Development of Non-Contact Metrology for Thin Foldable Glass

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Abstract

After chemical strengthening, non-uniformity of ion on the surface of thin foldable glass (TFG) causes non-uniformity of residual stress, thereby decreasing bending strength. In this study, the bending strength could be predicted by measuring the curvature of TFG due to the non-uniformity of residual stress.

Author Keywords

Thin foldable glass; bending strength; residual stress; phase measuring deflectometry; foldable display

1. Introduction

The thin foldable glass (TFG) having a higher strength and a thinner thickness is used for a foldable display. Current, the durability quality of the TFG is managed through repetitive bending test. However, this contact type inspection method not only creates surface defects, but also has the disadvantage of process loss due to particle scattering when cracks occur. Therefore, the development of a bending strength inspection method of a non-contact type is strongly required. Breakage to the glass occurs when stress is highly concentrated on the defect generated on the surface, and the stress required for breakage can be explained by the following theory [1].

$$\sigma_f = \frac{K_{IC} - K_{IC}^{CS}}{Y\sqrt{c}} \tag{1}$$

Here, σ_f is fracture strength, K_{IC} is critical stress intensity factor, K_{IC}^{CS} is critical stress intensity factor after chemical strengthening, Y is geometric factor, and c is initial crack depth. In K_{IC}^{CS}, compressive stress is expressed as negative and tensile stress as positive. Equation (1) shows that the factors affecting the bending strength of the TFG are surface defects, residual stress, and physical properties of the raw material. In order to manage the bending strength, corresponding these factors must be monitored. Among these factors, the most notable in the field is surface defects that occur during the production process. However, since the TFG is very thin, it is not easy to develop a technology to distinguish surface defects from external particles of tens of nanometers. Even if this is distinguished, there is a problem that consistency may be lowered if a defect occurs in the process stage after the inspection. Therefore, we took a different approach from the existing direction of technology development and noted that residual stress affects crack. In this study, an asymmetric free curved surface influenced by the residual stress of the TFG was optically quantified using a phase measuring deflection method. It was verified whether it was possible to predict the bending strength through the measured curvature variables.

2. Measurement devices and setup

Phase Measuring Deflection (PMD)

In order to measure the asymmetric free curved surface of TFG in the production process, sophisticated three-dimensional shape measurement equipment is required. The method using an interferometer is excellent in terms of accuracy, but as the measurement area is limited, there is a time limit in measuring the surface of the TFG. The moiré method investigates a specific pattern on an object and measures the degree of the deformation of the irradiated pattern. However, it has limitations that must be applied to an opaque object. The PMD measures the change in slope of each surface by incident a periodic stripe pattern on the surface of the object, as shown in the Figure 1. And then it analyze the phase of the pattern deformed by the shape of the object. That is, assuming that the shape of the object to be measured is $z=z(x,y)$, the x-axis tilt component ($\partial z/\partial x$) and the y-axis tilt component ($\partial z/\partial y$) can be obtained according to the direction of the pattern incident through the PMD. When the two gradient components in the x-axis and y-axis directions obtained from the measured phase are integrated, the three-dimensional shape of the object can be restored. Using the PMD, the curvature of the transparent TFG can be quantified by overcoming the limitations of existing technologies [2].

Bending strength evaluation

We installed two flat plates in the universal testing machine, put TFG between them, and measured the load when the TFG is broken. The load at this time is recorded as bending strength [3].

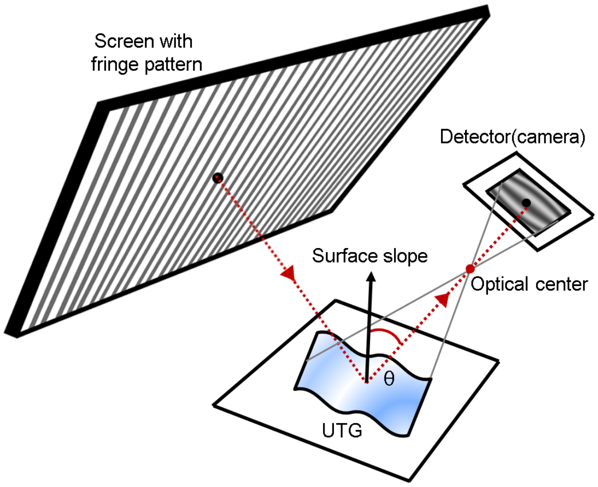

Figure 1. Schematic diagram of phase measuring deflectometry system.

3. Result & Discussion

A cross-sectional image of the broken TFG can be found in the Figure 2(a). During a folding process, cracks are propagated by tensile stress concentrated on the lower defect of the TFG. And then it creats a hemispherical smooth mirror part around the defect. When the crack propagates upward, a hackle is created and the glass is broken. Figure 2(b) shows the mechanism of the glass strengthened through chemical treatment. For chemical strengthening, the bare thin glass is immersed in a bathtub containing a potassium nitrate (KNO_3) solution. At a temperature lower than the cooling point, sodium (Na^+) ions with a small ion radius (0.98Å) of the glass surface are replaced with potassium (K^+) ions with a large ion radius (1.33Å). Since the volume of potassium ions is much larger than that of sodium

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ions, the glass surface is expanded. However, the hard atomic network of glass prevents deformation of the surface. As a result, a surface compressive stress (σ_{SC}) is generated. And a central tensile stress (σ_{CT}) for balancing is generated inside the glass. In order to break the glass, an external stress that can penetrate the compressed stress layer on the surface is required. [4]. Figure 2(c) shows the composition changes of each potassium ion and sodium ion according to the thickness direction measured by a scanning electron microscope (SEM-EDS) having an energy analysis spectrometer. The penetration depth of potassium ions is consistent with the fracture critical depth shown in the Figure 2(a). It can be seen that the TFG is damaged when the crack propagates to a depth greater than the detpth of the compression layer (DOL) of the TFG. Figure 2(d) shows the stress distribution schematic diagram according to the thickness of a general rigid cover glass and the TFG. The 1 dotted line indicates the position where the stress in the TFG is 0. The thickness ratio of the compression layer ($DOL_{Rigid\ glass}$) and the entire rigid cover glass is about 1/50. Since the thickness of the compression stress layer is very thin compared to the total thickness, the internal tensile stress present inside is also very low. However, the thickness ratio of the compression layer (DOL_{TFG}) and the entire TFG is about 1/5. As this result, a very high tensile stress is formed inside compared to the rigid cover glass. If the concentration and in-plane uniformity of potassium ions on the surface of the TFG are decreased, it will have a great influence on residual stress. This change in residual stress will also affect curvature.

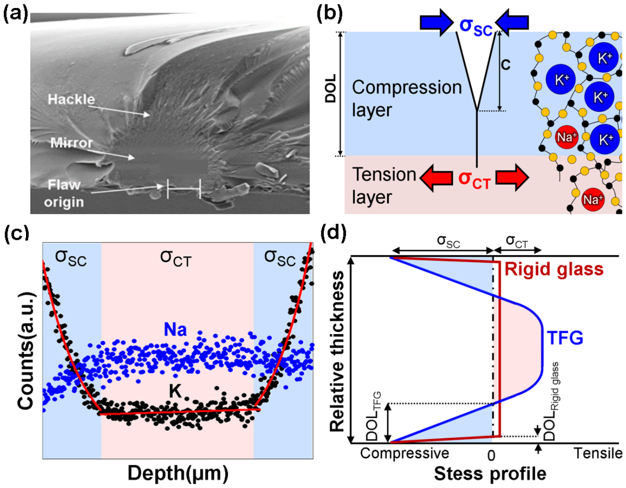

Figure 2 (a) Fractography of TFG (b) A diagram of the fracture mechanism occurring in TFG. (c) SEM-EDX depth concentration profiles of TFG. (d) Comparision of the stress profile between TFG and rigid glass.

After the TFG is physically cut, the first healing process by chemical etching is performed to improve illuminance and remove defects. The second healing process is proceed through a chemical reinforcement process [5]. Figure 3 (a-c) shows that the curvature of the TFG according to the reinforcement process measured by PMD. Inserted images show the curvature of each folding area as a three-dimensional image. Compared to the first healing process (Figure 3(a)), it can be seen that the shade difference in the TFG increases after the chemical reinforcement process (Figure 3(b)). In particular, the shade difference of the outer area is very large.

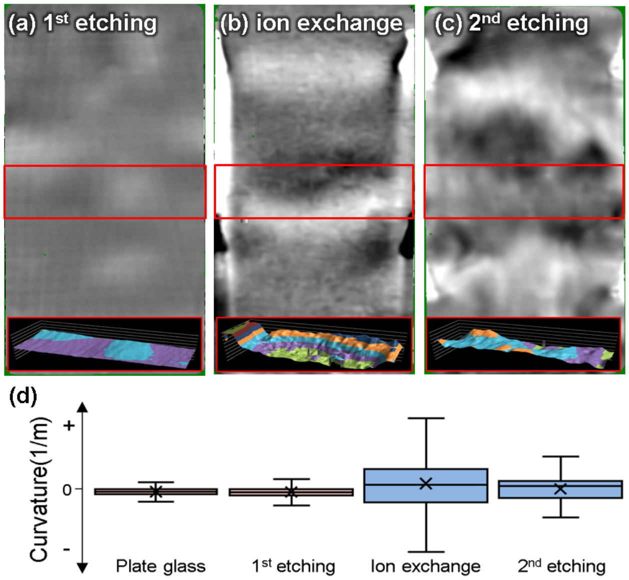

Figure 3. Curvature images of TFG after (a) 1st etching, (b) ion exchange and (c) 2nd etching process. The lower inserted images show the curvature of each folding area as a 3D surface plot. (d) Average curvature value and standard deviation in the folding area of TFG according to each strengthening process

After the second healing process (Figure 3(c)), the shade difference in the TFG decreases compared to the chemical reinforcement process (Figure 3(b)). Figure 3(d) shows the curvature of the folding area quantified. The average curvature between the bare TFG and the TFG after first healing process is equally negative and concave, and the standard deviation is similar. After the chemical reinforcement process, the average curvature increased dramatically and the standard deviation also increased. The average curvature decreases after the second front healing process. However it shows a positive convex shape, it can be seen that the TFG surface expands due to the penetration of potassium ions with a large ion radius after the chemical reinforcement process. The formation of the compressive layer after chemical reinforcement increases the curvature, and the decrease in the thickness of the compressive stress layer after the second healing leads to a decrease in curvature. From this result, it can be confirmed that there is a relationship between the residual stress and the curvature of TFG.

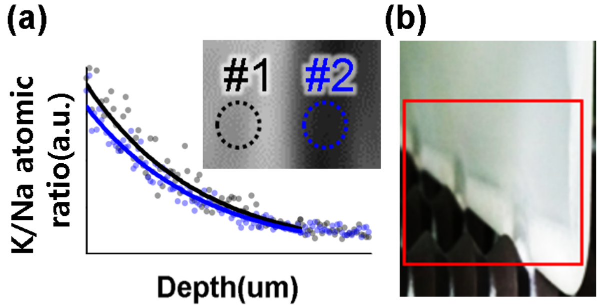

Figure 4. (a) Atomic ratio of K ions and N ions of each shaded position of curvature measured by XPS and SEM-EDS. (b) Image of the contact point with the cassette and the TFG during chemical strength process.

As shown in the Figure 4(a), a gray position 1 position having a high curvature and a black position 2 position having a low curvature were selected in the image measured by the PMD and composition analysis using X-ray photoelectron spectroscopy was performed. The potassium ion composition ratio to sodium of 1 position was higher than that of 2 position. However, the thickness difference of the compressive layer is not confirmed. It is judged that the surface concentration can affect the curvature more than the diffusion rate of potassium ions. As shown in Figure 4(b), if ion exchange salts remain unevenly in the contact point between the TFG and the cassette, partial ion substitution will be occured and the compressive stress of the TFG will be non-uniform [6].

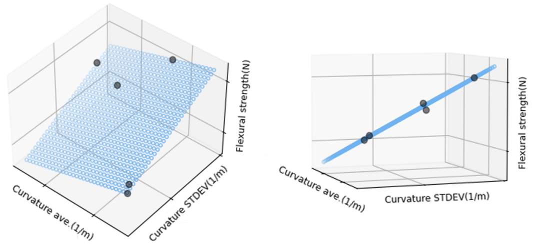

Figure 5. 3D multiple linear regression model of bending strength versus curvature parameters of TFG.

In order to confirm the effect of curvature on the bending strength, the curvature and bending strength of the TFG were measured. A multiple regression model was developed that can predict the bending strength using the measured data as shown in the Figure 5. The coefficient of determination of this model was 0.96. From this result, it was confirmed that the higher the curvature average in the positive direction and the lower the curvature deviation, the higher the bending strength.

4. Conclusion

During the chemical reinforcement process, residual salts generated at the contact point between the cassette and the TFG can induce a non-uniform ion exchange and produce asymmetric free surfaces of the TFG. A slight non-uniform stress difference on the TFG surface may show a large curvature difference. In this study, the asymmetric free curved surface of transparent TFG was optically quantified using the PMD. And it was confirmed that the bending strength increases when the curvature, which is influenced by the potassium ion distribution on the surface, is uniform. In addition, a bending strength prediction model with a coefficient of determination of 0.96 was derived by applying the measured curvature variables. If the bending strength prediction model is supplemented with more measurements, a quality control of the TFG through optical monitoring will become more reliable.

5. References

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