Enhanced Low-Temperature Mechanical Reliability of Foldable Screen

Shuangbing Zhang*, Shuang Wang*, Chenzhe Li*, Ying Shen*

***Hefei Visionox Technology Co., Ltd, Hefei, China**

Abstract

Foldable smartphones are becoming increasingly popular. Enhancing the mechanical performance of foldable phones at low temperatures is particularly important. In this study, finite element analysis (FEA) was used to examine the failure mechanisms and influencing factors of this issue. The results indicate that due to the viscous nature of the adhesive layer, the panel undergoes significant overall stretching during unfolding. By optimizing the design of the metal support layer and the stacking structure of the folding module, the mechanical reliability of foldable screens at low temperatures can be significantly enhanced.

Author Keywords

Foldable Screen; Mechanical Simulation; Low-temperature; Metal support sheet; Stacking Structure; Mechanical Reliability.

1. Introduction

Nowadays, foldable mobile electric devices are becoming increasingly common. How to improve the mechanical performance of foldable phones has become a major concern for both original equipment manufacturers and panel manufacturers. Products with inward-folding waterdrop-shaped displays have become the mainstream type because they are more compact than wedge-shaped ones, but at the same time, the waterdrop design requires a more complex hinge design. Over the past three years, with the rapid development of hinge technology, foldable phones have become thinner and lighter. These extreme designs enhance the user experience while also placing higher demands on the mechanical reliability of foldable screens.

To ensure the robustness of foldable screen, it is necessary to maintain low folding stress through optimization of the stacking structure of the foldable display modules. The stress generated in foldable displays can be analyzed through finite element simulations [1-3]. In recent years, this has prompted the development of various simulation models to gain structural understanding and improve design.

Thanks to the efforts of the engineers, we are very pleased to see that through optimizing the stacking structure and materials, foldable screens can even withstand one million folds in standard dynamic bending tests without failure. However, compared to traditional low-temperature dynamic bending test conditions, foldable panel is still prone to malfunctions in complex user scenarios, especially when unfolded at extremely low temperatures after being folded for a long time. Figure 1 shows the typical failure phenomena that occur when a foldable screen is rapidly unfolded in a -20 ℃ environment after several hours of bending. A very obvious crack can be observed near the centre of the curved area of the screen. Detailed analysis indicates that the encapsulation layer and the touch layer at the corresponding position have already fractured. Regrettably, there are no research reports on this issue in the existing literature. In this work, we will explore for the first time the causes of this failure phenomenon and discussion some potential improvement measures. These results may provide some valuable guidance for enhancing the low-temperature mechanical reliability of foldable screen.

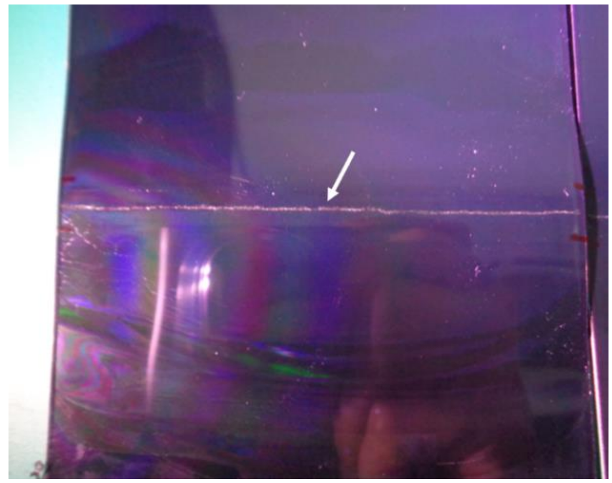

Figure 1. The typical failure phenomenon that occurs when the foldable screen is rapidly opened in -20℃ environment after being bent for several hours.

2. Experiment and Simulation

Through performing a series of fold-hold-unfold cyclic bending tests, the initial failure shown in figure 1 was observed to occur during the unfolding process of the screen, thus merely analyzing the stress in the bent state is insufficient. The folding and unfolding procedure of foldable display is simulated by nonlinear finite element method to analyze bending stress. In order to obtain more accurate results, a viscoelastic adhesive constitutive is adopted.

As shown in figure 2a, a typical foldable display module is a composite stacking structure composed of cover window, AMOLED panel (PNL), the backside film (BPF), and the metal support layer (BKT). These multiple functional layers are bonded by optical clear adhesive (OCA) to form a film stack. The AMOLED PNL itself also consists of multiple components including a flexible substrate, thin film transducer (TFT), thin film encapsulation (TFE), the touch sensor layer.

The metal support sheet is patterned in the bending area with through-hole to ensure bending performance. The single hole is elongated and all the holes are arranged with a staggered arrange, which is shown in figure 3. Where a value represents the interval between adjacent holes in lengthwise direction of holes; b value represents the spacing between the centerlines of adjacent holes in width direction; c is the width of the single hole; d is the length of a single hole. To accurately reflect the influence of the metal support sheet, a three-dimensional model instead of the 2D plane strain model is considered in this work. Figure 2b shows the morphology after bending. It is clear that we are considering a water-drop shape inward folding design.

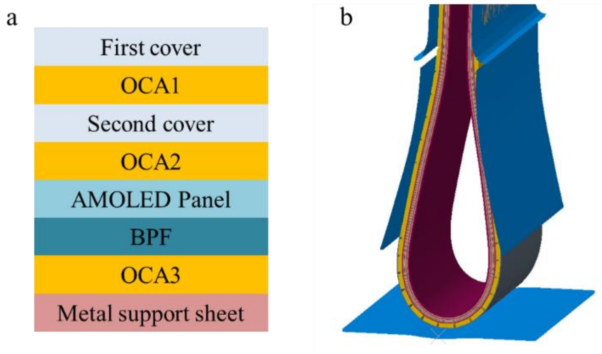

Figure 2. A schematic diagram of stack structure (left) and water-drop shape (right) considered in this work.

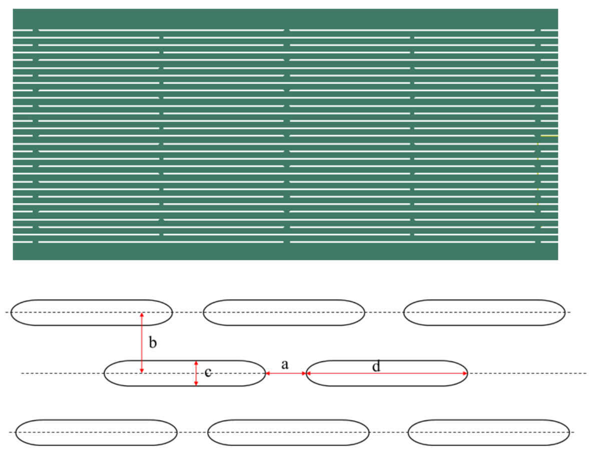

Figure 3. A schematic diagram of pattern structure of the metal support sheet.

3. Result and Discussion

Failure Mechanism Discussion:

The crack shown in Figure 1 is related to the fracture of the touch layer film within the panel, hence the stress in the touch layer of the screen's bending area is the focus of analysis.

The strain distribution of the touch layer within the foldable screen in the folded state is shown in Figure 4a. Due to the inward folding shape and the neutral layer of the screen being near the encapsulation layer, the touch layer experiences compressive strain. Generally, compressive stress may cause structural instability, leading to delamination, but it is unlikely to directly cause the formation of cracks. Furthermore, extreme bending tests were conducted on the module, and the results showed that even when the bending radius was far below the current design value, the screen did not fail. As the radius decreased further, cracks appeared in the array layer. These results are consistent with the fact that in actual experiments, failure did not occur during the folding process.

When the foldable screen is kept in a folded state for a period of time and then rapidly unfolded, the strain distribution in the touch layer of the panel is shown in Figure 4b. The strain in the touch layer does not return to the stress-free state prior to folding; rather, it transitions from compressive strain in the folded state to significant tensile strain. The tensile stress provides a sufficient driving force, resulting in the fracture of the touch layer. Furthermore, the strain distribution of the touch layer after the screen is unfolded is uneven and exhibits a periodic pattern. This periodic pattern corresponds to the design of the metal support components, with local peaks in the strain distribution coinciding with the holes in the metal support plate and near the short rib structures of the metal support plate, as illustrated in Figure 4c.

Extract the strain results along the path indicated by the white dashed line in Figure 4C and plot them in Figure 5. Clearly, the strain in the touch layer has changed from compressive strain (-2.4%) in the folded state to significant tensile strain (2%) in the unfolded state. Furthermore, the strain distribution along this path exhibits a sinusoidal pattern. This indicates that the surface of the panel is not flat, whether in the bent or unfolded state, but rather exhibits a wavy form.

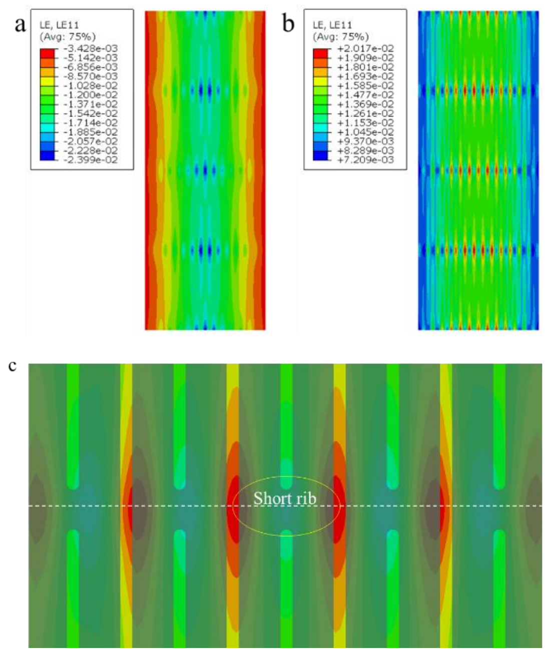

Figure 4. (a) The strain of the touch layer in the folding area of the foldable screen in the folded state. (b) The strain of the touch layer in the bent area in the unfolded state after being bent for a period of time. (c) The correspondence between strain distribution and the pattern structure of metal support sheet.

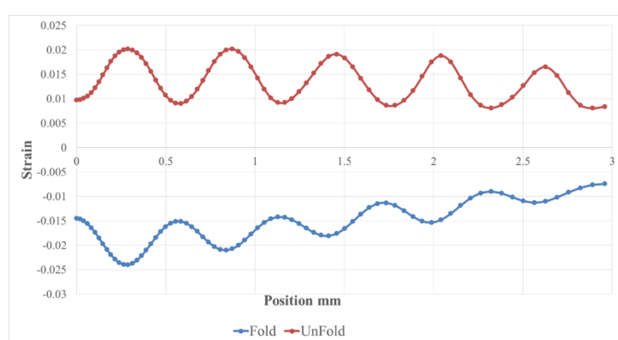

Figure 5. Strain results along the path indicated by the white dotted line in figure 4C.

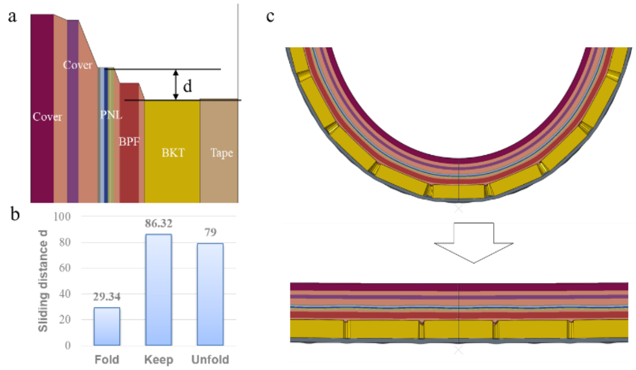

Figure 6. (a) Shear slippage of each layer at the edge of the screen. (b) d value at different state. (c) The morphology of the screen in folded and unfolded states.

As shown in figure 2a, foldable module is a composite stacking structure where the multiple functional layers are bonded by soft OCA to form a film stack. The difference in Young's modulus between OCA and functional layers exceeds five to six orders of magnitude. The shear deformation dominates in the soft adhesive layers of the laminated structure of foldable display while the normal strain-induced deformation is negligible [4]. The sliding distance d of the panel edge relative to the hinge is shown in Figure 6b. When the screen completes folding from the flat state, the panel edge slides outward by 29.34um relative to the hinge. During the period in which the screen remains curved, due to the viscoelastic characteristics of the adhesive layer, significant creep deformation occurs in the adhesive layer, resulting in the overall shear slip increasing from 29.34um to 86.32um. Increasing the storage temperature or extending the storage time further exacerbates the overall slip. During the unfolding process, especially in low-temperature environments or when the device is opened rapidly, the shear deformation of the OCA cannot recover promptly. When the foldable module is fully unfolded, a residual slip of 79um remains. Therefore, these data confirm that when a screen is bent for an extended period and then rapidly straightened, it undergoes significant overall stretching due to the delayed deformation recovery caused by the creep of the adhesive layer.

Furthermore, the mesh structure in the bending region of the metal support determines that during bending, the long ribs coordinate deformation through twisting, while the short ribs coordinate through bending. Due to the high stiffness characteristic of the short rib structure of the metal support layer, the short ribs inevitably exert normal compressive stress on the screen, causing the adhesive layer to accumulate at the positions corresponding to the holes in the metal support plate. When the screen is unfolded, the adhesive layer cannot return to its original position, resulting in the screen exhibiting a wavy shape as shown in Figure 6c.

Effect of Metal Support Layer:

It is well known that the structural design of metal support components affects the folding performance of foldable screens. However, simulation analyses typically focus on evaluating the fracture risk of the metal components themselves [3], without analyzing the risk of panel failure at low temperatures resulting from the design of the metal support components. In this section, the impact of different structural designs on stress when the screen is rapidly unfolded after prolonged bending is discussed, with the aim of providing an optimization method for the design of metal support structures. For detailed design information, please refer to Table 1. Evidently, the main design parameters that vary are the length d and width c of the holes.

Table 1. Pattern design DOE

	a mm	b mm	c mm	d mm	Etch
Base	0.52	0.32	0.12	10	No
DOE1	0.52	0.32	0.07	10	No
DOE2	0.52	0.32	0.03	10	No
DOE3	0.52	0.32	0.07	2.3	No
DOE4	0.52	0.32	0.12	10	Yes

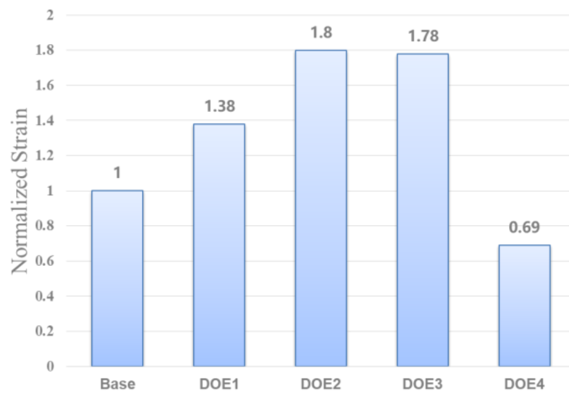

Figure 7. The normalized strain results of touch layer in the unfolded state for different designs of metal support layer.

Figure 7 shows the normalized strain results for different designs. The screen bending stress increases as the width and length of the holes decrease. When the width of the hole is reduced from 120 um to 30um, the stress increases by 80%; when the length of the holes is reduced from 10mm to 2.3mm, the stress increases by 78%. Reducing the length and width of the holes increases the stiffness of the metal support plate, resulting in greater panel slippage relative to the hinge. Therefore, the screen will undergo greater overall tensile deformation during the unfolding process. Further increasing the width and length of the holes in the support components compared to the base design would weaken the support for the panel, particularly when the back of the panel is subjected to external impact, and would fail to provide adequate protection for the panel.

To enhance the bending performance of the screen at low temperatures, we designed an additional solution (DOE4). Considering that the short rib structure of the metal support plate exerts pressure on the panel in a bent state, the outermost material of this structure was etched away to reduce compressive stress. The final structure is shown in Figure 8. Simulation results indicate that the optimized design can reduce stress by approximately 30%. To verify the effectiveness of this optimized design, we conducted physical sample tests on both the optimized design and the basic design. To ensure the validity of the data, five samples of each design were tested. The results showed that all five samples of the basic design experienced panel damage, whereas all five samples of the optimized design successfully passed the tests without any damage.

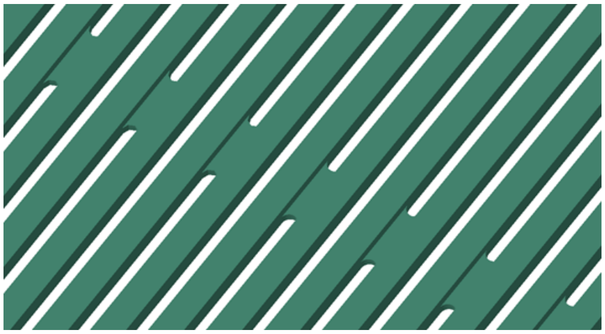

Figure 8. The local structure of the optimized design DOE4

Effect of Stacking Structure:

In this section, the impact of module stacking structure on bending stress is briefly discussed. The focus is on the structure beneath the AMOLED panel. The screen's ability to withstand external impacts is becoming increasingly important. To enhance this performance, one possible solution is to add a layer of high modulus material between the metal support plate and the backside film. This design change is considered as DOE1. After prolonged use, the crease defect affects the user experience. One of the factors influencing this performance is the plastic deformation of the organic backside film. To address this issue, one possible technical approach is to replace the original organic backside film with high-modulus elastic materials such as ultra-thin glass or ultra-thin metal sheets. This design change is referred to as DOE2. In DOE3, all technical changes have been taken into consideration.

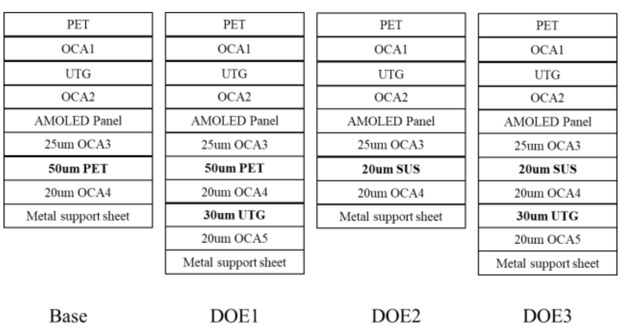

Figure 9. Stacking structure information for different DOE.

Figure 10 shows the normalized strain results of the touch panel layer under different stack designs when the screen is rapidly unfolded after a specified bending time. The simulation results indicate that replacing the original organic back film with a single-layer ultra-thin steel sheet can significantly reduce the stress on the touch panel layer, thereby improving the screen's low-temperature bending performance. Of course, in terms of product bending reliability, the ultra-thin steel sheet can also be replaced with ultra-thin glass, but the panel fabrication process would face more challenges. It is worth noting that DOE3 appears to effectively balance low-temperature bending performance and foreign object impact resistance. However, DOE3 is expected to significantly increase the stress on the adhesive layer near the ultra-thin steel sheet, so it should be paired with an OCA that has appropriate adhesive and cohesive strength.

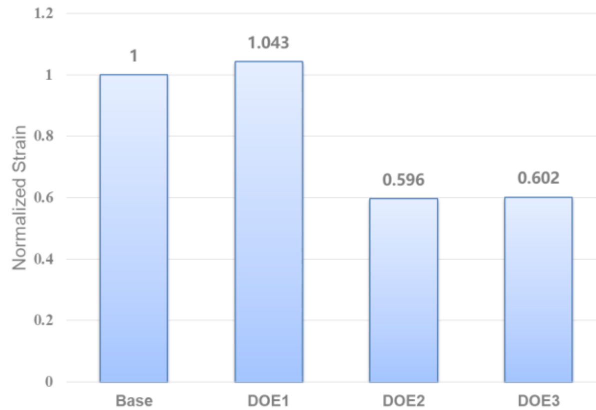

Figure 10. The normalized strain results of touch layer in the unfolded state for different stacking design.

4. Conclusion

The foldable screen is prone to failure when the screen is rapidly opened in low-temperature environment after prolonged folding. This work analyzes for the first time the failure mechanism and influencing factors of this issue. The results show that the panel undergoes significant overall stretching during unfold process due to the delayed recovery of creep deformation of adhesive layer. The short rib structure of the metal support layer inevitably exert pressure on the screen, resulting in a wavy appearance of the screen.

The effects of pattern designs of metal support layer was discussed. Reducing the length and width of the holes increases stress, implying a decline in the screen’s low-temperature bending performance. An optimized pattern design was proposed through etching the outermost material of the short rib structures, and its effectiveness was confirmed by experiments.

The effect of module stacking structure was analyzed. Replacing the original organic backside film with a single ultra-thin steel sheet can significantly reduce the stress, thereby improving the screen’s low-temperature bending performance.

5. References

1. YZ Jia, ZZ Liu, D Wu, JF Chen, H. Meng Mechanical simulation of foldable AMOLED panel with a module structure. Organic Electronic. 65(2019)185-192.
2. J. Cao, A. Es’haghioskui, P. Dong, Z. Gong, HY Yuan Mechanical simulation and debonding risk analysis of OLED panels with optical clear adhesives. Displays 83(2024)102722.
3. WQ Wang, YZ Jia, HQ Li, MY Jiang, Z. Zhang Mechanical simulation of foldable organic light-emitting diode display supporting layer. J. Soc. Inf. Display. 29(2021)723-730.
4. S. Li, XL Liu, R. Li, Y. Su Shear deformation dominates in the soft adhesive layers of laminated structure of flexible electronics. Int.J.Solid.Struct. 110-111(2017)305-314