Real-Time Analysis of Surface Strain in Bending Films for Development of Flexible Devices

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ABSTRACT

Preventing fracture in materials and devices integrated on largely bending film substrates has attracted much attention due to the rapid development of flexible electronics and soft robotics. We propose the surface-labeled grating method that is the fundamental and efficient technique for measuring surface bending strains with a single-nanoscale (<1.0 nm) in real time [1].

1 Introduction

Even by deformation at the nanometer scale, strain above the fracture limits inevitably damage any materials, which is the difficulty encountered in developing functional materials for soft robots, biomedical systems, and flexible electronic devices [1-4].

Herein, we present the surface-labeled grating method capable of real-time measuring the surface bending strain in various flexible film substrates, with high accuracy and precision in a single nanometer scale (<1.0 nm). We successfully determined a fracture limit of functional materials integrated on flexible film substrates via the quantitative analysis of their surface bending strain, merely by attaching a soft optical grating label on surface of target materials and measuring the diffraction angle of a probe beam. Furthermore, the surface bending strain was reduced by 50% through multi-layering of the film substrate, maintaining the original thickness; the surface bending strain remained well below the fracture limit. The use of the film substrate with reduced strain successfully suppressed the cracking of hard coatings and the breakdown of an organic transistor [1].

2 Experiment

To measure the surface bending strain, a thin polydimethylsiloxane (PDMS) label with an optical grating (period Λ = 4 μm) was attached to the surface of a target film, as illustrated in Figure 1a. A He–Ne laser beam (wavelength: 633 nm) was incident on a labeled film substrate placed on the laboratory-made optical setup (Figure 1b). The laser beam passing through the film diffracted depending on the grating period; thus, the increase in an applied strain ($\Delta L/L$: L is the distance between the film edges) resulted in extensive bending of the film and simultaneously changed the distance between diffraction beams (D) on the screen in Figure 1c. This change in the diffraction angle (α) allowed the real-time quantitative determination of surface bending strain induced in the film, in the same manner as we previously reported [2,3]. However, the previous procedure required the direct inscription of an optical grating on the surface of target materials using photochemical or lithographical technologies, thus limiting versatility of the method. To overcome this limitation, we employed a grating label that can be formed directly on various target films. The label is very thin (≤1 μm) and soft (2 MPa modulus); hence, it never disturbs the bending of the films, enabling accurate measurement of the surface bending strain in various materials.

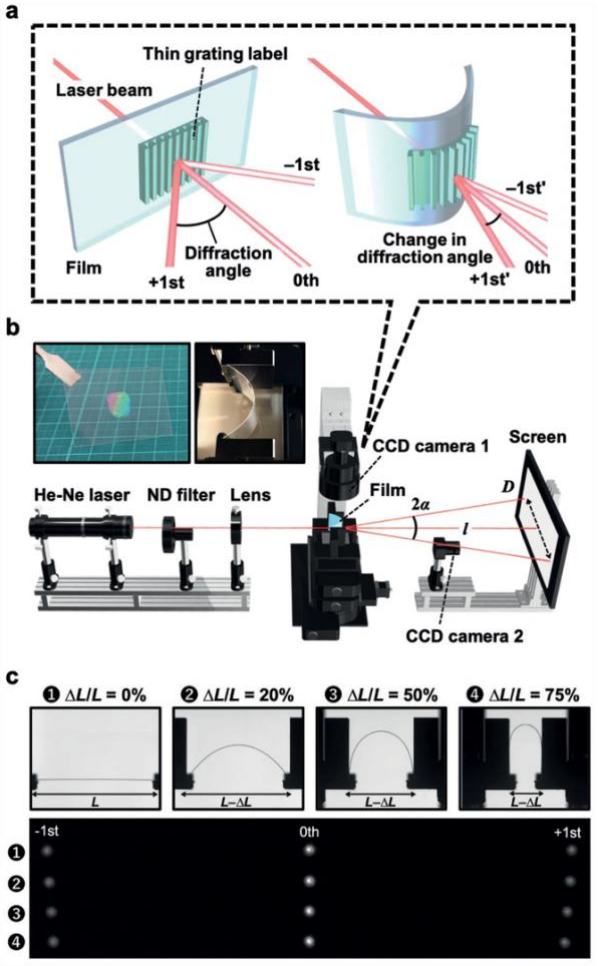

Fig. 1 a) Schematic of underlying principle of surface bending strain analysis using a soft, thin grating

label, termed surface-labeled grating method. b) Optical setup used for surface strain measurements of bent films. The symbols α, *l*, and *D* represent diffraction angle, distance between the surface of the labeled film and the screen, and distance between the diffracted beams, respectively. c) Profiles of films obtained using a charge-coupled device (CCD) camera 1 during bending process (top). The corresponding applied strains (∆*L*/*L*) defined as the change in the distance of the film ends (∆*L*) per the initial distance of ones (*L*) are indicated on the images. Images of diffracted and transmitted beams corresponding to the respective applied strains are observed on a screen during bending process using CCD camera 2 (bottom). Reproduced from [1].

3 Results and Discussion

Figure 2a shows the surface bending strains in commercially available polyethylene naphthalate (PEN) films, as a common substrate used in flexible electronic devices. As the applied strain imposed on the PEN films with various thicknesses increased from 0% to 75%, the bending strains on the outer surfaces gradually increased from 0% to 0.7% (75 μm thickness), to 1.1% (100 μm thickness), and to 1.6% (125 μm thickness); conversely, the strains on the inner surfaces gradually decreased from 0% to −0.7%, −1.1%, and −1.6%, respectively. These results indicate that the outer and inner film surfaces are subjected to tension and compression as expected. The error bars showed only < ±0.05% strain, indicating that the surface-labeled grating method provides the precise surface bending strains.

Compared to existing optical methods, the surface-labeled grating method is more versatile with respect to targeted materials because the label is merely attached to any surfaces as required; in the case of the others, targeted materials have to exhibit crystallinity or optical anisotropy, which significantly limits the types of measurable materials. To demonstrate this versatility, we measured the surface bending strains of three representative samples: a cyclo-olefin polymer (COP) film exhibiting amorphousness and no optical anisotropy, a polyimide (PI) film with colored appearance, and a glass plate as an amorphous inorganic material (Figure 2b).

Remarkably, these strains are comparable to a nanoscale deformation. Figure 2c shows the relation between displacement (|∆Λ|) and surface strain in the 75 μm thick PEN film. The displacement is on the nanometer scale (0.5–1.0 nm), even including error bars. Such quantification for surface bending strain in polymeric materials with a single nanoscale resolution has never been achieved through the other methods. Also note that the surface bending strain in the film remained unchanged even after the 100 000th bending (Figure 2d). Hence, the surface-labeled grating method is the powerful tool for achieving the accurate and precise measurement of the surface bending strain in the bending target flexible films with significantly high resolution and repeatability.

To prove the accuracy of this method, we used the modified Elastica theory which is an analytical model of curvature for a single-layer bent film that we recently reported [3]. As shown in Figure 2e, let *s* be the distance along the axis of the bent film from origin *O*; the expression for the angle between the line tangent to the bent film and the *x*-axis is θ (*s*). The angle θ (0) is also expressed by β, dividing the bending of a film into two groups: $0 \le \beta < \pi/2$ (Figure 2e top) and $\beta = \pi/2$ (Figure 3e bottom). These calculated results were consistent with the experimental curvatures. By substituting theoretical curvatures into $\varepsilon_s = h/2R$ (where ε_s denotes surface bending strain), we subsequently obtained the theoretical surface bending strains. All the theoretical surface bending strains in the polymer films were entirely consistent with those obtained experimentally (Figure 2a,b). The surface bending strain in the thin glass obtained from the experiment was also consistent with that calculated from the Elastica theory (Figure 3b) [3,5]. These consistencies clearly indicate that the surface-labeled grating method yields accurate strains, suggesting that this method has a considerably wide range of measurable materials compared with the conventional optical methods.

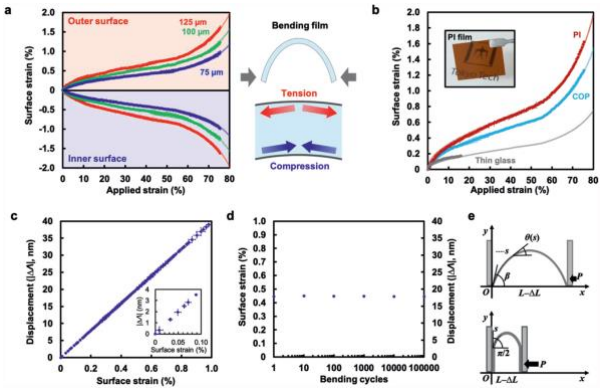

Fig. 2 a) Surface strains measured by the surface-labeled grating method (plots) and theoretically calculated from the modified Elastica theory (lines) during bending of PEN films (left). Blue, green, and red correspond to films with thicknesses of 75, 100, and 125 μm, respectively. Red and blue areas show strains in outer and inner surfaces, respectively. Error bars represent standard deviations of the measurement results. Schematic of surface strain induced in PEN films by bending (right). b) Demonstration of versatility for surface-labeled grating method. Surface bending strains in the 125 μm thick PI film (wine red), the 100 μm

thick COP film (sky blue), and the 55 μm thick glass plate (gray). Plots and lines correspond to the values measured using surface-labeled grating method and the theoretically calculated ones, respectively. Inset shows image of the PI film. c) Displacement as a function of surface strain in the bending PEN film with a thickness of 75 μm. Inset shows a magnified view of the surface strain in the range of 0 to 0.1%. d) Surface strain in 75 μm thick PEN films as a function of bending cycles at an applied strain of 50%. e) Analytical models of bent films induced by axial compression *P*. Top: model for bent film when the film surfaces are not in contact with the film holders ($0 \leq \beta < \pi/2$). Bottom: model for bent film when the bent film surfaces are in contact with the film holders ($\beta = \pi/2$). Reproduced from [1].

4 Conclusions

The surface bending strains in various flexible materials were quantitatively analyzed by the surface-labeled grating method with a single-nanometer resolution. The real-time strain analysis we achieved has multiple benefits: high resolution, precision, and a wide range of measurable materials. The reliability of the measurements was confirmed using the modified Elastica theory. Although only transparent materials were tested using the transmissive diffraction system in this study, the development of a reflective diffraction system will expand the applicability of this method to non-transparent materials. The surface-labeled grating method, therefore, is a practical tool that allows the analysis of surface bending strain in the elaborately designed materials such as programmable materials, hybrid composites, and multi-layered structures, and contributes to the development of advanced flexible electronic devices and soft robots.

References

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