Development of a Crack Cutting Method for Glass Plates Used for Flat Panel Displays

K. Suzuki¹, Y. Shishido¹, T. Shino², M. Iwai², T. Uematsu³
¹Department of System Engineering, Nippon Institute of Technology
Miyashiro, Saitama 345-8501, Japan
²Engineering Division, THK CO., LTD
Shinagawa, Tokyo 141-8503, Japan
³Department of Mechanical Systems Engineering, Toyama Prefectural University
Kosugi, Toyama 939-0398, Japan

Abstract
With a purpose to develop a new breaking method for brittle materials with high precision and high accuracy, indentation of glass surface using an inclined pyramid type indenter is proposed. It was reported that for an indentation angle of θ₁=3°, crack occurs straight in the inclination direction along the diagonal corners of the indent even for a single indent, and the probability of occurrence of the crack is rather high even for low loading. In this paper, study on the crack occurrence mechanism, analysis of the distribution of various stress, strain and hydrostatic pressure along with 3D FEM analysis using ductile fracture criteria is performed. As a result of this analysis, the fracture coefficient (C value) distribution, the qualitative measurement of crack propagation as well as propagation position of the indentation by a single pyramid indenter was obtained. Intermittent indentation using an indenter with an indentation angle of θ₁=3° at a uniform interval of δ=30μm along the ridge direction was performed. As a result connection between adjacent cracks along the diagonal could be achieved. On breaking the glass panel along a direction parallel to the diagonal crack direction, a good surface could be obtained. Finally a prototype inclined pyramid indenter type scribing machine based on the research results was manufactured and was found to work satisfactorily.

Keywords: LCD glass, Scribing, Crack cutting method, Pyramid Indenter, Inclined Indenter, FEM analysis

1 INTRODUCTION
For the purpose of developing a new breaking technology for brittle materials, the authors have been carrying out fundamental research on crack initiation and its control for indentation into a glass panel with a diamond pyramid indenter. In the previous reports [1 - 3], the condition of crack occurrence was investigated from the viewpoints of the indentation angle and the loading weight. As a result, it has been found that, in case of the indentation angle of θ₁=3°, straight crack occurs only in the direction of inclination of the indenter along the line passing through the diagonal corners of the indent even for a single indentation. The probability of the occurrence of the crack was found to be rather high.

In this study, in addition to a 3D FEM analysis of the various stresses and strains using ductile fracture criteria, the modulus of rupture was also evaluated, and the mechanism of crack initiation with an inclined pyramid indenter has been studied. To cause high precision breaking in brittle materials, the condition of crack propagation and breaking characteristics of the glass plates were investigated for intermittent indentation with an inclined indenter.

2 CRACK PROPAGATION BY A SINGLE INDENT
2.1 Crack propagation in indentation by a pyramid indenter
Experiments on glass indentation at an inclination were carried out by setting the workplace at an inclination on the wedge spacer vise of a micro Vickers hardness tester as shown in Figure 1. The experimental conditions were listed in Table 1. A standard diamond pyramid indenter (facing angle of 136° and angle of indentation of 148°) of a micro Vickers hardness tester was used for indentation into a thin glass plates (t 0.7mm) used for LCD panel, and set on the wedge spacer. Indentation conditions such as loading weight of W=2, 5N, loading speed of V=3mm/min and holding time of t=10s were used with varying indentation angles of θ₁=0°, 3°, 5°, and 7°.

Figure 2 shows the condition of the cracks and the frequency and position of the crack initiation at a low loading weight of W=2N at which the crack propagated remarkably. No crack propagation was observed for the indentation angle of θ₁=0°. For the indentation angle of θ₁=3° crack propagated from both corners of the diagonal in the direction of inclination and the probability of crack propagation in the inclination direction was 90%. In the
Table 1: Specifications of the experimental devices and conditions.

<table>
<thead>
<tr>
<th>Indentation device</th>
<th>Micro-Vickers hardness tester (MVK-C, AKASHI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indenter</td>
<td>Diamond pyramid indenter: facing angle 138°, ridge angle 148°</td>
</tr>
</tbody>
</table>
| Indentation condition | Loading weight: W = 2, 5 N, Indentation angle: θ = 0, 3, 5, 7, 10°  
|                    | Temperature: 23 °C, Humidity: 91 %  
| Common indentation condition | Loading speed: Vw = 3.0 mm/min, Holding time: t = 10 s  
|                    | Number of Indentation: n = 10  
| Workpiece          | Alkali free glass for LCD (NASS, t 0.7 mm) |

Figure 1: Schematic illustration of the inclined indentation experiment.

Figure 2: Influence of Indentation angle on crack initiation.  
(W=2N, Probability of occurrence in parenthesis)

Figure 3: Influence of loading weight on crack initiation.

Figure 4: Crack observation method and examples of observation.  
(θ=3°, W=2N)

2.2 Effect of loading weight

Figure 3 shows the condition of the cracks for the loading weight of W=2 and 5 N with an indentation angle of θ=3° for which crack occurred only in the direction of the inclination. For the loading weight of W=2N, the probability of occurrence of the crack only in the direction of the inclination was 90%. For the weight of W=5N, the occurrence probability of the crack only in the direction of the inclination was 60%.

2.3 Investigation of the mechanism of crack initiation

For investigating the mechanism of crack initiation in the inclined indentation method, the position of the crack initiation and the propagation direction of the crack were observed in detail.

The propagation of a crack, which occurred from the indent corner, in the thickness direction of the glass was observed by setting CCD cameras on both sides of the crack. Figure 4 shows the observation method and examples of the observation. The widths of the cracks observed from both sides were same (b=4μm), which means that the crack propagated in the direction perpendicular to the glass surface. It was also found that the depth of the crack calculated from the relationship, H=b/2sinθ, was 8μm which is larger than the depth of the indent (by nearly 3μm).
3 ESTIMATION OF CRACK PROPAGATION MECHANISM FOR INDENT CORNER USING FEM ANALYSIS

To investigate the crack propagation mechanism, FEM analysis for the distribution of the various stresses, strains and hydrostatic pressure was performed using the ductile fracture criteria. The qualitative measurement of the crack propagation as well as the propagation position of the indentation by a single pyramid indenter was obtained from the analysis result of the fracture coefficient (C value) distribution.

3.1 Analysis parameters and method

Analysis model and indent condition

Figure 5 shows a 3D indentation model for the analysis constructed using I-DEAS (SDRC). The model is constructed by using about five thousand triangular pyramid type elements. An elastic-plastic analysis of this model was performed using the conditions shown in Table 2. Analysis software is Deform 3D (SFTC Co.), which is a very commonly used analysis software in the field of plasticity. The top of the indenter forms a facing angle of 135° and ridge angle of 148° and indentation angles of θ1 = 0, 3, 5, and 7° similar to those in the experiments are used. Indentation depth is 2.87μm from the surface of the glass panel (t 0.7mm) sample. This indentation depth value is the same as that obtained by applying a 2N loading weight on the pyramid indenter. The indentation speed is V = 0.05mm/s (3mm/min), which is the same as that of the micro-vickers hardness tester.

Material properties of the test glass panel were obtained from the tensile test data. Tensile test piece size was decided as per JIS8: width = 25, thickness = 0.7, and length = 50mm. The tensile test was performed on a standard tensile tester at a speed of f = 10mm/min. The measurement of the elongation was carried out by means of an extensometer mounted on the tester.

Analysis using modulus of rupture value

(1) Present analysis method and problems

The analysis of the stress-strain during the interference between the outer work layer and the grinding wheel was based on the assumption of ductile fracture of brittle material in grinding up to now. However, it is difficult to obtain a 3D material variation in the breaking of brittle materials with respect to crack propagation direction and control mechanism using the 2D analysis results.

Further, it is generally difficult to make estimates regarding the ease of crack initiation and initiation point from the analysis results for stress and strain. This is because various stresses and strains of a complex nature are believed to be involved.

In the shearing of steels, it was previously thought that the ease of crack initiation was due to a large hydrostatic pressure, and the direction of crack initiation (extension) was influenced by the value of the shear stress increment and the principal stress direction. In recent years however, various ductile fracture criteria have been proposed and the fracture coefficient value obtained using these has been increasingly used in crack generation mechanisms.

(2) Ductile fracture criteria for the analysis

The equation used for the analysis is a modified version of the Cockcroft & Latham fracture equation (Table 2).

The ease of crack initiation can be estimated from the analysis result of the modulus of rupture (C value). For the sake of comparison, the analysis has to be carried out in the same manner for each type of stress and strain.

<table>
<thead>
<tr>
<th>Analysis device</th>
<th>CPU : Pentium-III (600MHz)=2, 512MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software</td>
<td>Make out model : I-DEAS (SDRC)</td>
</tr>
<tr>
<td></td>
<td>3D FEM analysis software : Deform-3D (SFTC)</td>
</tr>
<tr>
<td>Physical properties type</td>
<td>Workpiece : Elasto-plastic solid</td>
</tr>
<tr>
<td></td>
<td>Indenter, Holder : Rigid</td>
</tr>
<tr>
<td>Indenter</td>
<td>A standard diamond pyramid Indenter for a micro Vickers hardness tester (facing angle of 135° and ridge angle of 148°)</td>
</tr>
<tr>
<td>Analysis condition</td>
<td>Number of analysis step : 100</td>
</tr>
<tr>
<td></td>
<td>Number of elements : 5000 (Triangular pyramid)</td>
</tr>
<tr>
<td></td>
<td>Indentation angle : θ1 = 0, 3, 5, 7°</td>
</tr>
<tr>
<td></td>
<td>Indentation speed : Vw = 0.05mm/s</td>
</tr>
<tr>
<td></td>
<td>Depth of Indent : h = 2.87μm</td>
</tr>
<tr>
<td></td>
<td>Friction coefficient : μ = 0.05 (Glass &amp; Indenter)</td>
</tr>
<tr>
<td></td>
<td>Material property : Young's modulus 70GPa</td>
</tr>
<tr>
<td></td>
<td>Poisson's ratio 0.24</td>
</tr>
<tr>
<td></td>
<td>© = 2382.06±2.58E−08 (plastic stage)</td>
</tr>
</tbody>
</table>

Table 2: Analysis devices and conditions.

(3) Definition of physical conditions pertaining to processing

The presence of unwanted scrap within the circumference of the indent after indentation was not observed. The occurrence of large cracks within the perimeter of the indent was not observed and the indent was cleanly transcribed onto the glass panel. From now onwards, it shall be considered that the indentation is caused due to plastic deformation, and the glass will be handled as an elasto-plastic solid.

3.2 Results of the analysis

Stress-strain and hydrostatic pressure distribution

At first an analysis as shown in Figure 6 is carried out to explain the deep relation between the hydrostatic pressure distribution and the ease of crack formation at the section in the vicinity of the bottom of the indent. In accordance with the experimental results, indentation angle θ1=3° was used for the analysis.

Figure 7 shows the analysis results. Since sections 3 and 4 are symmetrical about the X-axis, as is evident from Figure 6, the hydrostatic pressure distribution will be the same at both the sections and therefore only section 3 is shown in Figure 7.

Although analysis for each type of stress-strain was carried out, no large difference in the hydrostatic pressure distributions between the sections was observed. It can therefore be said that it is quite difficult to estimate the crack initiation direction as well as the point of initiation from the hydrostatic pressure, stress and strain distributions alone.
Distribution of modulus of rupture (C value)

Analysis of the modulus of rupture (C value) was performed. Figures 8(a) - (d) show the C value distribution at various cross sections and indentation angles.

For the indentation angle of $\theta_1=0^\circ$, the C value distribution remained the same at all the sections (1 – 3).

In the case of $\theta_1=3^\circ$, the C values of the ridge directly under the cross sections 1 and 2 are rather high (0.035 at the section 1) compared to that at the section 3.

However, when $\theta_1$ increases to $5^\circ$ and $7^\circ$, the C value becomes larger and the difference in the C values at the various sections reduces as shown in Figures 8(c) and (d).

3.3 Observations

For $\theta_1=0^\circ$, the C value directly below the ridge is small at any section compared to other values of $\theta_1$. These values being the same, the application of a larger load may result in a randomly occurring cracks by the various corners in a direction A – D as shown in Figure 6.

In the case of $\theta_1=3^\circ$, the C value below the ridge line at section 1, 2 is higher compared to that at section 3. Due to this the possibility of crack initiation in A and B directions can be estimated to be high.

In the case of $\theta_1=5^\circ$ and $7^\circ$, the C value is large at all the cross sections, however, a large difference between the C values is not present. Therefore, although the formation of a crack may be easier than in the case of $\theta_1=3^\circ$, the control of this crack propagation is very difficult compared to $\theta_1=3^\circ$.

The above estimates agree with the experimental results (shown in Figure 2).

![Figure 6: Schematic illustration of definition for indent and several sections.](image)

![Figure 7: Distribution of hydrostatic pressure under the indent. unit(MPa) ($\theta_1=3^\circ$, $h=2.87\mu m$, $V_r=0.05mm/s$).](image)

![Figure 8: Influence of distribution of modulus of rupture (C value). ($h=2.87\mu m$, $V_r=0.05mm/s$).](image)
4 CRACK PROPAGATION USING REPEATED INDENTATIONS

With a purpose of developing a new breaking technology for brittle materials, investigation on crack initiation and control using a pyramid type diamond indenter on a glass panel was performed.

4.1 Crack initiation by two successive indents

Indents were formed on a glass panel at designated distances by fixing it onto the vise of a Vickers micro hardness tester and the influence of the distance between the indents on crack initiation was investigated. Schematic explanation of the distance between the indents is shown in Figure 9. Here, the length of indent is "c", the gap between the indents is "e", and the distance between adjacent indent corners is "d".

For the indentation angle of $\theta_1=3^\circ$, cracks occurred from both corners of the diagonal in the direction of the inclination. In this study, the probability of occurrence of the crack in the direction of the inclination was 90%.

Keeping the indentation angle $\theta_1$ constant at $3^\circ$, the upper limit of the gap between the adjacent corners "d" was investigated. After making the initial indent, the second indent is made by moving the indenter in the direction of increasing inclination angle ($\theta_1$) and decreasing inclination angle ($\theta_1$).

The interval between two consecutive indents are $d=0, 5, 10, 20, 30, 40\mu m$. Figure 10 shows the influence of the interval between the adjacent indentations on the crack initiations.

With the formation of the second indent, connection between the adjacent indents was found to occur for the intervals $d=10-30\mu m$, because of the enlarged corner to corner distance found in this direction compared to the perpendicular direction of the indentation.

4.2 Breaking of the glass panel by several intermittent indentations

Extension and continuity of the crack by several intermittent indentations are carried out for a fixed loading weight of 2N. Figure 11 shows the indentation condition and the observation direction for the fractured surface.

Vertical indentation method case

In the case of the vertical indentation method, several indentations were made at indentation intervals of $d=5\mu m$ (connected) and $10\mu m$ (not connected).

The result shows that in two cases crack did not occur, but in other three indents crack occurred in continuation. However, large unevenness is observed on the cross-section shown in Figure 12(a), and hence this may not be of any practical use.

Inclined indentation method case

Corresponding to the indentation angle $\theta_1=3^\circ$ and intermittent indentations at a maximum indentation interval of $d=30\mu m$, the edge condition of the surface after breaking is shown in Figure 12(b).

The separated section does not show any large unevenness, rather this is considered to be very uniform. A cleanly cut surface of the glass could be obtained even with an indentation spacing of 30$\mu m$; therefore the possibility of using intermittent indentations by a square indenter to break the glass panel with high precision was confirmed.

5 NEW Scribing MACHINE UTILIZING REPETITIVE INDENTATION OF INCLINED IN舍得TER

5.1 Proposal of repetitive indentation method

It was found from experiments that the pyramid indenter should be set at an angle of 3 degrees from the normal line to the feed direction in order to realize fine cutting with perpendicularity, flatness and low chipping as shown in Figure 13.

For the actual production, the glass plate workpiece must be fed at high speed. This is realized by using a high speed repetitive motion of the indenter. To realize this a scribing machine with a high frequency of vibration is proposed. The required frequency $(f)$ of the indenter is calculated as follows:

$$f = \frac{(1000 \times V) / 60}{(c + d) / 1000}$$

where,
$V_f=$feed speed of the indenter (m/min), $a=$diagonal length (μm), $d=$gap between the indents (μm)

By considering a diagonal length of 25μm at $W=2N$, the distance (−10 ~ 30μm) between indentations for the connecting cracks yielded at adjacent indents and a table feed speed ($V_w=6$m/min) of the existing scribing machine, a frequency between $f=1.8$ ~ $6.7$ kHz is required to be applied to the indenter. The vibration frequency in this range can easily be realized using a commercially available multi-stacked type piezo transducer.

5.2 Performance of the developed scribing machine

Figure 14 shows the scribing by the machine developed using the above research results. Figure 15(a) shows the cut section with the indented part, micro crack of critical region and fractured region. Figure 15(b) shows a crack running almost perpendicular to the surface. From the cross point of two scribing lines shown in Figure 15(c), cracks or chipping are not observed. These figures indicate that the developed scribing machine meets the demands of precise scribing of a glass plate. Figure 16 shows an example of a narrow glass material cut with this method. This special cutting is realized by a deeper crack with the inclined pyramid indenter. Therefore, this inclined pyramid indenter method is named as "Crack cutting method".

6 CONCLUSION

In this paper, a new scribing method with an inclined pyramid indenter is proposed and the crack occurrence mechanism is investigated experimentally as well as theoretically by FEM. The crack propagation condition between adjacent indents is investigated experimentally, and it is found that the distance between indents for a successful crack propagation exists between −10 and 30 μm. Using the experimental and analytical results a new scribing machine with a vibrating pyramid indenter is developed. It is found from the experiments that the glass plate for flat panel display is scribed successfully with a high aspect ratio and without chipping. The cross section characteristics show good perpendicularity on the glass surface and good flatness without any chipping. Thus, it is concluded that the new scribing method "Crack cutting method" will have great use in the market.

7 ACKNOWLEDGMENTS

The authors would like to express their heartfelt thanks to Beldex Co., Ltd for their kind cooperation in this research.

8 REFERENCES