Behavior and effect of plasma after passing through the slit

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The behavior and effect of plasma during and after passing through narrow slits have been investigated. It is important to know them in case of improving a material that has three-dimensional complex structure. We have studied them by using the sample which simply represents the three-dimensional complex material. This sample consists of slit plates, spacers and a base plate. The modification sources, which modify the material, were introduced into the sample through these slit plates. The behavior and effect of the plasma were estimated by measuring the change between the contact angle before the plasma improvement and that after the plasma improvement. We treated the material in oxygen plasma mainly. This plasma was generated by a discharge reactor of induction (coil) type. It has been found that this plasma can go on along a very complex route with twists and turns and treat the part behind the material. We have found that this plasma can pass through the narrow slit, and that the selected plasma, which has the designated characteristics, can be made by using plates with slits of various shapes.

Keywords: plasma improvement, three-dimensional material, complex surface, slit, plasma behavior

1. Introduction

Surface modification of various materials with plasma has been used widely and applied to many industrial fields [1] [2]. That can improve material surface characteristics [3]. Recently necessity of treatment of the surface of three-dimensional materials increases. It is important how much area of a complicated material is improved and whether the surface is uniformly modified throughout the material. The complex surface has many narrow slits (gaps). Therefore, it is necessary to know the behavior and effect of plasma during and after passing their slits. If these things are elucidated, one can expect expansion of the applicable field of low temperature plasma. However, those problems have not been investigated too much until now.

In this study, we have investigate plasma routes and plasma effects on the surface of materials during and after passing the narrow slits when the surface modification by plasma is carried out. We pay attention to very complex routes of plasma with twists and turns in particular. A simple model [4] (sample) representing this phenomenon was developed successfully and for investigating this phenomenon in detail, it was modified by oxygen plasma generated by using the inductively coupled RF discharge [5] [6].

2. Method

2.1. Sample and materials

The three-dimensional material used in this experiment is shown in Fig.1. This simply represents three-dimensional complex materials. We call it the sample. It consists of slit plates, spacers and a base plate. The slit plates have narrow gaps. The spacers, the base plate, and the slit plates are made of aluminum. The spacers were put between the base plate and the slit plates. The modification sources, which modify the material, were introduced into the sample through these slit plates. All sides of the sample were covered with plates in order to prevent the plasma from invasion except the slits. The plasma routes are changed by increasing the number of spacers as shown in Fig.1 (a). The thickness of the spacers and the width of the slit gaps can be changed. The step number in the sample can be varied, too.

The glassy carbon plates (GC; Showa Denko, SG-3) were used in this study in order to check (estimate) the effect of surface modification. The plate is 25 mm in length, 50 mm in width and 0.6 mm in thickness. It was washed with ethyl alcohol and water, and then it was dried before plasma treatment.
Cold plasma treatment was carried out by R.F. glow discharge plasma. As shown in Fig.2, a plasma apparatus of inductively coupled was used for the treatment. This plasma apparatus has a coil (3 in Fig.2; copper $\phi 123.5$ mm), and an earth electrode (5; stainless steel $\phi 100$ mm) in a Pyrex glass discharge vessel (4; inside diameter 250 mm). R.F. power from a R.F. electric power source is supplied to the coil through a matching box (2). A High-frequency current is passed through a solenoidal coil (in fact, the coil has only one to several turns). The RF magnetic field of the current within the coil is directed toward the axis of the coil and induces a vortex electric field. This field will couple to electrons, produce ionization by electron collisions, and thus sustain a discharge. In actual experiments, a glass filled with gases is inserted into the coil so that stable discharge is sustained in the glass envelope. This type of discharge is known as inductively coupled, or H-type. Because, RF power is supplied to plasma through a glass vessel. Therefore, the self-bias does not generate in this discharge type [7] and the plasma sheath voltage on the surfaces of an electrode and a wall becomes low. Samples were put on the earth electrode. The discharge (treatment) chamber was evacuated to high vacuum in advance. The mass flow of gas was controlled in 15 ml/minute. Then, a designated power (13.56 MHz) was supplied to the coil. R.F. discharge plasma was generated and flowed toward the earth electrode. The conditions for this improvement are shown in Table 1.

**Table 1: Treatment conditions**

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<table>
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<tr>
<td><strong>Pressure</strong></td>
<td>5.32 Pa</td>
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<tr>
<td><strong>Frequency</strong></td>
<td>13.56 MHz</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>50 W</td>
</tr>
<tr>
<td><strong>Gas</strong></td>
<td>Oxygen</td>
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<tr>
<td><strong>Gas flow rate</strong></td>
<td>15 ml/min</td>
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<tr>
<td><strong>Earth electrode diameter</strong></td>
<td>100 mm</td>
</tr>
<tr>
<td><strong>Plasma treatment time</strong></td>
<td>2, 4 min.</td>
</tr>
<tr>
<td><strong>Sample</strong></td>
<td>Glassy carbon</td>
</tr>
</tbody>
</table>

Fig.1 The three-dimensional material used in this experiment

Fig.2. Plasma apparatus.
2.3 Measurement of Contact angle [8] [9]

The contact angle with water at room temperature on each plate surface before and after the plasma treatment was measured by a goniometer-type contact angle meter (Erma, G-I) in order to estimate plasma-treatment effects. A drop of water (approximately 10 µl) was put onto each GC plate surface.

3. Results and discussion

The contact angles of GC plate surface before plasma treatment was about 80°. Figures 3 and 4 show the contact angles after O₂ plasma treatment. Their angles decreased (changed) as compared with one before this treatment. To decrease the contact angle means for the plasma to modify the GC plate surface. The contact angle was 40° even if the GC plate was put on the farthest location from the third slit (placed on the deepest region from the entrance of the sample). Namely, the contact angle decreased from 80° (untreated value) to 40°. In case that the plasma improvement time was long, the contact angles after the treatment were about 20° and these values did not depend on the place. This means that the plasma reached the GC plate surface and improved the surface characteristic.

The plasma arrived at the deepest part of the sample (container). We understand that the plasma could pass through the slit of each step and reach the backside of the material. Furthermore, in these figures the contact angles have no dependence on the measured position in case that the GC plate is put on which plasma is strong or in case that the treatment time is long. However, the contact angle of the GC surface at the entrance was not very small. If the modification sources treat the surface at some point perfectly and then they remove to the next point, the contact angles from the entrance of the sample (where plasma is introduced) till that point should be 0°. It indicates the following fact. A part of the modification sources were used only at the same point the other point and flowed to the distant region from the entrance. Namely, the modification effect in the sample had a saturation value against the plasma intensity. This is the same in case the treatment time becomes long. O₂ plasma generated by the reactor of induction (coil) type can pass through the narrow slits (gap), and can go on along a very complex rout with twists and turns, and can arrive at distant points (behind the material) from the small entrance of the sample. Then, they are able to extend after passing the narrow slit. We show this phenomena in Fig.5. At another view, the
selected plasma, which has the appointed characteristics, can be made by using the narrow slit (plate with the slit of various shapes).

4. Conclusion

The plasma generated by the discharge reactor of the induction (coil) type can go on along the narrow slits, and can pass through a very complex rout with twist and turns, and can arrive at distance points from entrance. As shown in Fig.5 it is able to extend after passing through the narrow slit, and it can repeat this behavior several times. A part of the modification sources was used only at the same point and the other part flowed to the distant region from the generated part of plasma. From these things, the plasma is very effective for surface reforming of the material which has the three-dimensional complex structure.

References
8. X. Wang, N. Yoshimura, IEEE transaction on dielectrics and electrical insulation, 6 (1999)