Surface Strain Analysis of Bending Substrates for Design of Flexible Devices

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ABSTRACT

Fracture and fatigue of bending flexible materials and devices prevent their commercialization. The problem is that quantitative understanding has not been explored on bending behavior of materials and devices. Here we report quantitative analysis of surface strain of bending substrates by a surface labeled grating method.[1,2] We built up a new optical setup to enable surface strain analysis. A soft thin grating label made of PDMS was attached on the target substrate, and a He-Ne laser beam was incident on the film during bending. Diffraction angle was precisely monitored to estimate surface strain. Surface strain in bending was able to be real-time evaluated with high accuracy from 0% to 10% without any information of the substrate such as Young's modulus, thickness and chemical structure.[1]

1 INTRODUCTION

Fracture and fatigue of bending flexible materials and devices prevent their commercialization. The problem is that quantitative understanding has not been explored on bending behavior of materials and devices. Here we propose a surface-labelled grating method that can be applied to any largely bending film, which allows separate probing of the front and back surfaces in two dimensions. The basic concept relies on a 1D or 2D diffraction grating that is linked selectively to either surface of the target material. The surface strains are then visualized by monitoring the diffraction angles of a probe laser beam. A separate elastomeric surface grating label can be attached onto either of its surfaces. Surface-relief gratings on low-modulus, amorphous poly(dimethylsiloxane) (PDMS) elastomers, in addition to being commonly used as stretchable-electronics substrates, are suitable as externally attachable surface labels.

2 EXPERIMENT

We employed PDMS-based relief gratings as surface labels as they can easily be attached to (and removed from) any surface to perform a strain analysis (*e.g.*, in stretchable electronics). This was inspired by our previous work on holographic materials.[3] The PDMS gratings can be conveniently fabricated by adapting techniques from a soft-lithographic approach (Fig. 1a), *i.e.*, by (i) adding a layer of prepolymer over a silicon master relief (the layer thickness can be controlled with appropriate spacers and a cover glass); (ii) polymerizing at elevated temperature to obtain the solid, crosslinked PDMS elastomer; and (iii) releasing the elastomeric surface-relief grating from the master. Such PDMS labels are isotropic, transparent, and of high optical quality (Fig. 1b). A 3D atomic force microscopy (AFM) image of an example PDMS grating is shown in Fig. 1c. At this stage we have only used a 1D surface label to validate the concept; however, it is straightforward to generalize the analysis to 2D by simply using a different master relief. An additional benefit for strain analysis is the softness of PDMS (elastic modulus *ca.* 2.1 MPa), which ensures that the surface label does not disturb the strain evaluation of the target material.

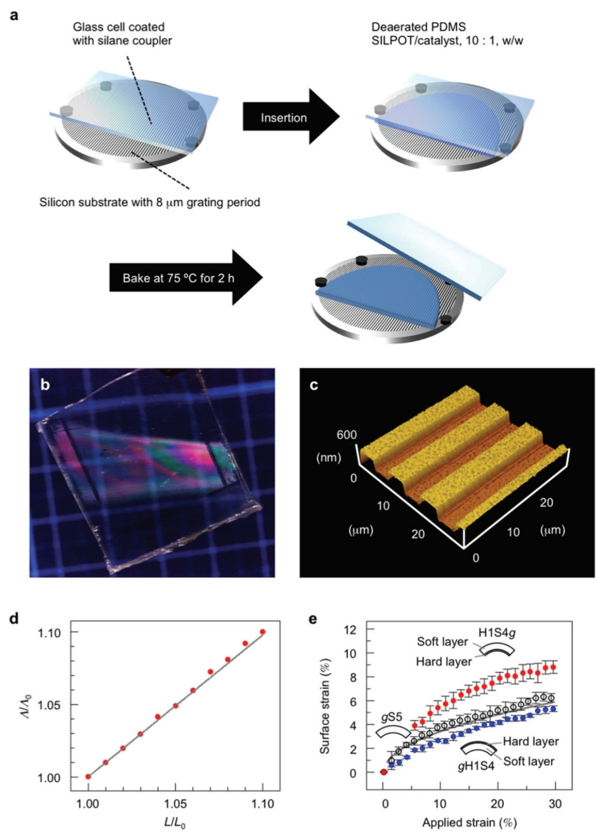

Fig. 1 Surface labelling based on surface-relief gratings in PDMS films.[1]

(a), Fabrication principle of PDMS-based surface-labelled gratings. For single-layer films, the glass cell is prepared using 500 μm spacers between a glass substrate and a silicon substrate, for a surface-relief grating with 8 μm periodicity. A mixture of Sylpot and catalyst (10:1 (w/w) for the soft film and 5:1 (w/w) for the hard film) was injected into the cell by capillary force and baked for 2 h at 75 °C. After removing the film from the substrates, a free-standing PDMS film was obtained. (b), Photograph of a 500-μm thick surface-labelled PDMS film. (c), An AFM image of a surface-relief grating on a PDMS film. (d), Simultaneous measurement of the strains generated under external mechanical stress using a thermomechanical analyzer (L/L_0). The surface-labelled grating method (L/L_0) shows that the strains match perfectly at least up to 10.0%. (e), Strains at the outer tensile surfaces of mechanically bent single-layer and bilayer (with hard and soft layers) PDMS films as a function of the ratio of pressed distance to the initial film length (applied strain). The grey line is the calculated surface strain. Mean values of n = 5 and 3 films are plotted for single-layer and bilayer films, respectively. Error bars represent standard deviation.

3 RESULTS and DISCUSSION

Fig. 1d shows control measurements in which the strain (under external mechanical stress) is simultaneously monitored using a thermomechanical analyzer (TMA) and the surface-labelled grating method. The strain values measured with these two independent methods match perfectly up to at least 10.0% strain, which is the limit of our TMA instrument. Fig. 1e provides the strains at the outer tensile surfaces of mechanically bent soft single-layer (elastic modulus: 0.44 MPa) PDMS films, as well as a bilayer PDMS film composed of hard and soft layers. All the bent films showed the same shape.

For the single-layer PDMS films (gS5), the surface strains can be considered “conventional”, *i.e.*, the surface strains measured by the surface-labelled grating almost agree with those calculated by equation employed by Rogers and coworkers.[4]

In contrast, the bilayer films exhibited anomalous tensions compared to the single-layer PDMS film. The hard layer in the surface decreases the surface strain in outward bending (gH1S4); however, the surface strain is increased in inward bending of the hard layer (H1S4g). Hence, the surface strains depend markedly on the details of the materials design, as can be conveniently monitored with the surface-labelled grating method. The bent shape of bilayer films was the same in appearance as mentioned above. Hence the equation that describes the bent shape of single-layer films with the sinusoidal curve might be also applied to the bilayer films. It is noteworthy that, unlike with conventional mechanics calculation, this method of analyzing the surface strain does not require knowledge of any materials properties, such as the film thickness and Young's modulus. This provides us with a facile analysis technique for multiple-layered films composed of various organic and inorganic materials. We believe this method is a useful tool for use in surface-strain control for flexible films. For example, it allows us to design surface-strain free bending films or films with positionally controlled surface strain, which are important for flexible electronics and biomedical applications. Finally, a strain analysis of a mechanically-bent poly(ethylene naphthalate) (PEN) film labelled with a PDMS layer was performed. This result also serves to highlight the method's ability for analyzing the surface strains of various films that may consist of metal, glass, and hybrid materials, in addition to common polymer films. As long as the film surface is flat enough to transmit or reflect a probe beam, strain can be measured even with light absorbing materials. Resolution of strain mapping basically depends on diameter of the probe beam, while can be further downsized by combination with a designed surface label with several tens micrometres. In this study, with the smallest applied strain, the surface strain of the films exceeded 0.5% because of the size and thickness of the films. By employing larger-area, thinner films, smaller surface strain will be measured.

4 CONCLUSIONS

The main purpose of the present paper was to introduce a simple surface-strain analysis technique based on surface-labelled gratings, which we used to pinpoint the delicate nature of strongly bending soft-matter films. In azobenzene-containing liquid-crystalline elastomers, the macroscopic deformation is dictated by a complicated interplay between the optical and mechanical properties (leading to compression-compression mode bending upon photoirradiation). Surface-labelled gratings provide a facile tool that can be used for a detailed experimental analysis of their mechanical/optomechanical response in two dimensions. In substrates used in flexible/stretchable electronics, PDMS-based external surface labels can be used to experimentally verify that the strains acting on the active components are within safety limits. The method can also be used for spatial strain mapping for samples with complex curvature, or can be applied to non-transparent objects, such as thin metal films, by monitoring the strain-induced changes in diffraction angles in a reflection mode.

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