Multi-Functionalities on the Moth-Eye Surfaces

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Moth-eye surfaces can prevent reflection with minute unevenness structure of nanometer size. A nano-imprinting process, which generates minute patterns of polymers using a mold, is a promising candidate for a high-throughput patterning process. In the present report, first of all, I describe the nano-imprinting processes based on the highly ordered anodic porous alumina. Anodic porous alumina, which is formed by the anodization of Al in acidic solution, is a typical naturally occurring ordered material. The anodic porous alumina can be formed even on the curved surface. We have been researching a continuous manufacturing process of the moth-eye surfaces on polymer films with the roll molds. Second, I mention optical characteristics of the moth-eye surfaces. Third, I report multi-functionalities of the moth-eye surfaces.

Keywords: Moth-eye, Nano-imprint, Biomimetic, Anti-reflection, Insect-slipping

1. Introduction

These days, FPD screen becomes larger and then improvement in quality of image has been greatly required. Generally, as commercial films diminishing reflection, there are an anti-reflection (AR) film and an anti-glare (AG) film. An AR film reduces reflection itself to improve the image dignity, used for plasma displays. Most of currently-marketed AR films are multilayer type. The multilayer type AR film can improve a characteristic by increasing layer numbers. As low cost is basically required for FPD, double-layers type films are usually used by the request of price. For PDP with an AR film, diminishing reflection is required. AG film makes reflection vaguely with scattering, used for a LCD display. For LCD with an AG film, improvement of clearness of a picture without whitish is required. We expected that the extremely low reflectance film enables both requirements.

Figure 1 is a photograph of a natural moth-eye structure. The moth-eye structure has an unevenness surface for anti-reflection. The structure serves as a survival mechanism by making the animal less vulnerable to predators [1]. Recently, researches and developments for the industrial production of the moth-eye structures for anti-reflection have been promoted. These researches and developments are one of the representatives in biomimetics.

Recently, we have developed the continuous photo nano-imprinting of moth-eye structures with the seamless anodic porous alumina mold. This paper explores the technology of the development.

2. Artificial moth-eye surface

Figure 2 is the image of our artificial moth-eye surface. The moth-eye surface has a minute unevenness structure of nanometer-order. There is a decrease in refractive index from 1.5 at a plastic substrate to 1.0 at the surface which is the value of air. The difference of refractive indices is about 0.5.

![Fig. 1. Natural moth-eye structure.](image)
Individual projection has the cone-like shape. The diameter is lower than 250 nm and the aspect ratio is larger than 1.

When the pitch between adjacent projections is lower than the value of wavelength of incident light divided by refractive index of substrate, reflection becomes negligible. If the wavelength is 400 nm and the refractive index is 1.5, the pitch is required to be lower than 267 nm.

3. Production process of the moth-eye alumina mold

Nano-imprinting process, which generates fine patterns of polymers using molds, is a promising candidate for a high-throughput patterning process. When the pattern for imprinting is required to be fine, the manufacture of the mold is one of the most important assignments of the technology. The mold used for nano-imprinting has usually been prepared by electron beam (EB) lithography. However, this technique has a disadvantage of low throughput for preparing molds of large-size. The anodization of Al in acidic solution forms anodic porous alumina by self-organization illustrated in Fig. 3. The porous alumina is a typical naturally occurring ordered material. The porous alumina has cells of a uniform size with hexagonal closest packing. Every cell has same size 50-500 nm controlled by Voltage and has a pore of the size of one-third in the center. Generally, carbon is used as cathode and several acids such as sulfuric acid, oxalic acid, etc. is chosen by applied voltage [2]. The nano-imprinting processes based on the highly ordered anodic porous alumina had been researched eagerly [3].

Table 1 shows the characteristics of moth-eye producing processes. Lithography enables to produce moth-eye structures at small area but too expensive. And by lithography, we can’t produce moth-eye structures at large area and on a curved surface. On the other hand, porous alumina can be formed at large area and on curved surfaces. Therefore, porous alumina can realize a big-size roll mold required for roll to roll process with high productivity.

Table 1. Characteristics of moth-eye producing processes.

| Anodic Porous Alumina | Lithography (Electron Beam Drawing, Interference exposure) |
|-----------------------|-----------------------------------------------------------|
| Structure Formation   | Possible                                                  |
| Wide Area             | Possible                                                  |
| Roll Type Mold        | Possible                                                  |
| Production Cost       | Low Cost                                                  |

After anodization of aluminum, the surface of porous alumina has many straight hales. The surface of polymers transformed with a porous alumina has many simple cylinders. More processes are necessary for the mold formation to form a moth-eye structure. Figure 4 illustrates moth-eye alumina mold production process. An oxalic acid water solution is used as an electrolyte. High purity aluminum is

Fig. 2. Image of our artificial moth-eye surface.

Fig. 3. Formation of porous alumina.

Fig. 4. Moth-eye alumina mold production process.
anode-oxidized under constant voltage to transform into porous alumina. Next, porous alumina is etched with phosphoric acid water solution to enlarge pore diameters. By repeating these processes several times, a porous alumina mold with a taper shape is fabricated.

4. Production process of the moth-eye anti-reflection films

Figure 5 shows an image of a photo imprinting process with the moth-eye mold [4]. At first, the photopolymer is filled on the mold and the mold with the photopolymer is covered with the transparent substrate for example, Pet film, PMMA film and glass sheet. Next, it is irradiated with UV light over the covered transparent substrate and last a moth-eye sheet is detached from the mold.

Figures 6(a) and (b) show SEM images of the typical taper porous alumina mold. Figure 6(a) is the cross section image and Fig. 6(b) is the surface image of the mold. Figure 6(c) shows the FE-SEM image of the typical moth eye surface on the PET film. It is confirmed that the shape of the taper porous alumina mold can be properly transferred to the moth-eye surface.

5. Continuous production process

The continuous production processes of functional films with roll molds have also been developed in these days. Figure 7 illustrates an image of a continuous roll photo imprinting. The photopolymer is spread on the PET film. And then, the film is pressed on the roll mold and next irradiated with UV light.

The moth-eye surface is made on the PET film, continuously. Figure 8(a) shows the seamless roll mold for a moth-eye surface. Figure 8(b) is the photograph of the transferred moth-eye film. The moth-eye film has transparency and the green color is come from the protection film.

6. Characteristics of the moth-eye anti-reflection film

The moth-eye AR films have lower reflection than multilayer type and have low reflection throughout visible wavelength.
Figure 9 illustrates reflectance of a multi-layer type AR film and moth-eye AR films for angle of incidence of 5 degrees. The horizontal axis is wavelength of incident light. Generally, multilayer type AR films prevent reflection mainly on the wavelength that is the highest in visual sensitivity. On the other hand, the moth-eye AR films have lower reflection than multilayer type and have low reflection throughout visible wavelength.

Contrary, the value for a hydrophilic polymer is around 20 degrees. These phenomena reflect characteristics of polymers.

We put an insect on the plastic plate and turned the plastic plate 360 degrees. When the surface was smooth, the insect was getting on the plastic board. In contrast, on the moth-eye surface, the insect slipped down from a plastic board for 90 degrees. Most insects slipped down on moth-eye surfaces.

8. Summary
1. The anodization of Al roll in acidic solution forms a big-size roll mold with anodic porous alumina on the surface by self-organization.
2. The moth-eye anti-reflection films are fabricated with the roll mold, continuously. The productive and low-cost production process is thought to be realized by developing this process.
3. The reflectance of the moth-eye anti-reflection films is under 0.4%.
4. Moth-eye surfaces have also super water-repellent property and insect-slipping property.

The study of biomimetics in imitation of creatures is becoming popular, to reduce energy cost largely and to express new functions [5]. The moth-eye anti-reflection film can realize the higher anti-reflection function than conventional multilayer type anti-reflection films with low energy production cost. The moth-eye anti-reflection film is a representative in the researches and developments of biomimetics.

Because structures of creatures are formed by self-organization, it is anticipated biomimetics becomes the important index for application of self-organization.

The living body surfaces have multi functionalities with one structure. It is hoped that the structure to be formed by technique of the biomimetics develops multi functions.

7. Multi-functionalities of the moth-eye anti-reflection film
We verified the multi-functionality of our moth-eye films: reflection, contact angles with water, insect-slipping phenomena. As for the moth-eye surface consisting of a hydrophobic polymer, the contact angle of the water is around 140 degrees. On the other hand, the value for a hydrophilic polymer is around 20 degrees. These phenomena reflect characteristics of polymers.

We put an insect on the plastic plate and turned the plastic plate 360 degrees. When the surface was smooth, the insect was getting on the plastic board. In contrast, on the moth-eye surface, the insect slipped down from a plastic board for 90 degrees. Most insects slipped down on moth-eye surfaces.

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