Cuttability of AMLCD Glass Substrates Using a Four-Point-Bending Test

Technical Information Paper

Display Technologies

TIP 304
Issued: November 2004
Supercedes: February 2003

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Abstract

Glass cutting is one of the important processes in liquid-crystal display (LCD) manufacturing. Glass cutting consists of two processes, scribing and breaking. However, both processes have evolved through manufacturing experience and have not been analyzed theoretically, in particularly; no studies have been found which relate to the breaking process. In this study, theoretical and quantitative analysis is performed for the breaking process using a four-point-bending test of scribed sheet. From the results of the four-point-bending test, the breaking load of a scribed sheet was 40% lower than that of the theoretically calculated load due to the residual stress created by indentation and by sheet forming. For median crack depths greater than 100 μm, the breaking load increased to close to the calculated load due to stress relaxation by lateral crack growth. The four-point-bending test of scribed glass sheet is effective in identifying the breaking process, and is necessary to understand glass "cuttability".

1. Introduction

In the manufacturing process of liquid-crystal-display (LCD) panels, a large mother-sheet glass is cut into smaller display-sized sheets by either dicing or scribing. Though the dicing method is generally better than the scribing method for dimensional precision, the glass surface is easily contaminated by glass debris and coolant and its process speed is 10 times slower than that of scribing method. With the requirements of LCD panel manufacturers such as clean glass surface and large production volume, the scribing method has been a major technology in this market because of higher throughput and cleaner process than dicing.

The glass-cutting process using a scribing method is composed of two steps: the first step is a scribing process to form a median crack line on the glass surface using a tungsten carbide wheel or a diamond chip; the second step is a breaking process, in which the scribed sheet is separated along the median crack line by applying a tensile stress due to bending or local compression methods[1]. The most serious problem in the glass-cutting process is mis-separation at the cleaving process, which is believed to be caused by inappropriate scribing conditions, or by applying too much load during the breaking process. A few studies have been previously reported which identify glass-scribing conditions. Jackson and Scott have tried to optimize the cutting conditions of soda-lime glass by identifying the relation between scribe load and median crack depth[2]. As a function of lateral crack formation, Miwa *et al*, measured the weight of the glass chips created by scribing as an indicator of "glass cuttability," because no glass chips on the surface after cutting is one of requirement[3] of LCD makers. Though they have evaluated the scribing of glasses, no information about the breaking process was obtained and no theoretical analysis was done.

It is believed that the breaking load to apply the necessary tensile stress to cleave the median crack line can be determined by median crack depth based on fracture mechanics. However, it is commonly known in the manufacturing arena that a higher breaking load is necessary to separate scribed sheet, although the sheet was scribed at high enough scribing pressure to create a deep median crack. Current knowledge of both processes is still qualitative, based on the operators' experiences, in spite, of the necessity of quantitative and theoretical information on scribing and breaking processes for process optimization. Additionally, optimum scribing conditions are dependent on the glass composition and surface condition.

This study is intended to shed light on the phenomena of the glass-cutting process, both quantitatively and theoretically. In this paper, "cuttability" is defined to indicate both ease of crack initiation and ease of sheet separation as a characteristic of a glass. At first, the relation between scribe load and median crack depth was theoretically analyzed using fracture mechanism theory on Vickers point indentation. Then, four-point bending of scribed glass sheet was performed to obtain information about the breaking process. We have found that the theory of point-indentation fracture mechanism can be applicable with modification. Moreover, a higher breaking force is needed above a threshold depth because the stress is dissipated by lateral crack growth.

Table 1 — Mechanical properties of glasses.

Glass and maker[a]	Composition type	Density, ρ (Mg/m^3)	Young's modulus E (GPa)	Poisson's ratio, ν	Hardness,[b] H_v (GPa)	Fracture toughness,[c] K_{IC} ($MPa.m^{1/2}$)
AGC Soda lime (SL) (Ref. 11)	Soda lime silicate	2.49	71.5	0.21	5.6	0.75
Corning 7059 (Ref. 13)	Barium borosilicate	2.75	67.6	0.28	5.3	0.80
Corning 1737 (Ref. 14)	Alkali-earth aluminoborosilicate	2.54	72.1	0.22	5.5	0.83
AGC AN635 (Ref. 13)	Alkali-earth aluminoborosilicate	2.76	75.4	0.20	5.6	082
NEG OA2 (Ref. 13)	Alkali-earth-zinc aluminoborosilicate	2.72	70.3	0.17	5.8	0.82
NHT NA45 (Ref. 13)	Alkali-earth aluminoborosilicate	2.48	74.0	0.23	5.8	0.83

[a]Glass suppliers, AGC: Asahi Glass Co.; NEG: Nihon Electrical Glass; NHT: NH-Technoglass; and Corning.
[b]Measured by Vickers at 0.2-9.8N using same samples.
[c]Chevron notch short bar method for samples except soda lime. Double cantilever beam method for soda lime.

2. Experiments

2.1 Samples

Five kinds of commercially available non-alkali LCD substrate glasses and one soda-lime glass were used in this study. The density, ρ, and Young's modulus, *E*, Poisson's ratio, ν, hardness, *H*, and fracture toughness, K_{IC}, for these glasses are listed in Table 1, The thickness of all glass substrates was 1.1 mm. The substrates used for experiments in this paper were not the same as the samples used to obtain the mechanical properties shown in Table 1, because the substrates for the experiment were in as-received condition. *i.e.,* no thermal treatment was made in order to preserve their commercially available condition.

2.2 Preparation of scribed specimens

Single-edge notched beam (SENB) type sample pieces of 40 x 50-mm size were obtained from mother-sheet glasses by a conventional scribing method. The mother-sheet size is typically 320 x 400 mm or 360 x 465 mm and 1.1 mm in thickness. A lattice pattern, with 40- and 50-mm pitches for X and Y directions, was scribed on the mother-sheet glass, A median crack line for the four-point-bending test was formed at the center of the 50-mm edge on the opposite surface (without the lattice pattern). The reason we chose the opposite surface was to prevent the median crack growth during the separation of each sample by bending from the mother sheet. A numerically controlled (NC) scriber, TEC-II, made by Shirai Iron Ind. Co., with a tungsten-carbide wheel having a 4-mm diameter and 110° tip angle, was used for the scribing to prepare the sample pieces. The scribing table was a polyethylene coated polyurethane base with a thickness of 1.6 mm, which is commonly used in glass-sheet manufacturing processing. The residual stress distribution of some scribed samples was measured using a microscopic birefringence meter produced by Oji Scientific Instruments Co.

2.3 Four-point-bending test

A load tester, 131OF, made by AIKO Engineering Co., Ltd., was used for the four-point-bending test. Dimensions of upper and lower rods of the load tester are as specified in JIS R 1601 or ASTM C158-80, and are schematically illustrated in Fig. 1. The specimens are put on the lower rods, and the median crack surface faced down, with the median crack aligned parallel to the lower rods and positioned at the center of these rods. A four-point bending test was done within an hour after the introduction of the median crack line for every sample to prevent slow crack growth of the median crack due to environmental humidity.[4] The specimen was loaded at 5 mm/min of cross-head speed. After recording the failure load, the fracture surfaces of the broken specimens were observed with a scanning laser microscope (SLM), and the median crack depth was measured at the location at which the crack propagation started. This position was identified by Wallner lines on the fracture surface.

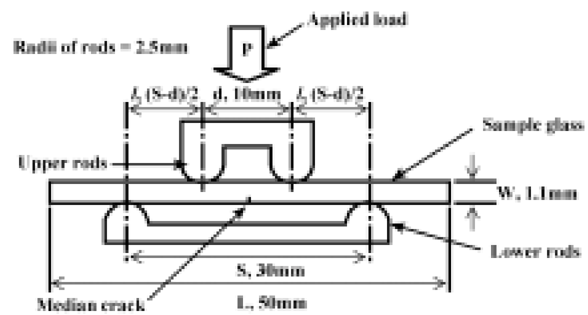
3 Results and discussion

3.1 Median crack depth vs. scribe load

The generation of the median crack by indentation has been studied previously using a Vickers hardness tester[5]. The median crack is generated during loading beneath a Vickers indenter, and the median crack size *c* is explained as a function of indentation load, *P*, and fracture toughness, K_{IC}, by Eq. (1) [6],

$$c^{3/2} = \chi \frac{P}{K_{Ic}} \quad , \quad (1)$$

Figure 1. **Schematic illustration of upper and lower rods of four-point bending test machine.**



where χ is a dimensionless constant that depends upon both the indenter and material.

Assuming the same relation as Eq. (1) between the scribe load and the median crack induced by the scribing, the 3/2 power of the median crack depths formed at each scribe load of sample glasses are plotted in Fig. 2 as a function of the normalized scribe load divided by fracture toughness. It is obvious that data of the sample glasses follow the linear $c^{3/2}$ *vs.* P/K_{IC} relationship. This result indicates that for all the sample glasses, it is possible to control the median crack depth by controlling scribe load. It also indicates that the median crack depth tends to depend on the glass composition. With soda-lime glass it is easier to generate median cracks than for non-alkaline glasses at a given scribing load. For the non-alkaline glasses, the ease of the median crack formation of individual glasses are not clearly differentiated by this evaluation method. The method can only classify the non-alkaline glasses into two groups by the relative ease of median crack formation, one comprised of AN635 and OA2 glasses and the other of NA45, code 7059, and code 1737 glasses. The belief in the manufacturing field that the ease of glass cutting depends only upon the ease of median crack generation, and that the depth of the median crack determines the ease of the sheet cleaving process by bending, is incomplete and generally incorrect. Median crack depth by scribing indicates the ease of median crack formation by applied scribe load, but does not quantify differences in the "cuttability" of each glass. The "cuttability" of the glass substrate must also include information about the breaking process, and not just the ease of median crack formation.

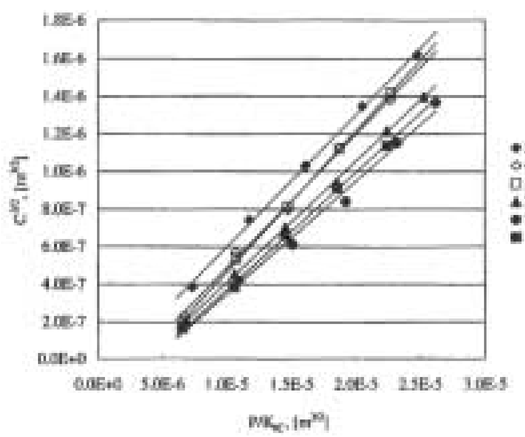
3.2 Four-point-bending test

The failure loads of each scribed glass sample were compared with the calculated failure loads, P_f, using Eq, (2) [7].

$$K_{IC} = \frac{3P_f l}{tW^2}\sqrt{\pi c}\cdot F_{IM}(\alpha), \quad (2)$$

where failure load P_f, sample thickness W, and the separation of adjacent upper and lower rods, l, are illustrated in Fig. 1. K_{IC} is the fracture toughness of the sample glasses in Table 1, c is the experimentally

Figure 2**. Median crack depth as a function of scribed load normalized by K_{IC}.**



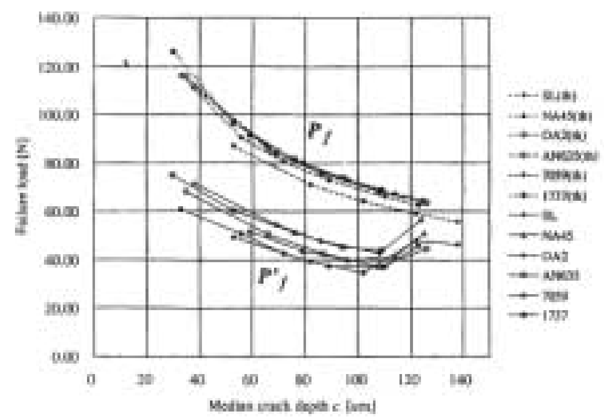
obtained median crack depth of the cleaved samples, sample length t is 40 mm, and F_{IM} (α) is given by Eq. (3) [7].

$$F_{IM}(\alpha) = 1.122 - 1.121\alpha + 3.740\alpha^2 + 3.873\alpha^3 - 19.05\alpha^4 + 22.55\alpha^5,\ \alpha = \frac{c}{W} \quad (3)$$

The experimentally obtained failure load P_f (shown by symbols with solid line) and calculated failure load P_f (symbols with dotted line) of all sample glasses are plotted in Fig. 3 as a function of median crack depth, The calculated failure load decreases with increasing median crack depth, and the difference among glasses is small due to the small difference of their K_{IC} values (0.75-0.83 MPa-m$^{1/2}$). The decrease in measured failure load of each glass with increasing median crack depth shows similar behavior as the calculated failure loads up to about 100 µm crack depth; however, the values are about 40% lower. For median crack depths greater than 100 µm, the failure loads of all glasses actually increase irregularly and approach the calculated value.

In order to clarify the tendency between a crack depth of less than 100 µm and larger than 100 µm, a ratio of (measured) to P_f [calculated by Eq. (2)] was plotted in P'_f Fig. 4 as a function of scribe load. This plot indicates that the onset of increase in P'_f/P_f occurs at a different scribe load for each glass, because the scribe load required to form the same median crack depths for each glass is different, as shown in Fig. 2. The ratio of the measured/calculated failure loads, *i.e.*, the degradation of the failure load of all glasses tends to decrease with increasing scribe load. It is suggested that the decrease of the failure load is mainly due to residual stress created by indentation from loading of the scribing wheel[8,9]. In previous studies, the failure load of samples cracked by indentation was approximately 30% lower than that by conventional methods[13]. However, in this work the disparity exceeded 30%. It means that crack propagation is accelerated not only by the residual stress created with

Figure 3. **Failure load of the scribed samples having various median crack depths.**



indentation, but also by other stresses. Significant differences were seen among glasses even though the dimensional conditions of scribing to create residual stress was consistent among all sample glasses. An explanation for these observations is that the failure load by scribing might be impacted by the combination of residual stress primarily due to indentation and the internal stresses of each glass in addition. The difference among glasses was due to the internal stress of each glass, which has been created by the thermal history, depending on the forming and annealing conditions by individual glass suppliers. The fracture toughness, K_{IC}, used for the calculation of P_f, is usually measured to evaluate samples which have been annealed to eliminate residual stress. However, actual glass products have not been fully annealed. It seemed that the OA2 and Code 1737, which showed the lowest decrease in failure load, might be better annealed or might have lower internal stress initially, and therefore exhibited higher failure load due to less effect of internal stress.

Figure 4. **Differential of calculated and measured failure loads as a function of scribe load.**

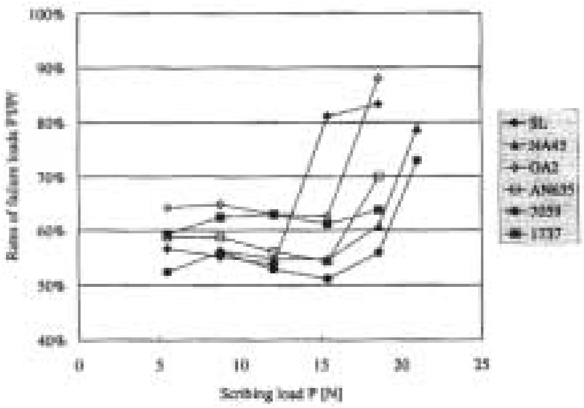
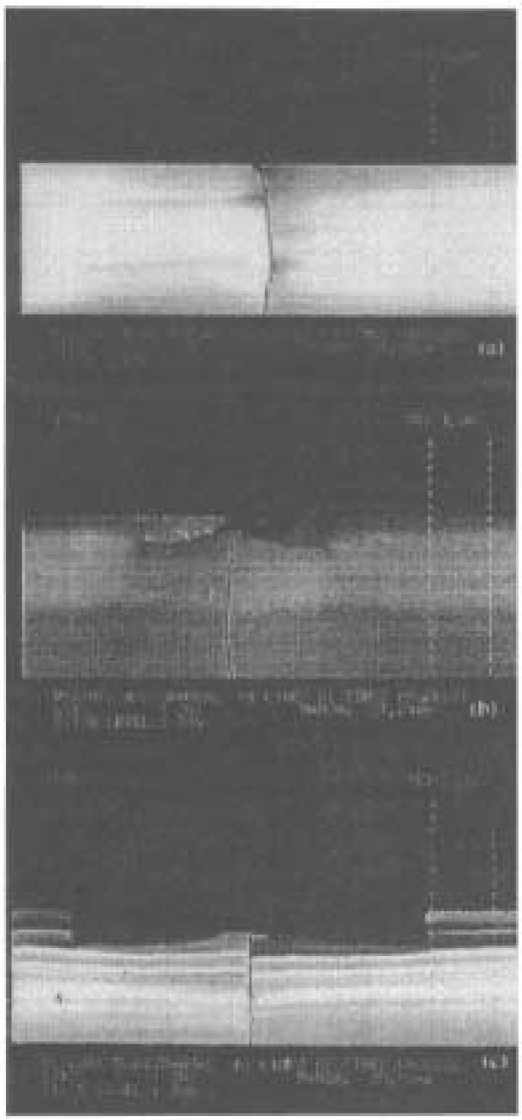


Figure 5. **Cross-sectional view of fractured specimens with median/lateral cracks in Code 7059 glass scribed at (a) 15.4N, median crack depth of 90 μm; (b) 18.6N, median crack depth of 110 μm and lateral cracks are left in the glass body; and (c) 21N, median crack depth of 125 μm and lateral cracks during scribing are left.**

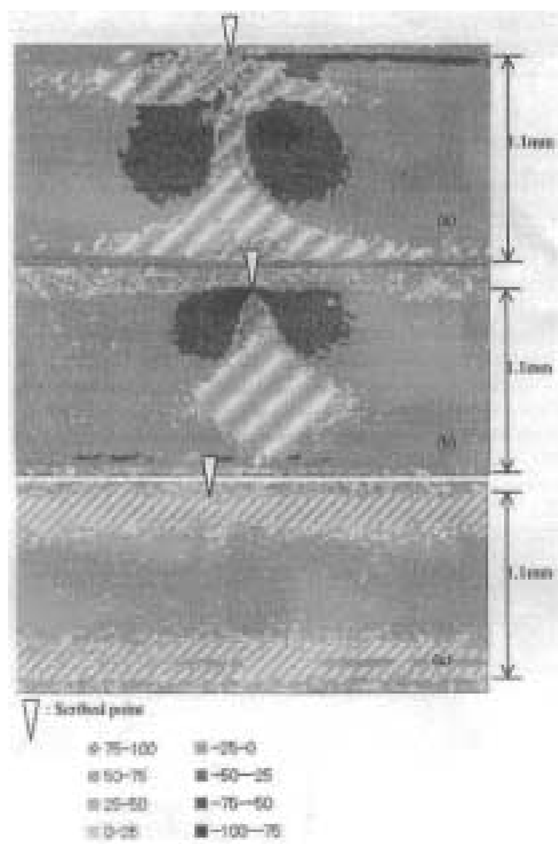


In order to clarify why failure load irregularly increased when the median crack depth was larger than 100 µm, SLM observation on the scribed surface was performed for the samples having median crack depths of 100-125 µm. Figure 5 shows cross section of scribed and fractured surfaces of code 7059 glass across the scribe line.

Figure 5(a) shows a median crack without a lateral crack. In Fig. 5 (b), the lateral crack is generated, but the crack end remains in the glass body when the median crack depth is 110 µm. When the median crack depth is 125 µm as shown in Fig. 5(c), the lateral cracks completely reach the glass surface and glass chips are created and removed. These glass chips were left from the scribed portion during scribing, *i.e.*, the lateral crack was completely propagated to the glass surface during the scribing. The failure load of the sample having a 125-µm median crack depth was higher than that of the sample having 110 µm of median crack depth. This phenomenon suggests the occurrence of stress relaxation by growth of the lateral crack.

The stress distribution on the cross section of the same scribed sample by SLM observation was observed before the bending test with a birefringence meter to identify the stress relaxation mechanism. The results of the observation are shown in Fig. 6.

FIGURE 6. **Cross-sectional retardation map of scribed sheet: (a) median crack depth of 90 µm, tensile and compression stresses are distributed widely; (b) medium crack depth of 110 µm, tensile stress is localized around the lateral crack; and (c) medium crack depth of 125 µm; no localized stress is seen after lateral cracks are left.**



Figures 6(a) and 6(b) show a 7059 glass sample with 90- and 110-μm median crack depths and lateral cracks remaining in the glass body. The compressed zone (hatched) and tensile (gray) zone exist symmetrically besides the median crack. The patterns are roughly in accordance with those of photo-elastic experiments, in which the compression zone is beneath the scribed portion, and the tensile zone is along the glass surface, symmetrically beside the median crack.[10] In contrast to Figs. 6(a) and 6(b), Fig. 6(c) indicates that for the a sample with a median crack depth of 125 μm and with lateral cracks removed by chipping, almost no residual stress was observed in the body of the sample sheet. It seems that the stress created by scribing is relaxed by lateral crack removal. It was confirmed that all samples having median crack depths larger than 100 μm showed lateral crack generation and its removal by chipping. It is concluded that the irregular failure load, which increased when the median crack depth exceeded 100 μm, was due to the residual stress relaxation mechanism by lateral crack growth.

4. Summary

We analyzed "cuttability" of AMLCD glass substrates quantitatively and theoretically. The median crack generation by scribing was theoretically analyzed as a fracture mechanism of indentation. The 3/2 power of the median crack depth is proportional to the scribe load, a relation which has been well studied as a fracture mechanism of point indentation by Vickers indentation. In addition, the four-point-bending test for scribed LCD glass substrates is proposed to evaluate glass sheet "cuttability" quantitatively, because this method incorporates both scribing and breaking performance. With this test, we identified that the breaking load of scribed glass decreased with increasing median crack depth up to an approximately 100-μm crack depth, and the breaking load increased in an irregular manner when the median crack depth was greater than 100 μm. This increase in the breaking load was caused by stress relaxation due to lateral crack growth toward the glass surface. To separate AMLCD glass substrate with minimum breaking load and without lateral cracking, a median crack depth of 100 μm is appropriate when the 110° angle wheel is used for scribing.

5. Acknowledgments

The authors would like to thank Dr. Y. Imamura, Mr. A. Okada, Dr. P. L. Bocko, and Mr. G. A. Luers of Coming Incorporated for their technical discussions..

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