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Analysis of Neutral-Plane Splitting for Foldable Displays Using Digital Image Correlation Method

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ABSTRACT

Strain control with neutral-plane splitting is an essential technology in designing foldable displays. We established a method for analyzing continuous changes in cross-sectional strain distribution throughout the folding process. Digital image correlation (DIC) method with an optical microscope successfully revealed that the neutral-plane position changes with the folding radius.

1 INTRODUCTION

Mobile communication devices must be practical and portable; however, conforming to both requirements may be complicated. In particular, for mobile devices, while large displays are practical, small displays are more portable. In foldable displays, the active display size is transformed by folding when necessary.

A foldable display experiences bending stress depending on its distance from the neutral mechanical plane, where the bending stress is zero. Two well-known methodologies are employed for suppressing bending stress for organic light-emitting diode (OLED) displays. The first approach focuses on reducing the display's thickness. However, an OLED display usually contains several functional films excluding the OLED panel. The other methodology involves placing the neutral plane around a weak layer of the OLED display such as the thin-film encapsulation or thin-film transistor layer, using additional films. However, this solution must finely balance the trade-off between the functionality and the foldability.

Neutral-plane splitting is a promising alternative technology for foldable displays [1–3]. Their configuration that are based on the concept of neutral-plane splitting possesses many neutral planes of multilayers, whereas in the conventional theory, multilayers only contain one neutral plane. Therefore, the position of the neutral plane is determined in each film or submodule (collectively for some films) in neutral-plane splitting, providing considerable freedom in designing a foldable OLED display.

Digital image correlation (DIC) method is a powerful tool for the analysis of strain distribution [4]. The strain distribution of the specimen with a random pattern is quantitatively calculated by tracking the subsets consisting of multiple pixels between the two images recorded before and after deformation as shown in Figure 1. The subset has specific luminance distribution, so it is possible to track the subset position before and after the deformation. The strain distribution is calculated from the change in the relative position of multiple subsets caused by the specimen deformation.

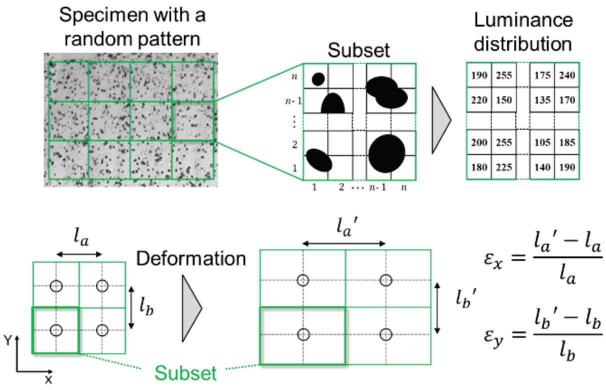

Figure 1. Schematics of subset tracking and strain calculation.

SEM-DIC method using a scanning electron microscope (SEM) was recently applied to study the cross-sectional strain distribution in flexible devices [5]. However, SEM-DIC restricts the specimen size and the analysis scale. For practical analyses, the dynamics of the strain distribution must be evaluated throughout the folding process without constraints in specimen size and analysis scale. In this report, we successfully established the strain analysis method for continuous changes in cross-sectional strain distribution throughout the folding process using optical microscopy and DIC method to clarify the details of neutral-plane splitting.

2 EXPERIMENT

Three specimens were prepared with a random pattern in the cross-section, first, a 100-μm-thick PET film, second, two 100-μm-thick PET films glued with 100-μm-thick adhesive (three layers) and third, three 100-μm-thick PET films glued with two 100-μm-thick adhesives (five layers) as shown in Figure 2. The elastic moduli of the adhesive and the PET film were 38 kPa and 9 GPa, respectively, and the size of the three specimens was 50 × 20 mm.

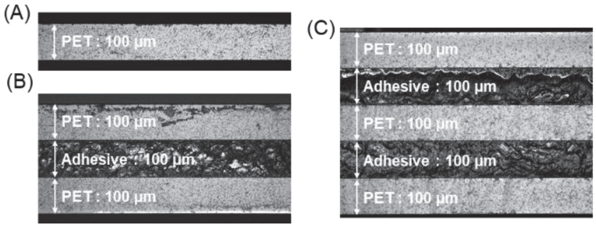

Figure 2. Cross-sectional images of three specimens with a random pattern, (A) a PET film, (B) two PET films glued with low-elastic adhesive (three layers), (C) three PET films glued with two low-elastic adhesives (five layers).

Figure 3 (a) shows a schematic illustration of the image acquisition process using an optical microscope. The strain distribution was analyzed with acquired images as the folding radius was continually changed. The folding radius (R) was defined as half the distance between the two plates, as shown in Figure 3(b), and the strain was calculated using DIC software.

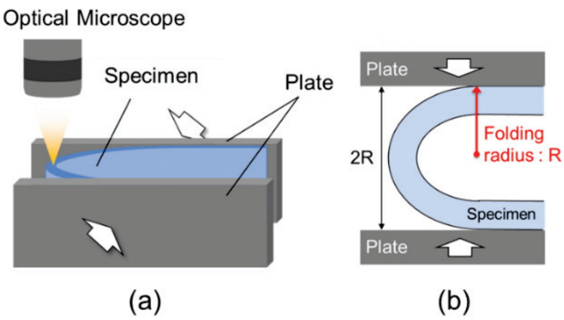

Figure 3. Schematics of (a) experimental geometry and (b) the definition of folding radius (*R*).

3 RESULTS and DISCUSSION

3.1 Validity of Cross-Sectional Strain Distribution Using Optical Microscopy and DIC Method

Figure 4 shows the DIC image for the cross-section of the 100-μm-thick PET film, for a folding radius of 6 mm. The magnitude of the folding strain in the circumference direction is indicated in different colors, where red (positive) and blue (negative) indicate the tensile and compressive strain, respectively. The neutral plane, where the folding strain is zero, is indicated in green. The strain distribution was determined using optical microscopy and DIC method.

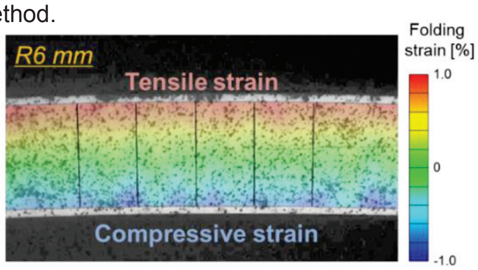

Figure 4. DIC image of cross-sectional strain distribution for a folding radius of 6 mm.

Figure 5 shows the quantified folding strain in the circumference direction as a function of distance from the bottom surface of the PET film with five lines indicated in the figure 4. The standard error for the approximate line corresponding to the average strain distribution was ±2.3 μm. Although it is widely accepted that the neutral plane is located at the film center in the thickness-direction under one material folding, the experimental results in this work indicate that the neutral plane was located 7 μm inside from the film center in the thickness-direction. To investigate this discrepancy, the strain distributions were calculated using a three-dimensional finite element method (3D-FEM). Figure 6 shows X strain at the folding tip for a folding radius of 6 mm with 3D-FEM. The neutral-plane position at the edge was different from that at the center in the width-direction.

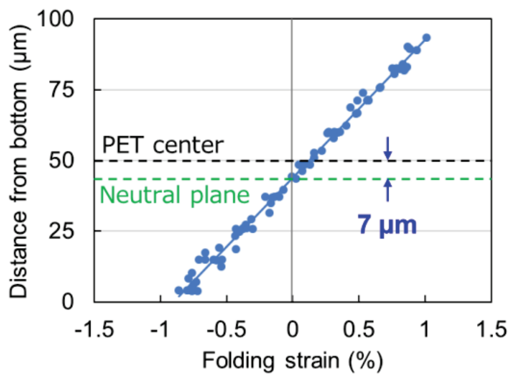

Figure 5. Folding strain in the circumference direction as a function of distance from the bottom surface of the PET film for a folding radius of 6 mm.

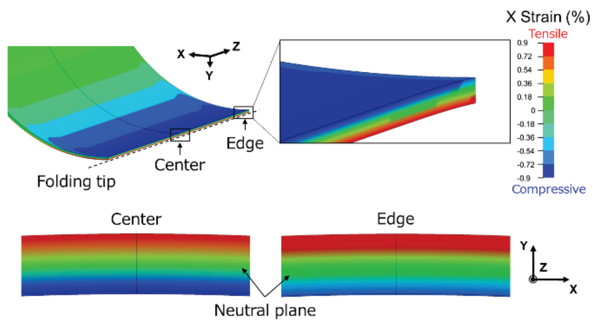

Figure 6. *X* strain distribution at the center and edge in the width-direction at folding tip for a folding radius of 6 mm with 3D-FEM.

Figure 7 shows the comparison of the strain distributions between DIC and FEM simulations as shown in Figure 5 and 6, respectively. FEM results show that the neutral plane at the width-direction center was located at the center toward thickness-direction, whereas the neutral plane at the width-direction edge was located 8 μm inside from thickness-direction center. Thus, the neutral-plane position results obtained using DIC method agree very well with those obtained by 3D-FEM at the width-direction edge. It is reasonable because DIC analysis was performed at the width-direction edge. This result indicates that DIC method with an optical microscope is effective for the strain distribution analysis of foldable displays.

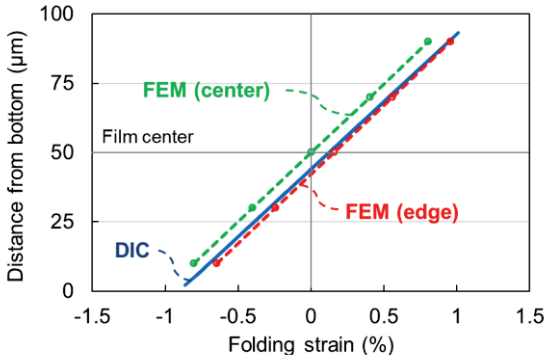

Figure 7. Comparison of folding strain, *X* strain, distributions between DIC and 3D-FEM simulations.

3.2 Continuous Observation of Neutral-Plane Splitting throughout the Folding Process

Figure 8 shows the DIC images of the cross-section of the specimen (B), two PET films glued low-elastic adhesive (three layers), during the folding process. Using optical microscopy and DIC method, we successfully analyzed the continuous changes in the strain distribution throughout the folding process. It was impossible to visualize the strain distribution of the adhesive layer due to the 3D deformation of the adhesive. The neutral planes, where the folding strain was zero, exist both inside and outside the PET films for a given folding radius, which indicates that neutral-plane splitting occurred.

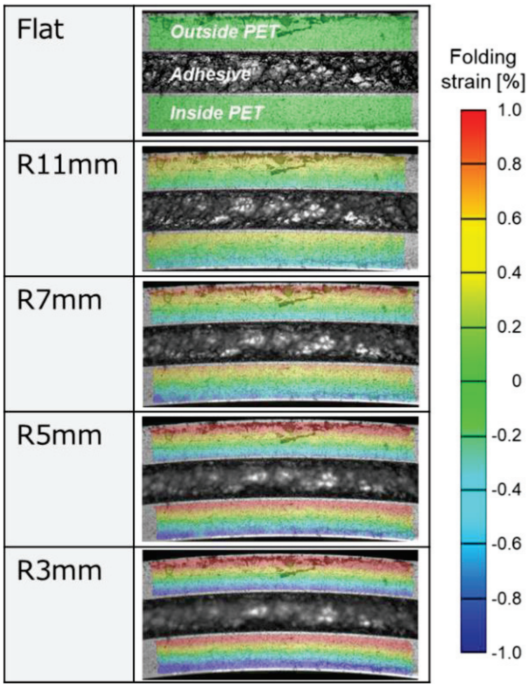

Figure 8. DIC images of cross-sectional strain distributions for folding radii of 11, 7, 5, and 3 mm.

Figure 9 shows the positions of the neutral planes of the inside and outside PET films as a function of the folding radius. The positions of the neutral planes approach the center of each PET film as the folding radius decreases. Generally, in perfect splitting, the neutral planes are located at the thickness-direction center of each film, thus the neutral planes come close to the positions in perfect splitting as the folding radius decreases. At first sight, it was strange that one neutral plane was asymmetrically divided into two neutral planes of the inside and outside PET films. However, this phenomenon is reasonable if we take into consideration the shift in the position of the neutral plane to the bottom surface at the width-direction edge as shown in Figure 7.

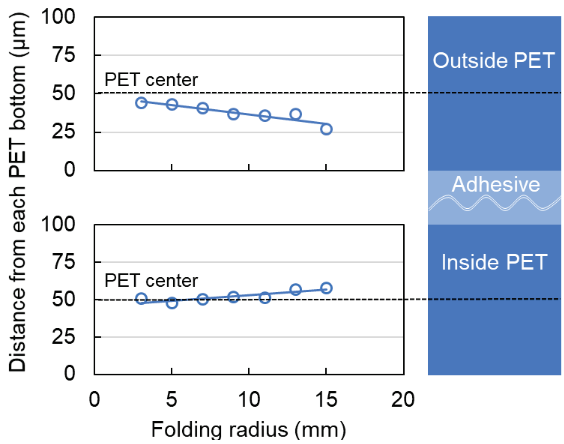

Figure 9. Positions of neutral planes for inside and outside PET films for folding radii of 13, 11, 9, 7, 5, and 3 mm.

3.3 Relationship between Neutral-Plane Splitting and Slip of Two Films

In principle, when the neutral plane splits, a shift in position between the inside and outside PET films will occur. To verify this, using specimen (B), two PET films glued with low-elastic adhesive (three layers), the relationship between the amount of shift and the folding radius was evaluated. As shown in Figures 10 (a) and (b), the shift amount was calculated from the displacement of the subsets in the tracking area with the DIC images recorded before and after folding at multiple locations from the folding tip to the PET edge. Figure 11 shows the results of the shift amount between the inside and outside PET films for folding radii of 3, 5, and 7 mm. The shift amount was zero at the folding tip and increased as the measurement location moved away from the folding tip. If the neutral plane splits perfectly, the maximum value of the shift amount is calculated to be 314 μm from the gap of the radius between the inside and outside PET films. The maximum shift amount increased with decreasing in the folding radius, which clarifies that the neutral-plane splitting proceeds as the folding radius decreases. It is also noteworthy that the shift amount decreased in the flat area, which can be ascribed to the relaxation of the shear deformation of the adhesive.

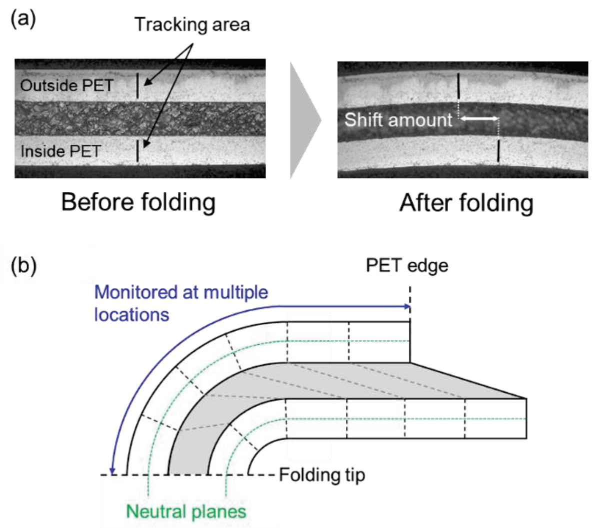

Figure 10. (a) Definition of shift amount between inside and outside PET films. (b) Schematic of measurement area.

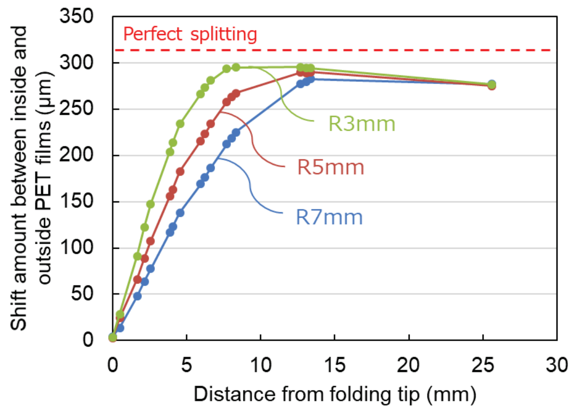

Figure 11. Shift amount between inside and outside PET films as a function of distance from folding tip for folding radii of 3, 5, and 7 mm.

3.4 Verification of Neutral-Plane Splitting for More Realistic Model Simulating Foldable Display Structure

Figure 12 shows the DIC image of the cross-section of specimen (C), three PET films glued with two low-elastic adhesives (five layers) for a folding radius of 5 mm. The neutral-planes exist near the center in the thickness-direction of each PET film, which indicates that neutral-plane splitting occurred almost perfectly for more realistic model simulating foldable display structure. Besides, the same tendency for the neutral-planes to approach the position of perfect splitting as the folding radius decreases was confirmed as for the three layers.

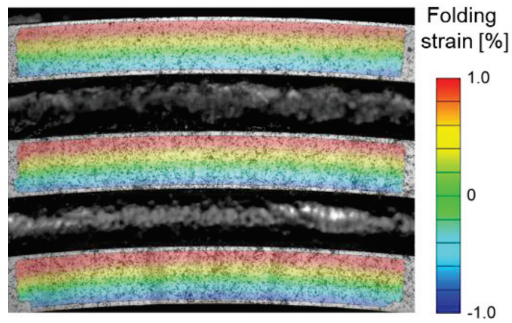

Figure 12. DIC image of cross-sectional strain distribution for a folding radius of 5 mm.

4 CONCLUSIONS

We established a method to conduct strain analysis for continuous changes in the cross-sectional strain distribution throughout the folding process using optical microscopy and DIC. This method clarified that the neutral planes of PET films glued with low-elastic adhesive approach the positions in perfect splitting as the folding radius decreases. The result was also supported by DIC evaluation of the shift amount between the inside and outside PET films at multiple locations from the folding tip to the film edge throughout the folding process.

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