Effect of Hardness on Surface Strain of PDMS Films Detected by a Surface Labeled Grating Method

Norihisa Akamatsu¹, Motoyuki Fukuhara¹, Shigenori Fujikawa¹², and Atsushi Shishido*¹

¹Laboratory for Chemistry and Life Science, Tokyo Institute of Technology, R1-12, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan
²International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
*ashishid@res.titech.ac.jp

In recent years, mechanical properties of flexible materials have attracted much attention for the development of stretchable electronic devices, flexible sensors and wearable biointegrated devices that would support the future ‘Internet of things’ (IoT) and ‘information technology’ (IT). For designing advanced soft devices, there is a strong demand to quantitatively analyze the deformation behavior of soft materials. Recently, a surface labeled grating method has been developed as a new tool to quantitatively measure the bending behavior of flexible films. In this study, we investigated the effect of hardness of the film to be measured on the surface strain evaluated by this method.

Keywords: Surface strain, Flexible polymer film, Bending

1. Introduction

In recent years, flexible curved devices that are highly compatible with environment are desired in the wide range of fields instead of traditional static flat devices. Familiar examples are curved displays installed on columns in train stations and soft wearable devices for health management [1-8]. Most recently, an electrical circuit sensor is built on a bending film substrate in order to develop a device that could be implanted in living bodies [9-11]. In the development of such flexible devices, dynamic properties of materials become the key. Specifically, “strain” is essential in improving the flexibility and durability of products.

Measurements of a surface strain of deformed materials weigh in many fields. The method to measure strain is roughly divided into two types: electrical and optical. The most common electrical method is the strain gauge, which is a sensor that detects the strain by mechanical stress as changes in electrical resistance [12,13]. It can measure diverse objects such as airplanes and automobiles, and provide highly accurate yet low-cost measurements of strain. However, as the measurement range of strain is relatively narrow, it is difficult to detect the large deformation of soft materials. On the other hand, the optical method is not affected by electrical noise, and includes the photoelastic method [14,15], the Moire method [16,17], a method with Fiber Bragg Grating (FBG) sensor [18-20] and X-ray diffraction [21,22]. All of them are unsuitable to bending materials, and their systems are complex.

Recently, we have developed a surface labeled grating method, which can quantitatively evaluate the surface deformation of flexible materials [23]. In this method, a periodic structure was introduced on the surface of the material and a probe beam diffracts at the surface. When the material deforms, the period of the structure changes and it causes changes in the angle of the diffracted beam, which are utilized for the evaluation of deformation of the material.

In this work, we report quantitative evaluation of the bending behavior of polydimethylsiloxane (PDMS)-based films with various hardnesses by the surface labeled grating method. Effect of
hardness of the films on surface strain was investigated.

2. Experimental

2.1. Preparation of PDMS films

Figure 1 shows the preparation method of a PDMS film with a periodic structure. The procedure was similar to that of a previous study [23]. To obtain PDMS films with different hardnesses, a base compound and a curing agent (SILPOT 184 W/C, Dow Corning Toray) were mixed at ratios of 5:1, 6:1, 7:1, 8:1, 9:1 and 10:1, respectively. After mixing for 30 min, degassing treatment was performed for 30 min. A glass cell was prepared by stacking a glass substrate coated with silane coupler and a silicon substrate with a grating structure (a grating period of 4 µm and a depth of 500 nm) through 500-µm thick spacers. By inserting the mixture of the base compound and the curing agent into the prepared cell at room temperature, and baking for 2 h at 75 °C, a colorless transparent PDMS film with a uniform thickness was obtained.

To examine the three-dimensional shape of the film surface, the surface was observed with an atomic force microscope (AFM; Oxford Instruments Cypher SPM). A periodic structure with a grating period of 4 µm and a depth of 600 nm was observed on the film surface. The structure with the same period and the almost same depth as that in the silicon substrate was successfully formed on the surface of the prepared PDMS films.

Table 1 shows Young’s modulus of the prepared PDMS films examined by AFM. The Young’s modulus of each film was between 0.5 and 2.2 MPa. We used these films to examine the effect of the hardness of the PDMS films on the surface strain.

Table 1. Young’s modulus of PDMS films.

<table>
<thead>
<tr>
<th>SILPOT:catalyst (w/w)</th>
<th>Young’s modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:1</td>
<td>2.2</td>
</tr>
<tr>
<td>6:1</td>
<td>1.8</td>
</tr>
<tr>
<td>7:1</td>
<td>1.5</td>
</tr>
<tr>
<td>8:1</td>
<td>1.0</td>
</tr>
<tr>
<td>9:1</td>
<td>0.9</td>
</tr>
<tr>
<td>10:1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

2.2. Film mechanical analysis system

Figure 2 shows the optical setup used for surface strain analysis. Each film has been cut with the size of 15 mm × 15 mm and was set on the stage. A He-Ne laser beam (MELLES GRIOT 05-LHR-151) at 633 nm was normally sent to the center of the films. The beam was always incident to the film surface with no periodic structure. The incident beam was diffracted at the grating structure formed on the surface of the films and projected on a screen placed far from the film. The distance between transmitted and first diffracted beams was measured using a CCD.
camera. Along with bending of the film by pressing, the distance between these beams was changed. The grating period of the surface of the film and the surface strain were calculated as described in the literature [23]. The measured surface strain was evaluated as a function of applied strain, which was defined as the ratio of pressed distance to the initial film length.

3. Results and discussion

Figure 3 shows the surface strain of PDMS films with six different hardnesses measured by a surface labeled grating method. For accurate measurements, three films with the same hardness were prepared, and each film was measured for five times. The standard deviation was calculated and expressed as error bars. When applied strain was increased, the films bent greatly, and the surface strain increased. This means that all PDMS films showed tension on the surfaces as the bending angle was increased. At the same applied strain, similar values were obtained in all films with different hardnesses, indicating that there is no effect of hardness.

If the surface strain of a bent film fits with the theory of solid mechanics, it can be estimated from a thickness ($h$) and a radius of curvature ($R$) of the bent film. $R$ is expressed with the following equation (1) employed by Rogers [24]:

$$ R = \frac{L}{2\pi \left( \frac{dL}{L} - \frac{\pi^2 h^2}{12L^2} \right)} $$

where $L$ is the film length, and $dL$ is the compressed distance. The theoretical value of surface strains was calculated with the equation and also shown in Fig. 3. Rogers et al. reported the calculation of surface strain on a bent silicon wafer, assuming that the shape of a wafer becomes a sine function [24]. Larger strains of PDMS films obtained by the surface labeled grating method might be due to a difference in the shape of bent films.

4. Conclusion

We investigated the effect of hardness of the films on surface strain accompanied by bending by measuring the surface strain of PDMS films with various hardnesses quantitatively by a surface labeled grating method. As the applied strain increased, the surface strain increased due to tension. Of particular interest is that the values of surface strain were not significantly different in all films, experimentally confirming that there was no effect of hardness of the films on the surface strain.

Acknowledgements

This work was supported by the Precursory Research for Embryonic Science and Technology program, “Molecular Technology and Creation of New Functions” (no. JPMJPR14K9), and the Japan Science and Technology Agency. This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI grant no. JP17H05250 in Scientific Research on Innovative Areas “Photosynergetics.” This work was supported by JSPS KAKENHI grant no. JP17J09899. This work was performed under the Cooperative Research Program of “Network Joint Research Center for Materials and Devices.” This work was performed under the Research Program for CORE Lab of “Dynamic Alliance for Open Innovation Bridging Human, Environment and Materials” in “Network Joint Research Center for Materials and Devices.”

References