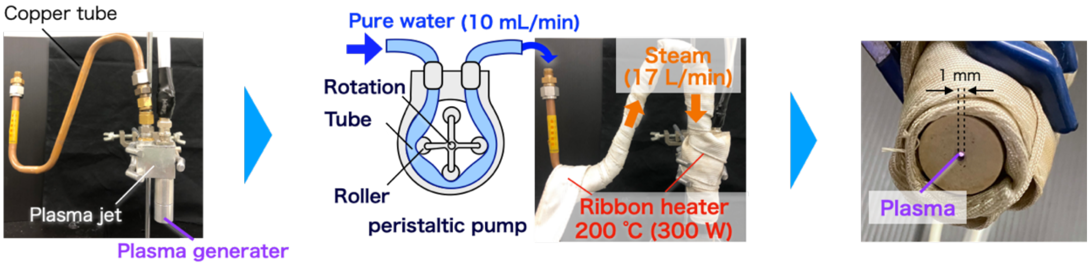

Fig. 2: Generation mechanism of steam plasma

Sterilization of *Staphylococcus aureus* by steam plasma irradiation

To investigate the bactericidal effect of steam plasma, a sterilization experiment was conducted in which *Staphylococcus aureus* was irradiated with steam plasma. The treated samples were prepared by dropping 1 mL of *Staphylococcus aureus* at $10^{4\text{-}5}$ CFU/mL onto agar medium and drying it. 10 mL/min water was introduced to generate steam plasma, and the treated samples were placed 10 mm from the irradiation port and irradiated with plasma for 10 and 30 seconds. The results are shown in Figure 3. It was found that even 10 seconds plasma treatment of *Staphylococcus aureus* could sterilize a wider area than the 1 mm diameter of the plasma irradiation port. Quantification of sterilization results will be reported in the presentation.

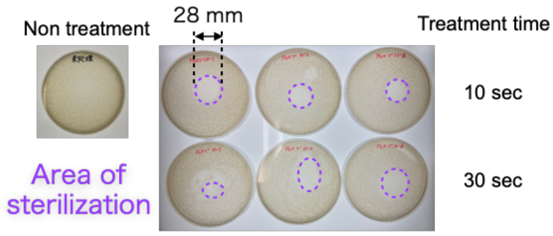

Fig. 3: Disinfection effect of *Staphylococcus aureus* by steam plasma irradiation

Design of steam plasma jet with built-in heater

It was found that the steam plasma jet introduced above can generate plasma and sterilize *Staphylococcus aureus*. However, water droplets were observed near the plasma port, probably due to the distance between the plasma port and the heating section. Since water droplets may prevent stable plasma generation, we considered that heating should be performed at a position closer to the plasma generator. Therefore, using 3D CAD, we designed a steam plasma jet with a built-in heater inside the plasma housing as shown in Figure 4. By integrating the heater into the plasma jet, we designed a device that can be heated close to the plasma generator and does not generate water droplets. In the presentation, we will report on the various characteristics of this device.

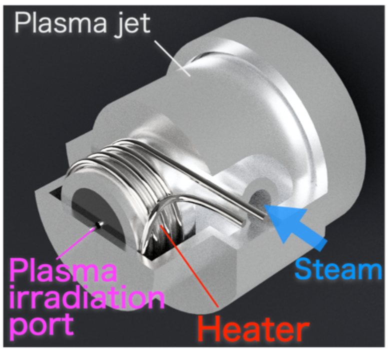

Fig. 4: Design of steam Plasma jet with built-in heater

[1] J. W. Schultze, A. Heidelberg, C. Rosenkranz, T. Schäpers and G. Staikov, *Electrochim. Acta*, **51,** (2005) 775.

[2] T. Takamatsu, H. Hirai, R. Sasaki, H. Miyahara, A. Okino, *IEEE Transactions on Plasma Science,* **41,** (2013) 119-125.