Quantitative Assessment of Hinge Creases in Folding Devices

Katherine Anne Lindberg, Dragan Pikula, Joy Banerjee
Corning Research and Development Corporation, Corning NY

Abstract
We present a novel, quantitative method for assessing cosmetic defects in folding devices, with a primary focus on hinge region creases which induce tactile and optical distortions. The technique applies to a range of devices, including foldable phones and IT devices showcasing diverse hinge designs from elliptical to tear drop.

Author Keywords
Hinge Crease; Foldables; Flexible Displays; Metrology; Data Analysis; Ultra-Thin Glass; Composite Display.

1. Objective and Background
Folding devices on the market utilizing a combination of polymeric and ultra-thin glass components in the display cover stack include cosmetic defects such as hinge region creases that result in a tactile response of a non-flat surface when moving across it and optical distortion of the reflected and transmitted light due to surface modulation. Examples of folding devices include flip and booklet styles from Samsung, Motorola, Oppo, etc. in the handheld sector where hinge designs can be non-tear drop (conehead; elliptical; U-bend) and tear drop (water drop) (1). This defect increases in magnitude with repeated folding and unfolding of the device as well as time under fold.

An example of this issue is illustrated in Figure 1. The optical artifact is a distortion of reflected light akin to a funhouse with distorting mirrors that is observed by the user in the off state. This distortion is a function of crease depth and crease width, both of which are dependent on the materials in the display cover stack and hinge design.

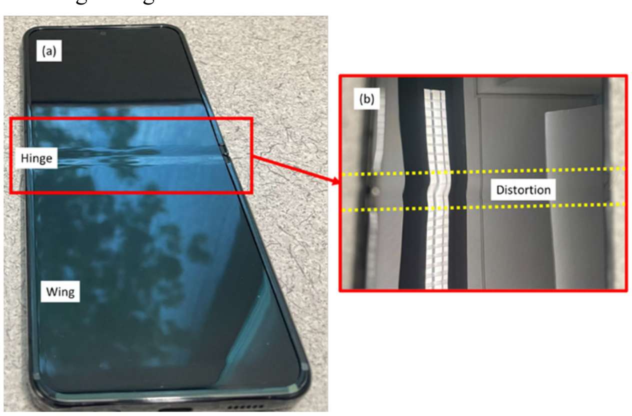

Figure 1: A representative folding device module in the off-state (a) shows distortion of an external environmental reflection in the hinge region, with a secondary image in (b) showing distortion of a linear ceiling light in the hinge region.

Quantitative assessment of the crease is required outside of the qualitative and subjective ranking of visual perception of the optical artifact observed from reflected sources in the off state (2). This allows for rigorous comparisons of stack design, hinge design, or other design characteristics which influence the crease shape (3). The extent of the distortion increases with crease depth and smaller radius of curvature (higher diopter; 1/R). Therefore, the gradient/slope and the curvature of the shape can be descriptive metrics for distortion.

2. Method
Characterization of creases in display cover stacks used in foldable devices requires surface shape characterization. Several commercially available methods exist for this type of measurement. These include 2D profiling methods such as stylus profilometry, optical profilometry, and 3D surface mapping such as contact coordinate measuring machine (CMM) measurement, optical CMM, deflectometry, and other methods. Here, we utilized phase measuring deflectometry which has several advantages such as short measurement cycle times (<30s), high data density (~300 µm x 300 µm pixel size), and is a non-contact measurement (4).

Samples are measured using deflectometry to obtain the surface shape. This surface data is then post-processed to obtain surface gradient (slope), and curvature. Corresponding line profiles extracted from these 2D maps are used to obtain metrics such as peak-to-valley of the relevant profiles.

3. Results and Discussion
Due to the non-uniformities of the hinge crease features and surrounding flat (wing) regions, higher order shape metrics such as gradient or curvature are useful in characterizing hinge creases. Figure 2a shows an example of the surface shape (height) of a new bendable device cropped to the region of distinctly identifiable crease after 24 hours of static bend. Horizontal profiles from the shape map depict the cross section of the crease at a specific location along the crease length and can be used to extract metrics like crease depth and crease width. An example of one such line profile, extracted at the location of Y=30 mm, is shown in Figure 2b. The crease depth is defined as the largest adjacent peak-to-valley of the shape profile. Crease width can be defined in several ways, including peak-to-peak width or the width between points from the crease center to where the surface height reaches some threshold.

Processing of the surface map yields several additional maps including the gradient, where the absolute value of the gradient is shown in Figure 2c, with corresponding line profile shown in Figure 2d. The absolute gradient map shows a pixel-by-pixel slope change for the shape where the rendered units are mm/mm and 0.0175 mm/mm slope change corresponds to 1 degree slope angle. The gradient value of each pixel is the RMS of the slope in the X and Y vector directions. This map shows two regions of changing slope to the top and bottom from the bottom of the crease. The region at the bottom of the crease and at the wings have low levels of slope. Gradient is a reasonable metric for shape evolution into the center of the crease, but it doesn't describe the entire crease especially at the bottom (peak negative curvature). However, the peak gradient does show the highest rate of change in the shape within the crease leading to optical distortion.

ISSN 0097-996X/25/5602-1057-$1.00 © 2025

Curvature is a second-derivative form of the shape that describes optical lensing for reflected light. The units of curvature are diopters (D) through which radius of curvature can be calculated as 1/D. In the case of determining curvature of a surface, there are two principal, orthogonal curvatures with independent signs and magnitudes. Negative and positive curvature values provide information on concave or convex aspects of the surface, respectively. Mean curvature, shown in Figure 2e, and the line profile shown in Figure 2f, is the average of the principal curvatures. In the case of crease features, where the features are largely uniform in the Y-direction, the principal axes of curvature are aligned with the X- and Y-directions.

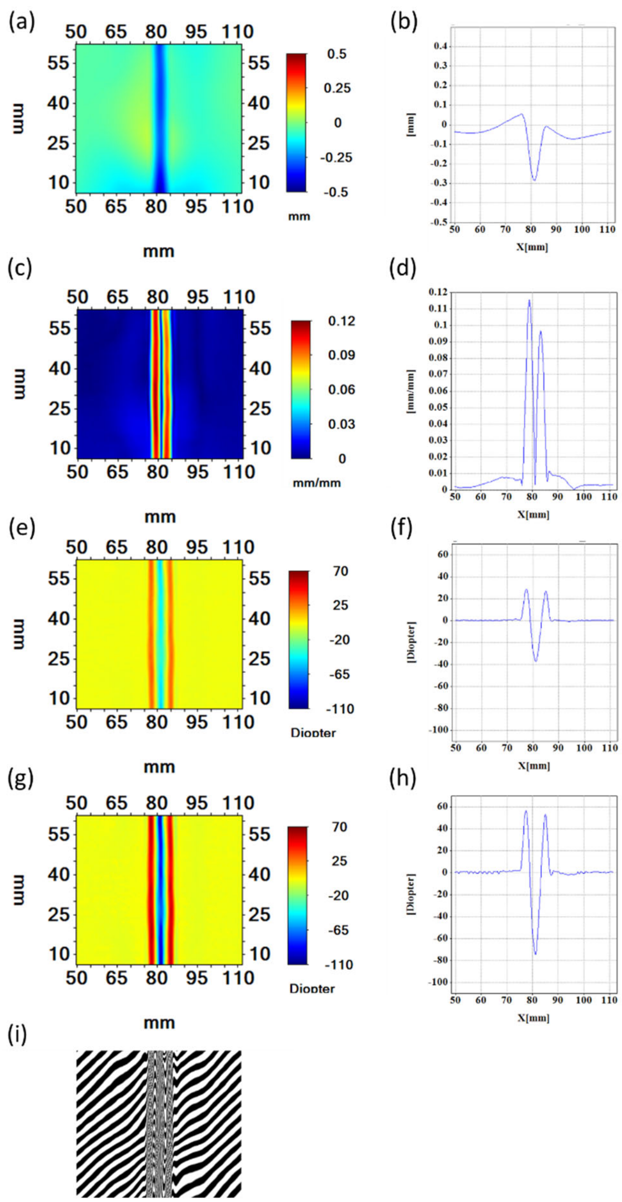

Figure 2: Example characterization of a foldable device (after 24 hours of 22 °C, 50% RH static bend) showing maps and corresponding horizontal profiles, respectively, of surface (a, b) shape, (c, d) absolute value of gradient (slope), (e, f) mean curvature, (g, h) extrema curvature, and zebra board image. Horizontal line profiles were extracted at position Y=30 mm.

The curvature in the X-direction changes quickly, resulting in large curvature values, while the curvature in the Y-direction is near zero. As a result, the mean curvature is ~1/2 the curvature in the X-principal direction.

Here we apply extrema curvature as the preferred metric over the more commonly utilized mean curvature, especially when viewing the entire sample surface, due to the anisotropic feature of the crease which is linear in the direction parallel to the crease (Y-direction here) (5). Extrema curvature combines minimum and maximum curvatures in the principal directions, where the highest absolute extreme value is chosen for each pixel and plotted with the original curvature sign, shown in Figure 2g and profile in Figure 2h. The extrema curvature allows for greater sensitivity in cases where the minimum and maximum principal curvatures are similar in magnitude but opposite in sign, resulting in a mean of zero but an extremum equal to one of the principal values. This allows for the greatest amplitude curvature value to be reported regardless of curvature direction. Direct comparison of the mean and extrema curvatures shown in Figure 2e and Figure 2g show the magnitude of the mean curvature is ~1/2 that of the extrema curvature, while the sign is largely maintained at each position. The line profile extracted from the extrema curvature map represents the curvature as calculated directly from the cross-sectional shape profile. This makes it a better 2D representation of the crease curvature.

The zebra board image depicting the user's view of a reflected line pattern on the creased display is shown in Figure 2i. The crease shape distorts the uniformity of the line features in a specific way. Comparing the regions of distortion of the zebra images to the various surface maps, the highest reflected distortion corresponds closely with the curvature maxima and minima locations.

Table 1. Example parameters extracted from the crease shape and processed profiles for the foldable device in **Figure 2**.

Condition	T=0h, pre-fold	T=24h, post-fold	Change (%)
Crease Depth (mm)	0.050	0.338	675%
Max absolute gradient (mm/mm)	0.015	0.108	720%
Peak-to-Valley Mean Curvature (D)	11	67	610%
Peak-to-Valley Extrema Curvature (D)	22	135	614%

Metrics obtained from the surface maps and line profiles provide quantitative information for comparing crease performance. These metrics include crease depth, gradient maximum or mean or minimum, curvature maximum or mean or minimum, distortion area, and peak-to-valley magnitude and distance ranges. An example of how some of these parameters change as a crease evolves over time when folded is presented in Table 1. In this example with a well-behaved crease, the different metrics track with similar percent changes after 24 hours of static bend at 22 °C (room temperature) and 50% relative humidity. As stated earlier, crease depth alone does not define the extent of distortion a user would observe in the off state since the crease width is also important. Maximum absolute gradient provides a measure of distortion but in a single region on one side of the crease. The curvature metrics provide a richer insight into the optical distortion with the extrema curvature having higher sensitivity for smaller changes in optical lensing from reflection, and extrema curvature from the 2D maps representing curvature values generated from shape line profiles.

These metrics can also be used to study crease formation and relaxation, uniformity along the device length, and differences between creases of different devices with different stack configurations (glass-only, different user-side lamination layers, etc.) or hinge designs (U-shape, teardrop, bend radius, etc.)

4. Impact/Conclusion

Characterization of the hinge crease features in foldable devices provides valuable information to quantify device performance with time or with changes to design parameters. Here we show the relative difference between several different characterization metrics which can be obtained from measurements of device surface. We have shown that the line distortion in the zebra board image, which depicts what a user would observe when a stripped pattern is reflected off the device surface, corresponds well to the curvature of the surface.

We propose the use of extrema curvature over mean curvature for the 2D visualization of the curvature of creased devices. We also propose using peak-to-valley magnitude of extrema curvature for the quantitative evaluation of crease.

5. References

1. Kim DW, Kim SW, Lee G, Yoon J, Kim S, Hong J-H, et al. Fabrication of practical deformable displays: advances and challenges. Light: Science & Applications. 2023;12(1):61.
2. Park W, Park K, Ryu J, Hwang K, Kim S, Song Y. Effects of crease features on crease visibility and goodness of smartphone foldable display. Affective and Pleasurable Design. 2023;71(71).
3. Jiang J, Liu Y, Wang W, Cheng Y, Jia Y, Zhang Z. P-13.3: Crease Improvement Method for Foldable OLED Module by Preloading Mechanism. SID Symposium Digest of Technical Papers. 2023;54(S1):919-20.
4. Huang L, Idir M, Zuo C, Asundi A. Review of phase measuring deflectometry. Optics and Lasers in Engineering. 2018;107:247-57.
5. Lo J, Manea A. Quantifying Screen Crease and Waviness in Foldable Displays. 2023.