Study of Factors Affecting Dynamic Bending Performance of Folded Flexible AMOLED Modules

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Abstract

This article establishes a water droplet bending model for flexible AMOLED display modules using nonlinear finite element software. Through analysis and comparison of different design conditions and practical verification, the factors affecting the bending performance of flexible AMOLED display modules are analyzed, including integrated edge design of display modules, pattern design of support components, and selection of adhesive for each layer.

Author Keywords

Flexible AMOLED display; drop-shaped; bending performance; mechanical simulation.

1. Introduction

With the widespread implementation of flexible OLED (organic light-emitting diode) displays in the mobile phone market, smartphones have surpassed their previous limitations of a straight form and introduced the innovative folding phone format [1]. Foldable phones not only provide a convenient way to carry mobile phones, but also largely meet consumer demand for large screen displays, providing an opportunity for the development of smartphones [2]. However, the development and use of foldable phones has brought about numerous risks and challenges, owing to their growing popularity and diverse range of applications. Problems such as delamination caused by bending, support parts fractures, and creases in the bend zone have surfaced [3].

In foldable display, each functional layer (such as cover film, polarizer, light emitting layer, substrate layer, etc.) is bonded into a whole using g optically clear adhesive (OCA) or pressure-sensitive adhesives (PSA). Researchers have conducted an investigation into the impact of bending on the functional layers. Hsien and colleagues [4] examined the bending behavior of touch display panels (TDPs) that had protective structures and those without. They discovered that immoderate bending creates significant tensile and compressive stresses on the ITO/PR conductive/insulating layers. These stresses rise with the curvature during bending, resulting in the breakdown of the display. Lee et al [5] analyzed the effect of the cover film on the bending behavior of foldable display by simulation and experiment. OCA as an adhesive is an almost incompressible material and cannot be considered as a simple elastomer. JIA et al [6] employed the fitting method to establish the analytical equations for the superelasticity and viscoelasticity of OCA. Liu et al [7] used OCA as a superelastic to develop a simulation model for a display module. The research established that thicker OCA results in decreased strain within the adhesive layer.

Currently, the morphology of droplets in foldable displays is classified as either U-shape or drop-shaped bending morphology. Wang et al [8] conducted an analysis on the impact of bending stress from different display modules with varying bending radii using the simulation software. Their findings indicate that the stress and strain of each film layer in the U-shape increases with a decrease in radius, while changes in radius have little effect on its stress and strain. Cheng et al [9] used finite element simulation to control the design of the neutral layer in the display module. This was done to enhance the folding performance of the module.

In practical applications, the stack design of foldable display and material selection directly impact the folding performance of the product. Based on this, this paper focuses on foldable AMOLED display, employing a combination of simulation and experimentation to analyze the effects of display bezel design, OCA, and support component design on the bending performance of individual flexible display. The successful application of these findings in products provides a certain reference for the design and manufacturing of subsequent foldable flexible display modules. The findings have already been successfully applied in a product, providing valuable reference for subsequent design and production of folded flexible display modules.

2. Description of the model

Numerical implementation: Foldable display is composed of several functional layers, such as the protective layer, flexible cover film, polarizer layer, display light-emitting layer panel (which includes FMLOC and flexible AMOLED), support parts, and adhesive layer [10]. The bending process of the folded display module can be modelled as a plane strain problem by simulation. Table 1 presents the thickness, density, elastic modulus and other parameters of each stacked layer. The cover film can be stacked with various materials to meet the demands of folding mobile phones. To better align with real-world applications, this paper analyses the simulation of subsequent combinations of UTG [11] (flexible ultra-thin glass) and PET (Polyethylene terephthalate) as the cover film stack.

In the simulation model, it is essential to employ the material properties in Table 1 and use the drop-shaped bending morphology to characterize the motion of the in-folding display while folding, whereby the bending radius of the drop-shaped bending amounts to 2.6 mm. Considering the actual force of the display on the mobile phone, in order to ensure that the foldable display maintains the stability of the water droplet form during the bending process, a support point will be set on the left and right sides of the water droplet tail (i.e., at the reverse arc) of the display module, as shown in Figure 1.

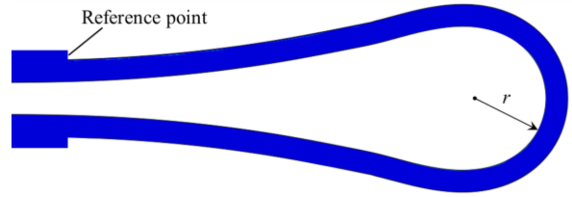

Figure 1. Foldable display simulation model schematic.

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Table 1. The stack structure of foldable display

Label (From top to bottom)		Thickness (μm)	Poisson ratio	Elasticity modulus (GPa)
Cover film	PET	60	0.3	4
	OCA0	50	0.25	5.1×10^{-5}
	UTG	30	0.3	73.3
OCA1		50	0.25	5.1×10^{-5}
Polarizer		68	0.3	4
FMLOC		10	0.3	3
Panel		30	0.3	3
Base film-PSA		15	0.3	5×10^{-5}
Base film		50	0.3	4
PSA		65	0.3	5×10^{-5}
Support parts (SUS)		150	0.3	194

Mesh verification: The model mesh size is a tetrahedral mesh of 0.05 mm in the thickness direction to ensure at least four layers of mesh for each film, as shown in Fig. 2. First order fully integrated cells were used. Since the simulation is a plane strain hyperelastic case, a hybrid formulation is also used. After verification of mesh-independence, the maximum difference in stress distribution on the symmetry plane was only 0.0035%. Therefore, the default mesh in Fig. 2 was used for all models.

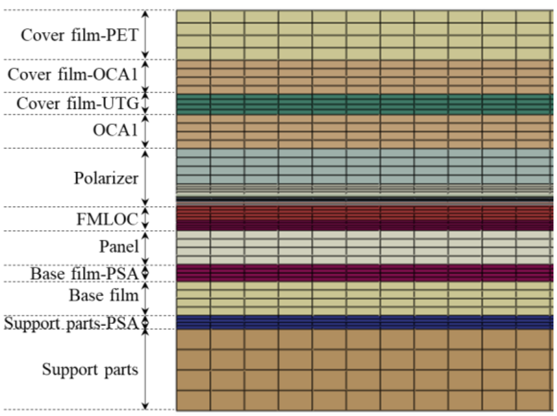

Figure 2. Part of the mesh in the display

3. Results and discussions

Influence of adhesive selection: As previously mentioned, foldable display is typically united into a singular entity using an adhesive bonding agent for each functional layer. When the foldable display is bent, each functional layer has a different bending radius, which creates a misalignment between the layers and stresses the adhesive between the functional layers. If the choice of adhesive is not appropriate, the adhesive will cause delamination between the functional layers of the foldable display due to the failure of the adhesive during the bending process [12], and in serious cases, the display layer will be damaged, which will lead to the scrapping of the foldable display. In severe cases, such failure can damage the display layer, and this results in the foldable display being scrapped. Therefore, the selection of adhesive properties is particularly important for the improvement of folding and bending performance.

OCA is commonly utilized as a bonding agent in flexible AMOLEDs due to its transparency and high light transmittance. It is a polymer material possessing a low elastic modulus [13]. The variation in Young's modulus between the different types of OCA adhesives appears to be insignificant, as they are all of a similar order of magnitude, but there are differences in adhesive properties, material cohesion and the rate of creep recovery after material deformation. Table 2 provides information on the properties of the three commonly used OCA adhesives.

Table 2. Comparison of the properties of different adhesive materials

Type	Young's modulus (kPa)	20kpa recover @25℃,10min	Adhesion to PET(gf/inch)
A	50	90%	≥650
B	46	80%	≥800
C	30	80%	≥650

Based on the simulation model established in Chapter 2, we conducted finite element simulations on the stacked display module of Table 1 using varying types of OCA adhesive. The final simulation results are presented in Fig. 2. By keeping the OCA1 unchanged and altering the OCA0, a comparison was made between split2 and split3. The results show that the maximum principal stress of the OCA0 in split3 is 5.92% lower than that of split2. The remaining layers of glue showed insignificant differences of less than 0.5%. By keeping the OCA0 constant and adjusting the OCA1, a comparison between split1 and split3 shows that the maximum principal stresses at the glue collocation for split1 are 10.16% lower than those for split3 at OCA1.

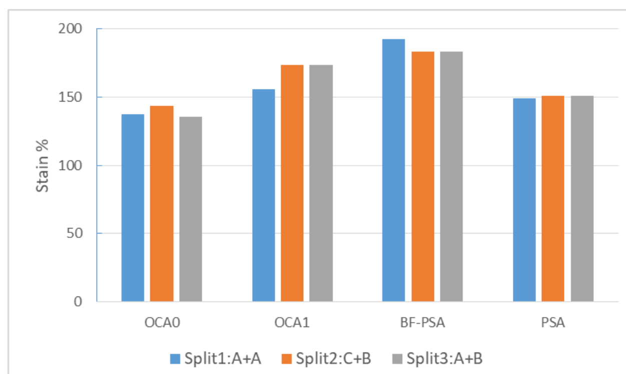

Figure 2. Strain simulation results of different OCA combinations

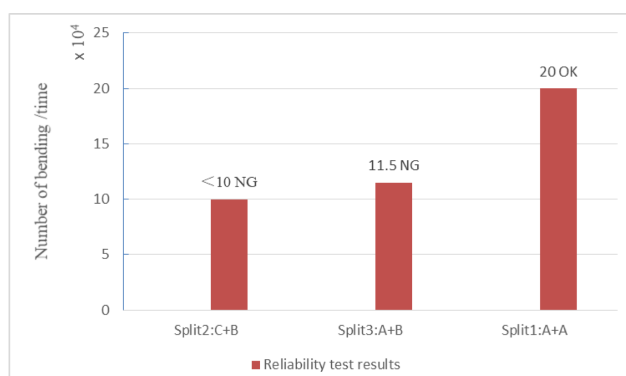

Figure 3. Experimental results of different OCA combinations

Based on the simulation results discussed above and the comparison of the three different OCAs presented in Table 2, it is evident that the selection of OCAs with higher cohesion and stronger creep recovery rate for the foldable display utilizing UTG as the Cover film is advantageous. This feature significantly reduces the stress value of the adhesive material in the display module and facilitates bending.

To determine the effect of various types of adhesive on the bending performance of the folding display, the above three different split adhesives were employed in physical production and bending tests. The accompanying test results are illustrated in Figure 3. The test results show that during the actual bending process, the Split2 adhesive collocation experiences delamination between the functional layers less than 100,000 times. Split3 performs better than Split2, but still falls short of the 200,000 times required by the standard [10]. To meet customer acceptance criteria, the Split1 OCA textbook collocation would be the preferred choice. This experiment's outcome aligns with the simulation analysis's conclusion. From the verification results, it can be seen that for the display module using the UTG scheme for Cover, using a higher creep recovery rate adhesive can effectively improve the bending times of the display module.

Influence of support Design: In addition to the impact of OCA materials, the design of support components, as a major material part of the module, is also critically important. The rear of the folded display module generally adopts a metal support member (e.g. SUS) to provide support and meet electrical and thermal conductivity requirements between the display module and the entire machine [14]. To achieve the flexibility of the display module, the back support will be pattern-etched in the bending region. This reduces stress during bending and decreases the rebound force. To align the appearance of the display module's water droplet shape with the terminal hinge design, it will be placed at the hinge support point (as shown in Figure 1) and the water droplet arc will be etched into the region of the blind groove design. This is intended to reduce rebound force.

The pattern uses through-hole etching, comprising a series of through-holes arranged in parallel with the bending direction and spaced at specific intervals. If the support is to be effective in thin metal material (such as 0.1/0.12/0.15mm), the strength of the support in the bending area can be impacted by the gap of the through holes in the pattern area and the etching depth of the blind groove region. In case the design value is unreasonable, it will affect the support's strength after etching leading to inferior bending performance. Using the spindle pattern design illustrated in Fig. 4 as a case study, this study examines the effects of pattern design and retention depth of blind slot etching on bending performance. Two patterns with distinct through-hole widths and blind groove designs are utilized on the 0.12 mm SUS material support. For their dimensional specifications, please refer to Table 3.

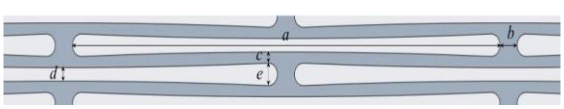

Figure 4. Schematic diagram of Pattern

(Parameters: through-hole length a, maximum through-hole width e, minimum through-hole width d, horizontal through-hole clearance b, and minimum through-hole lead hammer clearance c)

Table 3. Design parameter table of support components

Parameters	P1(μm)	P2(μm)
c: minimum through-hole lead hammer clearance	150	100
Blind groove etching retention depth	80	60

Table 4. Simulation results for different support designs

Item	P1	P2
Maximum strain of OCA0	99.7%	99.2%
Maximum strain of OCA1	122.5%	124.2%
Strain of PSA	4.70%	3.95%
Maximum stress of SUS（MPa）	840	733

Using the simulation model discussed previously, this study compares the maximum stresses of both support member schemes and the maximum strains of the remaining stacks within the display module through finite element simulation. The simulation results are shown in Table 4, based on the simulation outcomes, employing the P2 scheme reduced the maximum stress of the support member by 14.59% compared to the P1 scheme. Additionally, the risk of fracture for the support member during the bending process was lower. Furthermore, the two display modules had a negligible impact on the adhesive layer's strain. Therefore, the P2 scheme offers better support for bending the display module.

In order to verify the influence of the design of the support member on the bending performance of the folded display module, the above two designs are used for physical fabrication and bending test, taking into account the increased risk of fracture of metal materials at low temperatures, the actual verification is based on the low-temperature test, and the test results are shown in Figure 5.

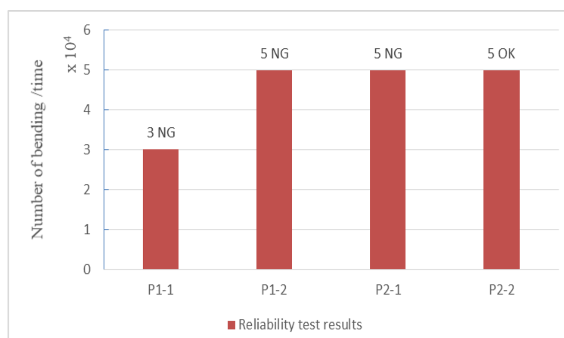

Figure 5. Schematic diagram of Pattern

(P1-1: Blind groove etching retention 80μm; P1-2: Blind groove etching retention 60μm; P2-1: Routine accuracy control; P2-2: Strict control of precision collection)

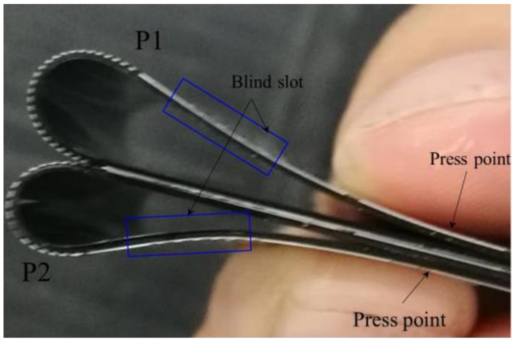

Figure 6. Two types of support design: manual bending of water droplet morphology

As illustrated in Figure 6, the P1 solution exhibits poor bending performance due to excess depth in the blind slot, resulting in an excessive rebound force on the display module in that area. This impairs bendability into a teardrop shape during bending and distorts the through-hole area, which leads to stress concentration at the top of the teardrop and ultimately results in a fracture in the pattern. After the blind groove depth is optimized to 1/2 of the thickness of the support member, the actual measurement of the bending enhancement of 66.66%. It can be seen that the blind groove retention depth should not be too thick, and taking into account the material fracture blind groove etching depth at the same time should not be too shallow, in summary, it is recommended that the blind groove etching for the 1/2 of the thickness of the support.

In order to verify the through-hole lead hammer gap design minimum value, in accordance with the P2 design for the fabrication, due to the actual processing process PATTERN etching there are precision errors, including the P2 design of the minimum tendon width precision control 0.1 ± 0.03mm, this support member design in the low-temperature bending 50,000 times the appearance of SUS fracture. After conducting a physical analysis, it was discovered that the support fracture of the minimum bar width is too small (less than the specification of the following line). In combination with the results of actual verification and testing, it is recommended to enhance control over the minimum bar width (ensuring it is greater than or equal to 80μm). This will result in an improvement of the bending performance. From the above, it can be seen that the P2 design compared to the P1 design scheme, the former actually performs better than the latter and matches the simulation results.

Influence of Flush Edge Design: Besides the impact of the folded materials discussed, the design of the module stack is equally crucial. To ensure that there is no overflow of glue and risk of bonding foreign objects on the four sides of the panel, OCA1 is commonly used as the bonding layer between the display module cover and polarizer. This is due to limitations in equipment layout and process. Thus, it can be observed that the OCA1 profile is typically smaller in size compared to the Panel profile. The profile's depiction can be seen in Figure 7 below.

When attaching the cover, the above design may result in incomplete bonding between the display module edge position cover and polarizer. As a consequence, the cover of the display module will be subjected to pressure from both sides during the bending process, leading to bending (as illustrated in Figure 8). Extended periods of bending are predisposed to raise the probability of bubbling or pulling of the OCA adhesive from the edges, which in turn leads to OCA peeling (i.e. delamination between cover and polarizer) as depicted in Figure 9.

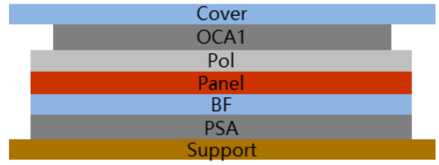

Figure 7. Schematic of the display module section of the OCA1 retracted design

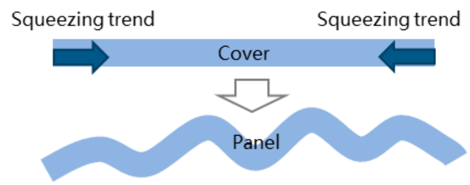

Figure 8. Diagram of Flexion Principle Analysis

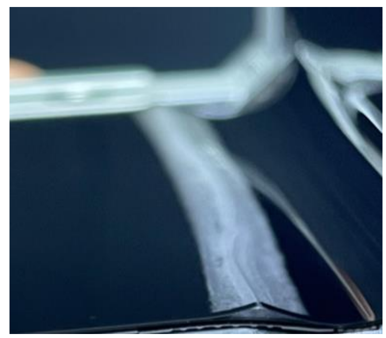

Figure 9. Diagram of failure display after multiple bends

Using the previously established design, the simulation model compares two different edge states through finite element simulation. The simulation results are shown in Table 5, the simulation results show that implementing the OCA1 adhesive with a flush edge design results in a 57% decrease in stress compared to the non-flush edge design (maximum OCA1 stress decreases from 0.14MPa to 0.06MPa). These results align with the actual fabrication of samples used in the bending test. From the above validation analysis, it can be found that the use of one-piece cut design is more conducive to bending performance improvement.

Table 5. Simulation results for different support designs

Design of OCA1	Maximum strain of OCA1	Results of test results
Inside-out design of OCA1	0.14MPa	13,000 times NG
flush design of OCA1	0.06MPa	200,000 times OK

The OCA1 and panel flush edge design is cut by laser. Since the Cover Film verified above adopts the ultra-thin glass UTG scheme, due to the fragile nature of the glass, the UTG will be broken when the edge is cut in one piece, so it is not possible to achieve the design where the cover film is equilateral to the OCA1 and the panel. If the cover film is made of CPI or PET, the process can meet the entire display module light-emitting layer and above the stack to achieve the flush design. Through the actual verification can be found, this design can also meet the terminal bending reliability standards (200,000 times).

4. Conclusions

To confirm the effect of display module stack design and material selection on its bending performance. This paper establishes the water droplet bending model of flexible AMOLED display module through nonlinear finite element software, and obtains the factors affecting the bending performance of flexible display AMOLED by analyzing and comparing different design conditions and supplementing them with actual verification, so as to provide a certain reference for the design and production of the subsequent folded flexible display module.

For the bending trajectory for the water droplet form of the display module, the support piece pattern lead hammer gap should not be too narrow, from the actual verification results suggest that more than 0.08mm, and in order to reduce the display module bending rebound force, the depth of the blind groove etching is recommended for the 1/2 of the thickness of the support piece; For the ultra-thin glass UTG as the cover of the display module, the use of adhesive material with higher creep recovery rate can effectively improve the display module bending times; when the adhesive material and panel integrated flush design, to avoid the material bending process of the bending effect leads to improve the bending performance.

5. References

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