Out-of-plane Strain Measurement of A Silicone Elastomer by means of A Cholesteric Liquid Crystal Sensor

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Understanding the three-dimensional deformation of soft materials is needed for development of soft robots and flexible devices. In particular, “strain” is an important indicator reflecting the deformation behavior of the soft materials. Among strain sensors, electrical sensors are commonly used for precise detection of strain caused by stretching, bending, and twisting. However, the electrical strain sensors are limited to “surface” analysis of soft materials due to difficulty of external connections. We report here local internal strain analysis in a silicone elastomer induced by stretching via the selective reflection of a cholesteric liquid crystal (CLC) sensor. CLC has the helical geometry of LC molecules, exhibiting the selective reflection. The selective reflection wavelength depends on the helical pitch: \( \lambda = nP \), where \( \lambda \), \( P \), and \( n \) represent the selective reflection wavelength, the helical pitch, and refractive index, respectively. Various external stimuli (e.g., temperature, light, and mechanical deformation) changes the pitch (\( P \)), then resulting in the reflected wavelength (\( \lambda \)) shifts. By using this attractive optical property of CLC to detect strain, we successfully quantified stretching-induced local internal strain in a polydimethylsiloxane (PDMS) film which is a polymeric material widely used as flexible components in soft robotics and medical devices.

Keywords: Soft materials, Mechanical analysis, Internal strain, Cholesteric liquid crystals

1. Introduction

Understanding the deformation of soft materials, such as polymers, elastomers, and liquid crystals, leads to the development of soft robots and flexible devices [1-6] and medical devices [7-11]. Strain is a key indicator reflecting the deformation behavior of the soft materials [12-16]. Among strain sensors, electrical sensors are commonly used for precise detection of strain caused by stretching, bending, and twisting [16-21]. However, the electrical strain sensors are limited to “surface” analysis of soft materials due to difficulty of external connections. The local internal strain measurement enables one to further understand the deformation of soft materials, thus sensors that can analyze “internal” strain of materials are needed.

We report here local internal strain analysis in a silicone elastomer induced by stretching via the selective reflection of a cholesteric liquid crystal (CLC) sensor. CLC has the helical geometry of LC molecules, exhibiting the selective reflection. The selective reflection wavelength depends on the helical pitch: \( \lambda = nP \), where \( \lambda \), \( P \), and \( n \) represent the selective reflection wavelength, the helical pitch, and refractive index, respectively. Various external stimuli (e.g., temperature, light, and mechanical deformation) changes the pitch (\( P \)), then resulting in the reflected wavelength (\( \lambda \)) shifts. By using this attractive optical property of CLC to detect strain, we successfully quantified stretching-induced local internal strain in a polydimethylsiloxane (PDMS) film which is a polymeric material widely used as flexible components in soft robotics and medical devices.

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common elastomer that composes soft robots and flexible devices. The local internal strain analysis enables strategic design by understanding the soft material deformation.

2. Experimental

The CLC sensor was fabricated by photopolymerization of a CLC mixture, which is composed of a nematic liquid crystal (E7, LCC Co., Ltd.), an acrylate monomer (A6CB: 4′-[6-(acryloyloxy)hexyloxy]-4-cyanobiphenyl), a crosslinker (HDDMA: hexanediol dimethacrylate, Tokyo Chemical Industry Co., Ltd.), a chiral agent (S811, LCC Co., Ltd.), and a photoinitiator (Irgacure 651, Tokyo Chemical Industry Co., Ltd.) as shown in Fig. 1 [27].

![Chemical structures of the CLC components.](image)

The CLC mixture was injected into a 10 µm glass cell with rubbed polyimide in Fig. 2a. To polymerize the CLC mixture, we irradiated the glass cell with ultraviolet (UV) light at 365 nm from a UV-LED (LHPUV365-2501, Iwasaki Electric Co., Ltd.). The obtained elastic CLC film exhibited green color reflection due to the helical axis perpendicular to the film plane. The CLC film (with \( T_g < 25 ^\circ C \)) was cut into the square shape (3 mm length × 3 mm width).

We prepared PDMS films embedded with the CLC sensor in the near-surface (PDMS\textsubscript{sur}) and middle in the thickness direction (PDMS\textsubscript{mid}). First, a PDMS mixture, which contains a 10:1 weight ratio of a base compound and a curing agent (SILPOT 184 W/C, Dow corning Toray Co., Ltd.), was inserted into glass cells with the cell thicknesses of 100 µm, 750 µm, and 1400 µm. Baking the cells at 75 \(^\circ C\) resulted in colorless transparent PDMS films with the cell thicknesses. Then, the CLC sensor was sandwiched with the 100-µm-thick and 1400-µm-thick PDMS films coated with a photocurable PDMS solution (KER-4690 A/B, Shin-Etsu Chemical Co., Ltd.) and irradiated with UV light. After keeping the film for 24 h at room temperature to cure the photocurable PDMS, we obtained a PDMS\textsubscript{sur} film as shown in Fig. 2b. A PDMS\textsubscript{mid} film was prepared in the manner using the 750-µm-thick PDMS films. The PDMS\textsubscript{sur} and PDMS\textsubscript{mid} films were cut to the rectangular shape with a length of 18 mm and a width of 5 mm.

![Fabrication of PDMS\textsubscript{mid} and PDMS\textsubscript{sur} films, where the CLC sensor is embedded in the surface and center of the films, respectively.](image)

3. Results and discussion

The CLC sensor does not affect the stretching deformation behavior of PDMS films, which was confirmed by a tensile deformation test. The tensile tests of PDMS\textsubscript{mid} films and PDMS films without CLC were conducted at a strain rate of 2 mm/min with a tensile testing machine (Instron 5493, Instron Ltd.). The obtained stress-strain curve of a PDMS\textsubscript{mid} film was in good agreement with that of a PDMS film without CLC (Fig. 3a). The elastic moduli of these films became equivalent as shown in Fig. 3b.

![Stress-strain curves (a) and elastic moduli (b) of PDMS\textsubscript{mid} and PDMS without CLC.](image)
As a result, the elastic CLC sensor, which is very thin and small in size, does not disturb the stretching deformation behavior of PDMS films.

To analyze local internal strain in PDMS films during stretching, we measured the reflection spectra of PDMS\textsubscript{mid} and PDMS\textsubscript{sur} films. Both films were stretched with a tensile testing machine, and subsequently the reflection spectra at each tensile strain were collected with a spectrometer (Maya2000, Ocean Optics Inc.) in Fig. 4. Figures 5a and 5b show the obtained reflection spectra of PDMS\textsubscript{mid} and PDMS\textsubscript{sur} films, respectively. We found that stretching of PDMS\textsubscript{mid} and PDMS\textsubscript{sur} films induced blueshift of the selective reflection peak wavelength in the spectra. We observed a difference of reflection spectra between PDMS\textsubscript{mid} and PDMS\textsubscript{sur} films, which may be due to a disorder in LC. However, it did not affect strain measurements because strain was calculated from the peak wavelength shift. These reflected peak wavelength shifts were reversible over 20 stretching cycles, showing that PDMS films and the CLC sensor are firmly adhered together. When a PDMS film is stretched, shrinkage in the out-of-plane direction is simultaneously induced so that the PDMS film keeps the total volume constant. Thus, the observed blueshift is due to the decreased film thickness and subsequent shortening of the helical pitch of CLC [28,29].

Fig. 4. Optical setup for measuring reflection spectra.

Figure 5c shows reflected peak wavelength shifts as a function of tensile strain. The out-of-plane strain ($\Delta \lambda / \lambda_0$, %) was calculated from the ratio of the reflection peak wavelength change ($\Delta \lambda$) during the stretching deformation to the initial reflection wavelength ($\lambda_0$) of the CLC sensor (Fig. 5c). The reflected wavelengths shifted by $\leq 95$ nm, indicating that the out-of-plane strain in the stretched PDMS\textsubscript{mid} and PDMS\textsubscript{sur} films was approximately 17% at a tensile strain of 50%. This result showed that the out-of-plane strain of PDMS\textsubscript{mid} films coincides with that of PDMS\textsubscript{sur} films. We revealed that local internal strain in the PDMS films during the stretching deformation was successfully analyzed by means of the CLC sensor.

Fig. 5. Reflection spectra of the stretched PDMS\textsubscript{mid} (a) and PDMS\textsubscript{sur} (b) films at each tensile strain. (c) Peak wavelength shifts of the selective reflection and the out-of-plane strain in stretched PDMS\textsubscript{mid} and PDMS\textsubscript{sur} films as a function of tensile strain.

4. Conclusion

We prepared PDMS films embedded the CLC sensor, and measured local internal strain of PDMS films during the stretching deformation. The elastic CLC sensor, which is very thin and small in size, does not disturb the PDMS deformation. The out-of-plane strains of the PDMS films in the near-surface and middle in the thickness direction became coincident, which was verified by the CLC sensor. The CLC sensor has the potential to measure local internal strain in bending and twisting. The local internal strain analysis using the CLC sensor therefore will further elucidate the soft material deformation behavior and promote the development of high durability soft robots and flexible devices.

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