

Weibull-Based Strength and Reliability Model of UTG for Flexible OLEDs

Yongxiao Gao, Shiyong Wang, Wei Qing, Lei Zhang
 Chengdu BOE Optoelectronics Technology Co., Ltd.

Abstract

This study employs the 2PB test method to collect strength data of UTG processed with different technologies, which shows good conformity to the Weibull distribution. The research explains the reasons for the differences in Weibull distribution parameters, highlights the necessity of controlling certain key specifications, and provides recommendations for glass selection. Furthermore, based on Weibull distribution parameters from multiple mass production projects and simulated stress levels, combined with the CDF of the Weibull distribution, a relationship model between predicted and actual failure probabilities of UTG under various stress levels is established. This study provides new insights into large-scale performance prediction and failure analysis of UTG in flexible display technology, making a significant contribution to improving the reliability and durability of OLED devices.

Author Keywords

Ultra-Thin Glass, Two-Point Bending Test, Weibull Distribution, Failure Probability Model, Flexible OLED.

1. Introduction

With the rapid development of flexible display technology and the emergence of new form factors such as foldable and rollable devices, Ultra-Thin Glass (UTG) has become an indispensable material in the manufacturing of flexible Organic Light-Emitting Diode (OLED) devices, owing to its superior optical performance, mechanical stability, and excellent thermal properties^[1-2]. UTG has been in mass production as an OLED cover material for over four years, with a future trend towards its use as a supporting component.

Despite extensive mechanical testing performed on UTG with varying thicknesses, materials, and structural configurations (such as dynamic bending, two-point bending (2PB), proof testing, pen drop), current research exhibits significant limitations^[3-7]. These studies typically focus on describing single instances of UTG failure or short-term mechanical behavior without providing a comprehensive statistical description of failure phenomena. This approach overlooks the inherent variability in UTG failure behavior, primarily stemming from the uneven propagation of original cracks under stress. Moreover, existing research fails to adequately address long-term failure probabilities under actual operational conditions, particularly in the context of varying stress levels. This gap in understanding poses significant challenges for the reliable implementation of UTG in foldable OLED devices, where long-term performance and failure prediction are crucial.

To address these limitations, we introduce the Weibull distribution, utilizing extensive data to compare differences between product batches and explain the reasons for these variations. Additionally, we predict the failure probability of UTG under specific stress conditions in flexible OLED devices, establishing and elucidating the connection between the predicted failure probability and the actual failure rates observed in experimental data from mass production projects.

2. Testing and Data Processing Methods

Testing Method: The 2PB test is a standard procedure used to

evaluate the bending strength of brittle materials such as UTG. The primary objective of this method is to assess the influence of intrinsic defects on the material's overall strength^[4-5]. In the 2PB test setup, the sample is placed between two parallel plates and a force is applied causing the parallel plates to move towards each other slowly until the sample fractures. The distance D between the parallel plates at the moment of fracture is recorded. At the moment of fracture, the maximum tensile stress σ on the surface of the specimen is the strength of the glass and can be calculated using the formula:

$$\sigma = 1.198E \frac{t}{D - t} \quad (1)$$

where E is the elastic modulus and t is the thickness of the UTG.

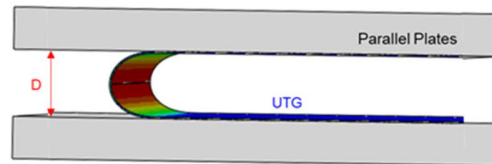


Figure 1. Schematic Diagram of 2PB Test.

The 2PB test is particularly valuable as it provides indirect insights into the distribution of defect depths within the glass. Given the challenges associated with directly measuring the depth of internal defects, the 2PB test serves as a practical and effective method for characterizing the strength of the glass, thereby reflecting the distribution of these defects.

Data Processing Method: To better understand the strength distribution of UTG materials, it is essential to consider the impact of intrinsic defects on the material's overall strength^[8]. The strength of glass materials is influenced predominantly by the depth of defects. Research indicates that the distribution of defect depths follows a Weibull distribution, which can be used to evaluate the strength distribution of products.

The cumulative distribution function (CDF) of Weibull distribution is given by:

$$F(\sigma; \lambda, \beta) = \int_0^\sigma f(\sigma; \lambda, \beta) d\sigma = 1 - e^{-\left(\frac{\sigma}{\lambda}\right)^\beta} \quad (2)$$

where β is the shape parameter indicating the variability of the strength data, and λ is the scale parameter indicating the overall strength level^[9].

To estimate the Weibull distribution parameters from a series of UTG bending strength data, a sufficient number of data points n (typically $n > 32$) are required. The parameters are determined using the Maximum Likelihood Estimation (MLE) method^[10]. This approach provides a robust and statistically sound way of estimating the parameters, ensuring accurate prediction of the strength distribution of UTG under various stress scenarios.

3. Discussion

Weibull Parameters of UTG - Factors and Impact: Two distinct batches of samples were prepared using new and conventional technologies. The new technology differs from the conventional one in several aspects, including material composition, manufacturing processes, and chemical tempering parameters. From each batch, 100 samples were selected for the 2PB test. Based on the 2PB strength data, the Weibull probability plot shown in Figure 2 was constructed.

The Weibull analysis for the samples produced using the new technology yielded a shape parameter $\beta = 5.164$ and a scale parameter $\lambda = 3847$. In contrast, the analysis for the samples produced using the conventional technology resulted in a shape parameter $\beta = 4.608$ and a scale parameter $\lambda = 3582$. The goodness-of-fit measures, including the Anderson-Darling (AD) statistic and the associated P-value, indicated a strong match between the empirical data and the Weibull distribution for both technology groups, suggesting that the Weibull model provides an accurate representation of the strength distributions for both sample sets.

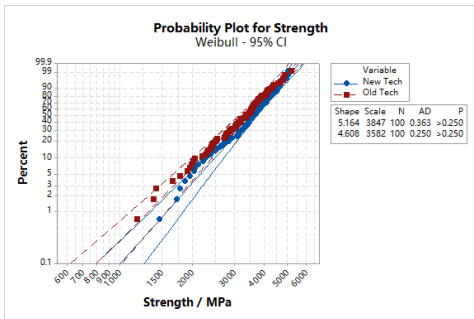


Figure 2. Weibull Probability Plots Comparing UTG Strength Distributions of New and Old Technologies. Finite element analysis, based on the stacking configuration and folding geometry of the foldable OLED module, enables the determination of parameter x in Equation 2. This allows for the prediction of UTG failure probability under specific conditions, as illustrated in Figure 3. The analysis reveals that at $x = 1000$ MPa, the failure rates for the conventional and new technologies are 2792 ppm and 951 ppm, respectively. These results quantitatively demonstrate that the UTG produced using the new technology exhibits a failure probability of approximately 30% compared to that of the conventional technology when subjected to a stress of 1000MPa.

To gain a deeper understanding of the Weibull parameters, it is crucial to elucidate their statistical significance and the influence of various factors in UTG processing and fabrication. The Weibull distribution is characterized by two key parameters: the shape parameter β and the scale parameter λ . In the following discussion, we will explore the statistical and physical implications of these essential parameters.

The shape parameter β is a critical indicator of the distribution's form and reflects the homogeneity of the material's strength. A higher β value suggests a more uniform material, which aligns with the reported strength interval for inorganic non-metallic materials ($1 < \beta < 10$).

Comparing the new and old technologies reveals several key differences. The new technology employs advanced materials and incorporates edge polishing in the edge treatment process, significantly improving the quality of the product's edges by

removing most edge chipping defects. As a result, products with superior edge quality exhibit a lower proportion of crack initiation sites at the edges during 2PB testing, indicating that the test predominantly characterizes the size of in-plane defects. This leads to a more concentrated distribution of defects and strengths, thereby contributing to a higher β parameter.

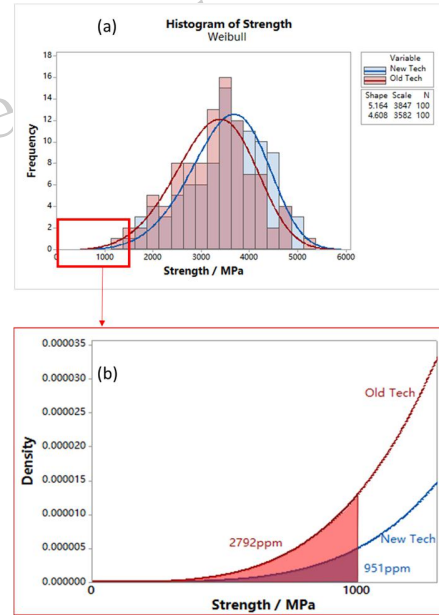


Figure 3. Strength Distribution Analysis of UTG Produced by New and Old Technologies: (a) Histogram of strength data overlaid with Weibull probability distribution curves; (b) Probability distribution plot comparing new and old technologies in the 0-1200 MPa stress range.

Additionally, the new technology not only selects products with a total thickness variation (TTV) $\leq 3 \mu\text{m}$ but also maintains a tighter thickness tolerance of $\pm 4 \mu\text{m}$ within a batch. In contrast, the old technology utilizes products with $\text{TTV} \leq 4 \mu\text{m}$ and a thickness tolerance of $\pm 6 \mu\text{m}$. A smaller TTV implies better uniformity within a single product, minimizing the likelihood of localized stress concentration during bending due to thickness variations. Similarly, a tighter thickness tolerance within a batch suggests a more concentrated strength distribution, which is reflected in a higher β parameter in the Weibull distribution.

Furthermore, the glass raw material forming method significantly influences the β parameter. Typically, glass forming methods can be categorized into down-draw, overflow draw, and float glass processes. In down-draw and overflow draw methods, the product does not come into contact with any medium during formation, interacting only with rollers in the annealing lehr once the temperature drops below the glass transition temperature (T_g). At this stage, the glass structure has stabilized, and any potential defects caused by contact with the rollers can largely be healed during the UTG production process, having minimal impact on the bending performance in 2PB testing. This results in a larger β value in the Weibull distribution. Conversely, float glass, formed on a bed of molten tin, may transfer defects from the molten tin surface to the glass. Moreover, during the annealing process on rollers post-formation, the temperature is relatively higher, closer to T_g . Since the internal structure of the glass is not fully stable at temperatures near T_g , defects formed during this period are more challenging to heal completely during UTG processing, thus

having a greater impact on strength uniformity.

The scale parameter λ in the Weibull distribution represents the characteristic stress level at which 63.2% of the samples fail. It is a crucial indicator of the material's overall strength and is influenced by various factors in UTG processing. The factors previously discussed as influencing the β parameter, such as edge polishing, TTV, and forming methods, also significantly impact the λ parameter. In addition to these factors, surface compressive stress (CS) and elastic modulus also play crucial roles in determining the λ parameter of UTG. The following sections will discuss the influence of these two key factors in detail.

Surface CS introduced during the strengthening process significantly affects the λ parameter. Chemical strengthening treatments impart compressive stresses to the glass surface, effectively inhibiting crack growth. Consequently, products with higher CS levels require greater applied stress to initiate crack propagation, resulting in a larger λ value in the Weibull distribution.

Additionally, the elastic modulus of the glass plays a vital role in determining the λ parameter. The elastic modulus, which represents the material's resistance to elastic deformation, is directly related to the interatomic bonding strength within the glass structure. A higher elastic modulus typically correlates with stronger interatomic bonds, leading to increased resistance to crack initiation and propagation. This enhanced resistance is reflected in a larger λ value in the Weibull distribution.

However, it is important to note that while using UTG with a higher elastic modulus can contribute to an increase in the λ value, thus improving overall strength, it also has significant implications for OLED foldable displays. The rebound force experienced by the OLED screen during the folding process is directly proportional to the elastic modulus of the UTG. As the elastic modulus increases, so does the rebound force of the folding screen, which in turn substantially increases the load on the hinge mechanism. This higher rebound force places greater stress on the hinge, potentially affecting its durability and performance. Therefore, when selecting the elastic modulus for UTG in foldable displays, a delicate balance must be struck between achieving higher strength (larger λ) and managing the increased rebound force to ensure optimal performance and longevity of the folding mechanism.

The Weibull parameters β and λ of UTG are collectively determined by a range of factors, including surface CS, elastic modulus, and processing methods such as edge polishing, TTV control, and forming techniques. The β parameter reflects the uniformity of the material's strength distribution, while the λ parameter indicates the characteristic strength level. These processing factors contribute significantly to both parameters by enhancing the uniformity and consistency of glass strength. The interplay between these elements not only affects the overall strength but also influences the reliability and performance of UTG in various applications. A comprehensive understanding of how these factors interact and their practical implications is essential for optimizing UTG products, with particular importance in emerging fields such as foldable display technologies, where both strength uniformity and characteristic strength play crucial roles.

UTG Failure Prediction vs. Reality - Analysis and Significance: To explore the relationship between the failure probability calculated through the Weibull CDF for UTG single-

strength and the actual failure rates observed during the pre-bending tests and consumer usage of assembled OLED modules, we analyzed data from past mass production projects (with individual shipments exceeding 500,000 pieces). One piece out of every 1,000 shipped was subjected to extreme 2PB testing after proof testing full inspection. All 2PB data collected throughout the product lifecycle were fitted to determine the Weibull distribution parameters β and λ . These parameters were then used in the Weibull CDF to calculate the failure probabilities under the specific stress conditions encountered in the OLED module state. The resulting failure probabilities were 460 ppm, 720 ppm, 1280 ppm, and 1330 ppm, respectively.

In contrast, the actual failure rates observed during pre-bending tests and consumer usage after the final assembly were significantly higher, at 880 ppm, 1820 ppm, 2550 ppm, and 4900 ppm, respectively. This discrepancy highlights the importance of considering post-processing factors and real-world usage conditions in failure rate predictions.

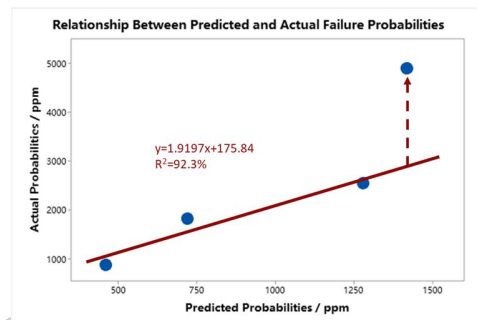


Figure 4. Correlation between UTG predicted failure probabilities and actual failure rates of foldable OLED modules during bending.

As shown in Figure 4, a scatter plot depicting the relationship between the predicted failure probabilities and the actual failure rates reveals a near-linear relationship described by the equation $y=1.9197x+175.84$. The fourth data point deviates significantly from this linear trend.

The observed linear relationship suggests a consistent pattern between predicted and actual failure rates, with actual rates being approximately twice the predicted values plus a constant offset. This relationship provides valuable insights for future failure rate estimations and quality control processes.

It is believed that the good match between the predicted and actual failure rates in the first three projects can be attributed to the following reasons:

a. During the proof test process, existing cracks in the UTG, when subjected to stresses exceeding the critical stress intensity factor, undergo steady-state propagation. However, the rate of crack growth under proof test conditions is relatively slow, and these cracks do not reach critical dimensions, hence passing the proof test. Subsequently, under cyclic stress during pre-bending or consumer usage, these cracks continue to propagate, eventually leading to failure. It is worth noting that due to the low sampling ratio (1/1000), products with cracks that grew but did not fail during Proof Test might not have been detected, contributing to the slope being greater than 1.

b. After the proof test, UTG undergoes several bonding processes. During these processes, environmental particles can interact with the UTG surface through rollers or pads, creating new defects.

These defects typically manifest as arc cracks and half-penny cracks, as illustrated in Figure 5 (a1, a2) and (b1, b2) respectively. These specific defect morphologies are consistent with those reported in the literature, as shown in Figure 5 (c) and (d)^[11]. The arc cracks and half-penny cracks generated during the bonding process become stress concentration points, leading to further crack propagation and eventual failure during subsequent pre-bending or consumer usage. This phenomenon explains why the intercept in our linear relationship is greater than 0.

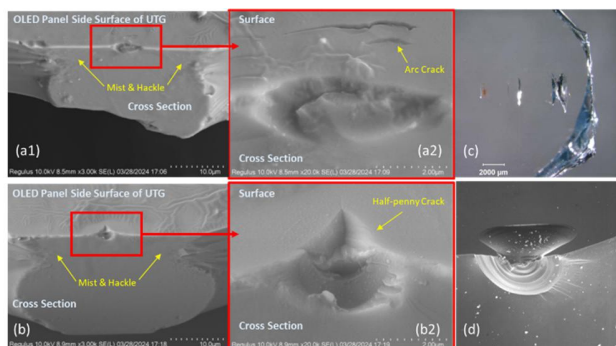


Figure 5. SEM images of defects causing glass fracture: (a1, a2, b1, b2) UTG bending failure in OLED; (c, d) similar cases reported in literature.

The observed linear relationship between predicted and actual failure rates holds true for the first three data points. However, the fourth data point significantly deviates from this established trend. This deviation can be attributed to the introduction of an additional variable during the assembly process:

It is important to note that during the assembly of the OLED screen with the folding device's hinge, battery, and middle frame for the fourth project, an unforeseen issue arose. The dimensional tolerances of certain components exceeded their upper limits, resulting in interference between the screen and the hinge mechanism. This interference introduced abnormal stress on the UTG surface, which was not accounted for in the initial Weibull distribution model. Consequently, this additional stress factor led to an abnormally high failure rate, explaining the significant deviation of the fourth data point from the previously established linear relationship. It also highlights the sensitivity of UTG to additional stresses that may be introduced during the final stages of product assembly.

For UTG, while larger β and λ parameters indeed reduce actual failure probabilities, we must also consider cost factors in real production processes. Improving these parameters typically involves stricter production controls and more advanced materials, inevitably increasing production costs. Therefore, while pursuing higher performance, we need to find a balance point that ensures product reliability while considering cost-effectiveness. This may involve analyzing market demands for different grades of UTG products and continuously optimizing production processes to achieve the best balance between performance and cost.

4. Conclusions

This study employed the 2PB testing method and Weibull distribution analysis to thoroughly investigate the strength characteristics of UTG in flexible OLED applications. The research revealed that different processing technologies, such as

edge polishing and raw material forming processes, significantly affect the shape and scale parameters of the Weibull distribution for UTG. This finding emphasizes the necessity of controlling key specifications like TTV, thickness tolerance, and CS value, providing important guidance for optimizing UTG processing techniques and raw material selection strategies.

Furthermore, based on the analysis of UTG sampling data from multiple mass production projects, combined with finite element simulation and the CDF of the Weibull distribution, we predicted the failure probability of UTG under specified stress levels for corresponding batches. We established a relationship model between predicted and actual failure probabilities, explaining the reasons for the slope and intercept parameters in the model.

The methods and findings of this study not only enhance the understanding of UTG behavior in flexible display technology but also provide crucial evidence for improving the reliability and durability of flexible OLED devices. Future research could further explore the impact of environmental factors (such as temperature and humidity) and dimensional factors (like bending area width and bending form) on UTG performance and lifetime, as well as its potential applications in other flexible electronics fields.

5. References

- Choi J, Kim HJ, Choi MC, Bae JH, Lee SJ, Kang IK. Recent advances in flexible and foldable OLEDs: Materials, fabrication, and applications. *J Mater Chem C*. 2021;9(5):1520-1550.
- Fujiwara Y, Kashima I, Akiba S. Ultra thin chemically strengthened cover glass with high impact failure resistance for foldable devices. *SID Symp Dig Tech Pap*. 2018;49(1):401-404.
- Zhu Y, Xu F, Wang X, Hou C, Zhao Y, Yin D, et al. Mechanical properties of ultra-thin glass used in flexible displays. *Opt Mater Express*. 2018;8(12):3607-3619.
- Mathewson MJ, Kurkjian CR, Gulati ST. Strength measurement of optical fibers by bending. *J Am Ceram Soc*. 1986;69(11):815-821.
- Gulati ST, Westbrook JD, Carley SF, Vepakomma HR, Ono T. Two point bending of thin glass substrate. *SID Symp Dig Tech Pap*. 2011;42(1):652-654.
- Kim SS, Chung WJ, Jung S, Shim G, Shon H, Kim S, et al. Analysis of fracture mechanisms of ultrathin glass for foldable display application. *J Am Ceram Soc*. 2023;106(1):569-581.
- Klein CA. Characteristic strength, Weibull modulus, and failure probability of fused silica glass. *Opt Eng*. 2009;48(11):113401.
- Danzer R, Lube T, Supancic P, Damani R. Fracture of ceramics. *Adv Eng Mater*. 2008;10(4):275-298.
- Weibull W. A statistical distribution function of wide applicability. *J Appl Mech*. 1951;18(3):293-297.
- Khalili A, Kromp K. Statistical properties of Weibull estimators. *J Mater Sci*. 1991;26(24):6741-6752.
- Quinn GD. *Fractography of ceramics and glasses*[M]. Washington, DC: National Institute of Standards and Technology; 2007.