Finite Element Analysis and Optimization Study of Ultra-Thin Glass Cracks in Flexible Displays[†]

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Abstract

This paper investigates the crack issues of Ultra-Thin Glass (UTG) in flexible displays. By establishing a finite element model, the influence of the thickness and modulus of each layer in the laminated structure on the stress distribution of UTG is systematically analyzed. The study found that the modulus of OCA0, the modulus of OCA1, the thickness of PI1/PET1, and the thickness of OCA1 are the main factors affecting UTG stress. Based on this, optimization strategies to reduce UTG stress are proposed, including increasing the modulus of OCA1, reducing the modulus of OCA0, and decreasing the thickness of PI1/PET1. This study provides a theoretical basis for the structural optimization design of flexible displays.

Author Keywords

Ultra-Thin Glass; Crack; Finite Element Analysis; Flexible Display; Structural Optimization.

1. Introduction

The development of flexible display technology has brought revolutionary changes to electronic devices. In the cover materials of flexible displays, Ultra-Thin Glass (UTG) and polyimide film (CPI) are the two main choices. Although CPI is widely used due to its mature mass production technology and excellent ductility, UTG is gradually becoming an industry trend, especially in foldable phone products of major brand customers. Compared with traditional CPI, UTG has significant advantages such as ultra-thinness, high strength, excellent resilience, and outstanding optical performance. Its thickness can reach the 30μm level, and combined with non-Newtonian fluid impact protection film, it can have exceptionally excellent impact resistance, remaining flat after multiple bends, with a light transmittance of over 91.8%, providing users with a better visual experience. However, the mass production technology of UTG still faces challenges, mainly in ensuring the yield and cost control of ultra-thin glass. With continuous technological advancements, UTG is expected to become the mainstream cover material for flexible display devices in the future, promoting the further development of flexible display technology.

Recent studies have shown that the crack growth behavior of UTG under cyclic loading is similar to that of thick glass [1]. With the widespread application of UTG, its crack issues are becoming increasingly prominent. To continuously improve the impact resistance and crease flatness of modules, the thickness and strength of UTG are constantly increasing, leading to an increase in bending stress. Since glass is a brittle material, surface microcracks are prone to stress concentration under bending stress, causing rapid crack propagation and eventually leading to glass breakage. Studies have found that cracks mostly occur at the edges of the glass, but in some cases, the middle area can also become the starting point of cracks. In addition, uncoated UTG is easily affected by humidity under cyclic loading, leading to accelerated crack propagation, while coatings can prevent moisture from contacting the crack tip, thereby slowing down crack growth [1]. These issues not only lead to product failure but also severely affect user experience. Therefore, research on UTG crack issues is of great significance, especially the study of the impact of bending stress and surface microcracks on glass strength.

This study aims to conduct an in-depth analysis and design optimization of UTG crack issues through finite element simulation. By establishing a finite element simulation model of the module, the impact of module structural design on UTG bending stress is studied; at the same time, a crack propagation theory is established, and through the "dislocation bending" control method, UTG that meets the stress conditions is selected to meet the requirements of long-term bending (>200,000 times). This study not only helps to improve the reliability and service life of UTG products, reducing failures caused by cracks, but also provides optimized design solutions for end customers, reducing production costs and enhancing product competitiveness. In addition, this study will also promote the technological progress of the UTG industry, improve product performance and reliability standards, and provide scientific basis for the formulation of technical specifications and quality standards in related industries.

2. Theoretical Research

2.1 Glass Fracture Mechanics Theory

The fracture behavior of glass can be described by fracture mechanics theory. In 1920, Griffith proposed the brittle fracture theory, which characterizes the stress field distribution at the crack tip through the stress intensity factor K. For a given crack shape, the stress intensity factor K can be expressed as:

$$K = \sigma\sqrt{\pi a} \tag{1}$$

where σ is the applied stress, and a is the geometric parameter related to the crack shape. When K reaches the critical value K_c, it is called the critical stress intensity factor, and the crack will undergo rapid propagation[2].

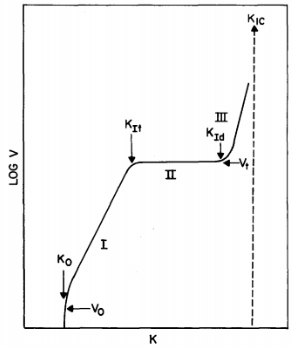

Figure 1. Schematic representation of the effect of crack tip stress intensity, K, on crack velocity, V, during slow crack growth.

Numerous studies have shown that under specific environmental conditions (temperature, humidity, etc.), there is a definite relationship between the crack propagation speed V and the stress intensity factor K. As shown in Figure 1, K_0 represents the threshold value for extremely slow crack propagation, at which the crack propagation speed is extremely low (in brittle materials <10^(-10)m/s), and the product can be used for a long time without rapid fracture; K_{Ic} represents the critical value for rapid fracture, and exceeding this value will cause catastrophic crack propagation[3].

Based on extensive experimental data, there is usually a certain proportional relationship between K_0 and K_{Ic}. Based on BOE's product development experience, K_0 is approximately 0.3 times K_{Ic}. Accordingly, the safe stress σ_{th} for long-term use of UTG can be derived:

$$\sigma_{th} - \sigma_{cs} = \frac{\sigma_s - \sigma_{cs}}{\frac{K_0}{K_{Ic}}} \qquad (2)$$

where σ_{cs} is the compressive stress formed on the glass surface by the low-temperature ion exchange method; σ_s is the simulation stress in the module stack design (excluding UTG internal stress). The safe stress calculated by this formula can be used to determine the minimum control value of 2PB test in product manufacturing[4].

2.2 Finite Element Simulation Model

This study uses finite element software to establish the simulation model. For the constitutive model of the adhesive material, a hyperelastic-linear viscoelastic model is used. Although hyperelastic-nonlinear viscoelastic constitutive models based on continuum mechanics theory have been proposed in recent years, due to their numerous parameters and convergence issues, this study chooses the more stable hyperelastic-linear viscoelastic model.

The linear viscoelastic part is obtained through DMA temperature scanning and frequency scanning experiments. This model is based on the rheological theory under small strain conditions and can better predict the mechanical behavior of materials under different strain rates when combined with the hyperelastic model. This study uses a 13th-order Prony series to describe the linear viscoelastic part [5]:

$$G(t) = G_0\left[1 - \sum_{i=1}^{M} g_i\left(1 - e^{-\frac{t}{\tau_i}}\right)\right] \qquad (3)$$

where $G_{(t)}$ is the relaxation modulus, G_0 is the instantaneous modulus, g_i and τ_i are the shear relaxation modulus and relaxation time, respectively.

For the nonlinear elastic and hyperelastic behavior of OCA (describing the tensile properties of OCA under large strains), this study uses the Yeoh model for calibration [6][7]:

$$W = \sum_{i=1}^{3} C_{i0}(I_1 - 3)^i + \sum_{i=0}^{3} \frac{1}{D_i}(J-1)^{2i} \qquad (4)$$

where W is the strain energy density, J is the volume ratio before and after deformation. For incompressible materials, J=1. Ci0 and Di are input parameters obtained through tensile experiments. I1, I2, and I3 are the three invariants of the Green deformation tensor, which can be expressed by the principal stretches λ_1, λ_2, and λ_3:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \qquad (5)$$

$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2, \qquad (6)$$

$$I_3 = \lambda_1^2\lambda_2^2\lambda_3^2, \qquad (7)$$

For uniaxial tensile tests, λ_1=λ, λ_2=λ_3=λ^(-1/2), the stress-strain relationship can be expressed as:

$$\sigma = [2C_{10} + 4C_{20}(I_1 - 3) + 6C_{30}(I_1 - 3)^2](\lambda - \lambda^{-2}) \qquad (8)$$

where σ is the nominal stress.

3. FEA Stack Up Analysis

3 Analysis of the Influence of Stack up Parameters on UTG Stress

This section mainly studies the influence of stack up parameters on the stress distribution of Ultra-Thin Glass (UTG). Through systematic finite element simulation analysis, the mechanism of the influence of stack up thickness and modulus on UTG stress is explored, providing theoretical basis and design guidance for reducing UTG crack risk.

3.1 Influence of Stack-up Thickness on UTG Stress

To study the influence of different layer thicknesses on UTG stress, this study designed a series of control experiments. In the experiments, considering every film mass production requirements，the UTG thickness was kept constant at 30μm, and the thickness ratios of other layers were changed for parameter research. Table 1 lists seven different stack up thickness ratio schemes.

Table 1. Stack Up Thickness Ratio Experimental Design

Stack up （Thickness Ratio）	**split1**	**split2**	**split3**	**split4**	**split5**	**split6**	**split7**
PI1/PET1	1	1.6	1	1	1	1	1
OCA0	1	1	0.5	1	1	1	1
UTG	1	1	1	1	1	1	1
OCA1	1	1	1	0.5	1	1	1
PNL	1	1	1	1	1	1	1
OCA2	1	1	1	1	1	1	1
PI2/PET2	1	1	1	1	0.5	1	1
OCA3	1	1	1	1	1	1	1
PI3/PET3	1	1	1	1	1	0.4	1
OCA4	1	1	1	1	1	1	1
BKT	1	1	1	1	1	1	0.8

The simulation results show that the influence of different layer thicknesses on UTG stress varies significantly. As shown in Figure 2, the thickness changes of PI1/PET1 and OCA1 have the most significant impact on UTG stress, while the thickness changes of other layers (such as OCA0, OCA2, etc.) have relatively little impact on UTG stress. This difference may be due to the direct contact between PI1/PET1 and OCA1 with UTG, and their thickness changes directly affect the stress transfer path.

Detailed analysis shows that the influence of the thickness of each layer in the stack up structure on UTG stress varies significantly. The thickness changes of OCA0, OCA2, PI2/PET2, OCA3, PI3/PET3, OCA4, and the support layer have little impact on UTG stress, indicating that UTG stress is not sensitive to the thickness changes of these layers. However, the thickness changes of the PI1/PET1 and OCA1 layers have a significant impact on UTG stress, as these two layers are directly involved in the stress transfer and distribution process.

To further explore the quantitative relationship between the thickness of PI1/PET1 and OCA1 and UTG stress, this study designed more detailed thickness gradient experiments (Table 2, Table 3). The experiments focused on the thickness changes of PI1/PET1 in the range of 20-70μm and the thickness changes of OCA1 in the range of 10-50μm.

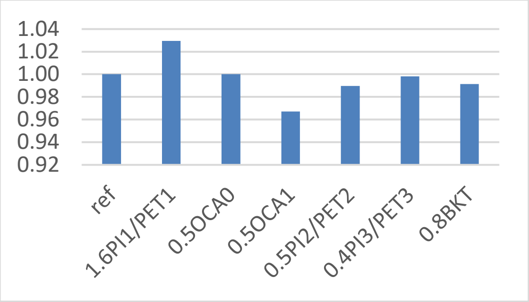

Figure 2. UTG Stress Variation Bar Chart

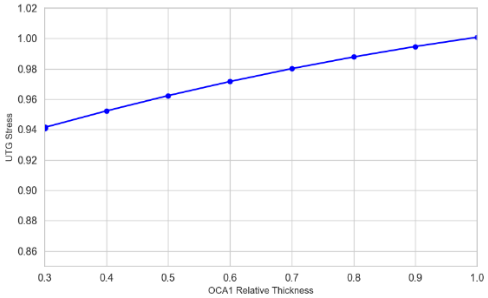

Figure 3. Relationship between UTG Stress and Thickness Changes of OCA1

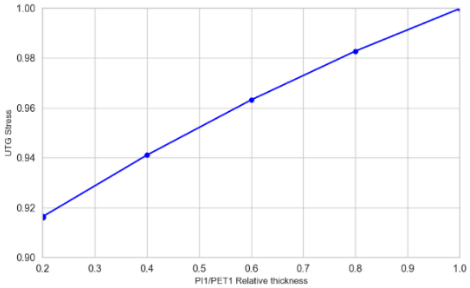

Figure 4. Relationship between UTG Stress and Thickness Changes of PI1/PET1

The research results show:

1. UTG stress is positively correlated with the thickness of the PI1/PET1 layer. This is mainly because the increase in the thickness of the PI1/PET1 layer causes the neutral layer of UTG to move to the upper surface, making the lower surface of UTG bear greater tensile stress.

2. UTG stress is also positively correlated with the thickness of OCA1, and when the thickness of OCA1 decreases to 10µm, the reduction in UTG stress is significantly increased. This indicates that OCA1, as a dislocation buffer layer, can reduce the tensile stress on the lower surface of UTG to the minimum when its thickness is reduced to a specific value.

In addition, this study also compared and analyzed the bending stress and rebound force of 30µm, 40µm, and 50µm thick UTG under the same stack up structure and bending radius conditions, as shown in Table 4.

Table 4. Comparison of Bending Stress and Rebound Force of Different UTG Thicknesses

ITEM	30UTG	40UTG	50UTG
Bending Stress	1	1.33	1.66
Rebound Force	1	2.41	4.66

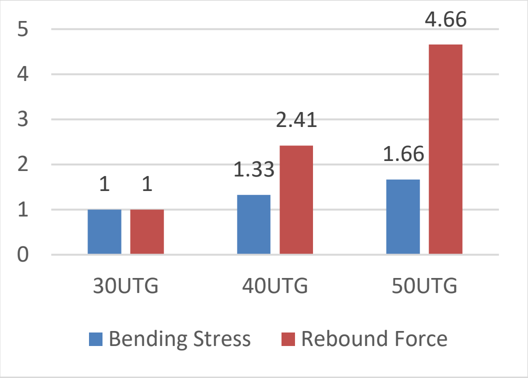

Figure 5. Relationship between Bending Stress and Rebound Force of Different Thicknesses of UTG

The experimental results show that UTG thickness is positively correlated with both bending stress and rebound force, and the increase in rebound force is greater than that of bending stress. This finding has important guiding significance for the selection of UTG thickness.

3.2 Influence of Stack-up Modulus on UTG Stress

To study the influence of the modulus of each layer material in the stack up structure on UTG stress distribution, this study designed a series of simulation experiments with different layer moduli. The experiments mainly focused on the modulus changes of key layers such as PI/PET, OCA0, and OCA1, as shown in Table 5.

Table 5. Stack Up Modulus Difference Experimental Design

Stack up (modulus)	DOE1	DOE2	DOE3	DOE4	DOE5	DOE6	DOE7	DOE8
PI1/PET1	E1	1.5E1	E1	←	←	←	←	←
OCA0	E2	←	3E2	E2	←	←	←	←
UTG	E3	←	←	←	←	←	←	←
OCA1	E4	←	←	3E4	E4	←	←	←
PNL	E5	←	←	←	←	←	←	←
OCA2	E6	←	←	←	←	←	←	←
PI2/PET2	E7	←	←	←	50E7	E7	←	←
OCA3	E8	←	←	←	←	←	←	←
PI3/PET3	E9	←	←	←	←	0.5E9	32E9	E9
OCA4	E10	←	←	←	←	←	←	←
BKT	E11	←	←	←	←	←	←	0.5E11

Based on the simulation results, the relationship between UTG stress and stack up modulus changes was plotted (Figure 5).

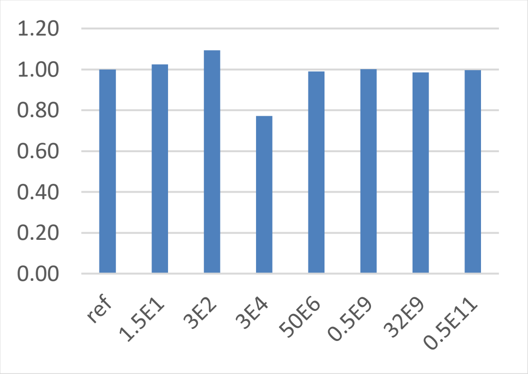

Figure 6. Relationship between Bending Stress and Rebound Force of Different modulus

Detailed analysis of the data led to the following main conclusions:

1. Increasing the modulus of OCA0 significantly increases UTG stress. This is because OCA0 is in direct contact with UTG, and its increased modulus weakens the dislocation buffering effect, transferring more tensile stress to the UTG bottom surface.
2. Increasing the modulus of OCA1 can significantly reduce UTG stress. This phenomenon is due to the increased modulus of OCA1, which plays a role in stress conduction in the neutral layer. When the neutral layer shifts to the lower surface of UTG, it reduces the tensile stress on the UTG bottom surface.
3. The modulus changes of other layers have relatively little impact on UTG stress, indicating that in structural optimization design, attention should be focused on the material selection of OCA0 and OCA1.

To further clarify the quantitative impact of the modulus of OCA0 and OCA1 on UTG stress, this study designed a more detailed modulus gradient experiment (Table 6/7). The experiment focused on the variation of the OCA0 modulus in the range of 0.25 times E2 to E2, and the variation of the OCA1 modulus in the range of E4 to 2.5 times E4.

Based on the simulation results，relationship between UTG stress and the modulus changes of OCA0 and OCA1 was plotted (Figures 6 and 7).

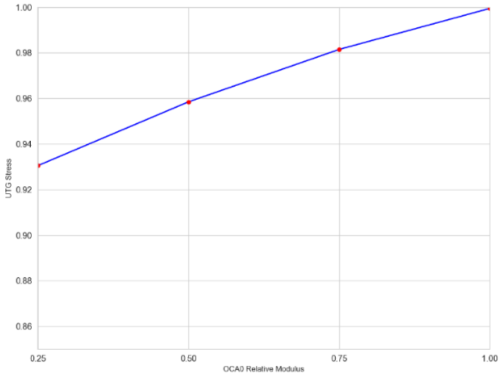

Figure 7. Relation between UTG stress and OCA0 modulus

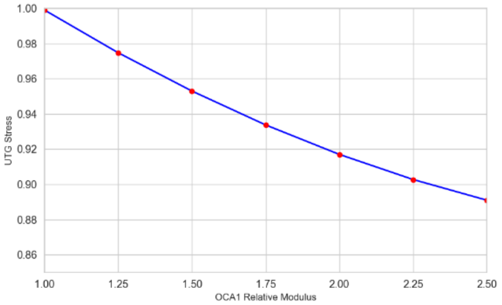

Figure 8. Relation between UTG stress and OCA1 modulus

The research results show:

1. UTG layer stress is negatively correlated with the modulus of the OCA1 layer, gradually decreasing as the modulus of OCA1 increases.
2. UTG layer stress is positively correlated with the modulus of OCA0, gradually increasing as the modulus of OCA0 increases.

4. Conclusions and Future Perspectives

This comprehensive investigation of UTG mechanical behavior in flexible displays through finite element analysis has yielded significant insights into structural optimization strategies. The research demonstrates that increasing the elastic modulus of the OCA1 layer effectively mitigates UTG stress, though this modification requires careful consideration of its effects on PNL film strain and adhesive layer stress. Maintaining optimal interfacial adhesion strength remains crucial during implementation. Similarly, reducing the OCA0 layer modulus presents an effective approach for UTG stress minimization with minimal impact on adjacent layers, provided adequate cohesive properties are maintained in the adhesive material.

While thickness reduction of the PI1/PET1 layer theoretically offers stress reduction benefits, this approach significantly compromises surface impact resistance, potentially increasing UTG vulnerability to mechanical damage. Furthermore, although reducing OCA1 layer thickness below 20μm achieves notable stress reduction, this strategy is not recommended due to potential compromise of the neutral layer dislocation mechanism and subsequent delamination risks.

Implementation of the optimization strategies requires consideration of multiple interrelated factors, including cost implications of modulus modifications and processing complexities from material parameter adjustments. Comprehensive evaluation of optical performance and long-term reliability remains critical.

Future research should focus on incorporating environmental factors and establishing reliability assessment systems. This study provides key insights for structural optimization of flexible displays, emphasizing the necessity of holistic approaches to UTG implementation challenges. Advancing this technology requires continued collaboration across materials science, mechanical engineering, and manufacturing to achieve optimal solutions for next-generation flexible displays.

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