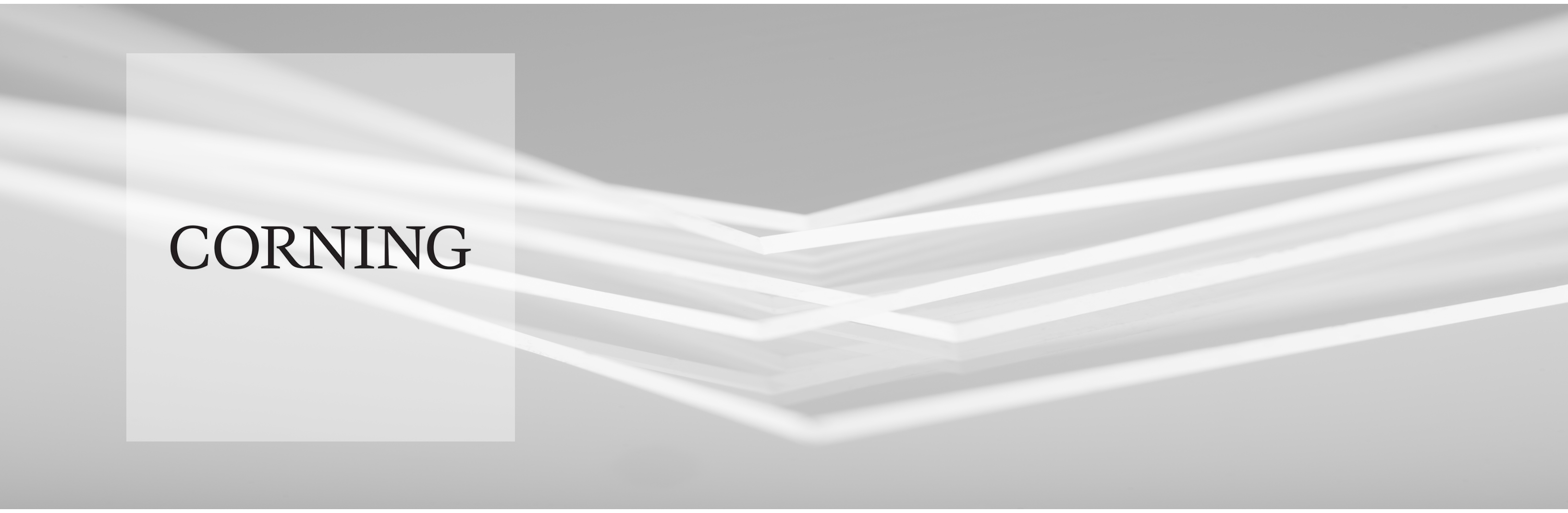
Fracture Analysis, a Basic Tool to Solve Breakage Issues

Technical Information Paper



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Biography

T. Ono received his B. S. and M. S. degrees in inorganic chemistry from Nagaoka University of Technology, Niigata, Japan, in 1988 and 1990, respectively. In 1990, he joined the Shizuoka Technical Center of Corning Japan K. K. where he has been engaged in research and development of the finishing technologies of LCD glass substrates and other glasses. He has also provided extensive fracture analysis support to resolve breakage problems in customer processes.

Abstract

Breakage of glass substrates in Flat Panel Display (FPD) manufacturing processes can cause serious problems of productivity and product quality/ reliability. It is known that the mechanism associated with breakage is crack propagation by tensile stress concentration at a damaged point on the glass, which serves as an origin of the breakage [1]. Elimination of breakage requires the elimination of the origin and/or reducing the tensile stress. However, this solution can be applied only if the location of origins and the kind of the tensile stresses is known.

Fracture analysis can provide information on both the tensile stress and the origin of breakage [2, 3]. This analytical technique gives important information in determining mechanism of breakage, such as direction of crack propagation, type of the stress, direction of impact and friction, location of the origin. All important information is "memorized" on the broken pieces and can be obtained through microscopic observation. A process where an origin is created is often different from the process where tensile stress is applied. The breakage mechanism can be understood by combining the information from fracture analysis with process information.

The analysis method will be explained using actual cases. Also, the application of the method for optimization of cell-cutting process will be explained.

Glass Breakage

The mechanism of glass breakage is that the crack propagates by tensile stress that is concentrated at the origin, which is a small damage site or crack on the glass surface, or in the glass body. The relation of the failure stress and size of origin is explained with Eq. 1 [4],

$$\sigma = \frac{1}{Y}\frac{K_{IC}}{\sqrt{c}} \tag{1}$$

where Y is constant depending on the crack and sample shape, K_{IC} is fracture toughness, and c is crack size. Glass with a larger crack size, c, could be broken at lower failure stress.

Although the stress applied for glass is lower than the failure stress, a crack can be propagated in the atmospheric condition, especially by water. This phenomenon is called Subcritical Crack Growth (SCG) caused by stress corrosion, in which the molecular of water cut the Si-O bonding chemically [5]. The durability of the stress corrosion of glass is indicated with n, crack growth parameter. The glass having large n value is durable for SCG, which means it has long life reliability. The reliability of several different FPD substrates were studied by Gulati et al. [6].

1. Origin

Origins are typically generated by such mechanisms as indentation, impact, or friction during FPD processes. There are many opportunities to generate these damages during FPD manufacturing. Indentation damage is irregularly generated when substrates are clamped or chucked on process stages where foreign particles, especially glass particles, are present. Therefore, once the breakage occurs, appropriate cleaning of the glass chips, etc. in the process is essential to prevent secondary breakage. The size of the damage has been characterized using Vickers point indentation [7]. The general relation between the crack size and load is explained with Eq. 2,

$$c^{\frac{3}{2}} = \chi \frac{P}{K_{IC}} \tag{2}$$

where c is crack size, P is load, K_{IC} is fracture toughness. χ is a constant which relates to the material properties and geometry of the indenter.

Damage by impact, which is principally the same as indentation but with loading speed much faster than that of indentation, is generated mainly on the substrate edge by rapid contact with the supporting rods of the cassette or the alignment pins. This damage is easily generated because stress is localized by point contact. Friction damage is created when placing glass into cassettes, rubbing with the alignment pins, and sliding on the lithography stage. This damage mode usually occurs after impact when the loading direction of the impact is not perpendicular to the surface or edge. When the friction damage is created, it can often be invisible, but becomes visible after acid etching.

Stress

Tensile stress is the force needed to propagate damage during substrate breakage. Thermal and mechanical stresses are the main sources of tensile stress in the FPD process. Thermal stress for the crack propagation is generated when a heated glass substrate is cooled, which can create tensile stress along the substrate edge. The magnitude of the stress is a function of temperature difference, ΔT, as shown in Eq. 3 [8],

$$\sigma = \lambda \frac{E\alpha\Delta T}{(1-\nu)} \tag{3}$$

where α is Coefficient of Thermal Expansion (CTE), E is Young's modulus, ΔT is temperature difference between inside and surface of the glass, ν is Poisson's ratio. λ is a constant that depends on Bio's constant that relates to the thermal conductivity of the glass and thermal diffusibility of coolant. The constant is 0.7 when the coolant is air.

In addition, CTE mismatch between glass and deposited film material increases the magnitude of stress. Mechanical stress is usually due to bending during handling of the substrate, which is generated when flat glass substrate is warped, frequently due to deposited film – substrate CTE mismatch. Bending stress is also generated when warped substrates become flat by vacuum chucking, or clamping. Panel sag during handling also generates bending stresses. Tensile stress by bending is generated not only at the edges, but also on glass surfaces. The tensile stress σ created by bending can be also calculated with Eq. 4 [9],

$$\sigma = \beta \frac{wa^2}{t^2} \tag{4}$$

where w is uniform load, a and t are short edge length and thickness of the glass substrate, respectively. β is the constant which decided ratio of short/long edges length.

Another source of mechanical stress is centrifugal stress by rotation with spin-drying or spin-coating processes. Stress increases with substrate size and with rotational speed.

In general, the failure stress has been used to evaluate mechanical strength of glass. However, the failure stress is strongly influenced by the size of the origin (non-conformity) on the glass substrate as indicated with Eq. 1. Understanding origin size and mechanism of breakage is useful information for identifying and eliminating breakage during FPD process. In the actual case, glass can be broken under the failure stress as calculated with Eq. 1 due to the residual stress created by damage such as impact or friction. These residual stresses accelerate the crack opening.

Fracture Analysis

When glass is broken, “footprints” of cracks are “memorized” on the fracture surfaces. These “footprints” map the fracture event and are strongly related to the origin creation, crack propagation and applied stress. Fracture analysis is structured with two parts, (1) observe the “footprints” on fracture surface to bring the information of origin and tensile stress, and (2) analyze the information with process information to identify the breakage mechanism. Table 1 shows the steps of the fracture analysis until obtaining the solution of the breakage issue [10].

Table 1. Process steps of fracture analysis

A. Obtain information from glass surface	**B. Obtain information from fracture surface**
Forking, Hertzian cone, Chatter mark, Residue	Wallner lines, Hackle marks, Mirror region, Sharra scarp, Origin
C. Process information Contact point/material, Contact speed/direction, Thermal cycle, especially cooling condition, Breakage loss/trend	
D. Permanent Solution	

Fracture analysis has been applied to various glass breakage events encountered in FPD manufacturing processes, and has provided enough information to identify where the breakage originated and how the flaw propagated. The source of the information is on two surfaces, the glass and fracture surfaces, shown as A and B in Table 1.

The details of information taken with the fracture analysis is well summarized in references [1-3, 10,12,13]. A brief explanation of this information is provided below.

A. Information from Glass Surface

Forking: Forking is crack branching. Qualitative magnitude of applied stress can be known from the number of cracks forking as shown in Fig. 1.

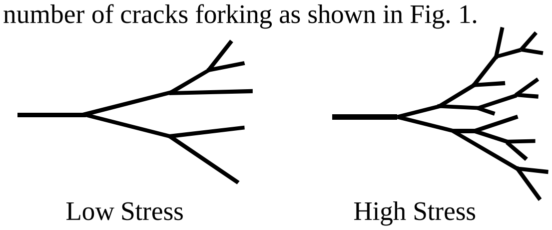

Fig. 1 Forking with high and low stresses

Hertzian cone: Hertzian cone crack is created by localized impact with a blunt, hard object. Schematic illustration of the Hertzian cone creation is shown in Fig. 2.

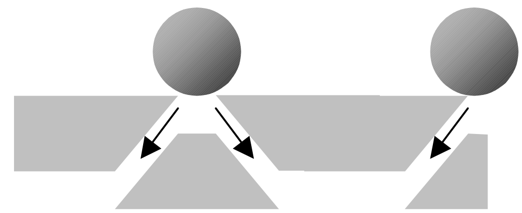

Fig. 2 Schematic illustration of Hertzian cone crack creation from cross sectional view.

Chatter mark: Chatter marks are created by friction, and their shape indicates direction of the friction. The cracks are concave, and curve toward the rubbing direction as shown in Fig. 3.

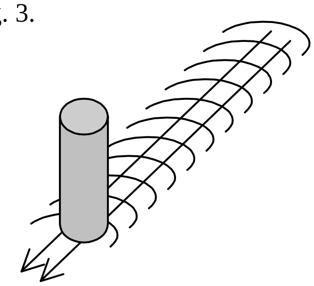

Fig. 3 Schematic illustration of relation between friction direction and shapes of Chatter marks. Drawing shows that the glass is stationary and the object is moving in the direction indicated by the arrows.

Residue: Residue provides information not only on the kind of material contacted, but also the timing when the origin was created or when the crack was run. Patterns on the glass surface such as TFT are ones of residue from the viewpoint of fracture analysis.

B. Information from Fracture Surface

Wallner lines: Wallner lines are rib shaped marks as shown in Fig. 4, which indicate crack propagation direction. The Wallner line is perpendicular to the crack propagation direction. There are three types of Wallner lines that are very useful in determining the course of events. These are primary, secondary and tertiary. Primary Wallner lines indicate that a surface or internal flaw was present prior to the failure event. Secondary Wallner lines occur when the fracture approaches terminal velocity, and tertiary occurs as a result of a mechanical shock, vibration or impact outside the crack front.

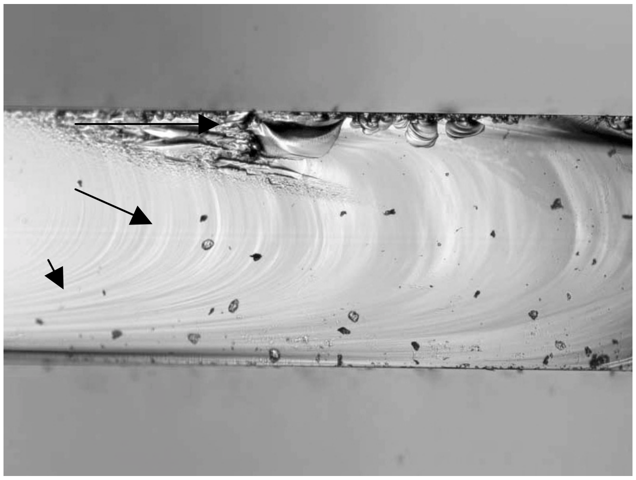

Fig. 4 Secondary Wallner lines created by crack propagation with bending stress. Cracks run left to right (arrow mark).

Hackle marks: Hackle marks are a definitive indication of the crack propagation direction. Typically two kinds of hackle marks can been seen, which are (1) twist hackle, appearing in the region where the tensile stress tilted (twisted) from the crack surface (Fig. 5) , and (2) mist hackle around the origin (Fig. 6). Mist hackles are commonly referred to as velocity hackles.

Mirror region: Around an origin, especially when tensile stress is high, a mirror region can be seen. The applied tensile stress can be calculated from radius of the mirror region [11].

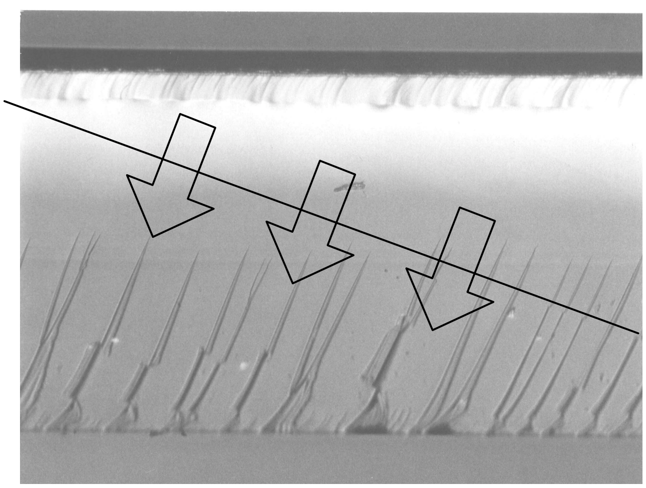

Fig. 5 Typical twist hackle mark created by breaking process following scribe process. The crack front was perpendicular to the Twist hackle marks, and crack propagation direction was parallel to the mark.

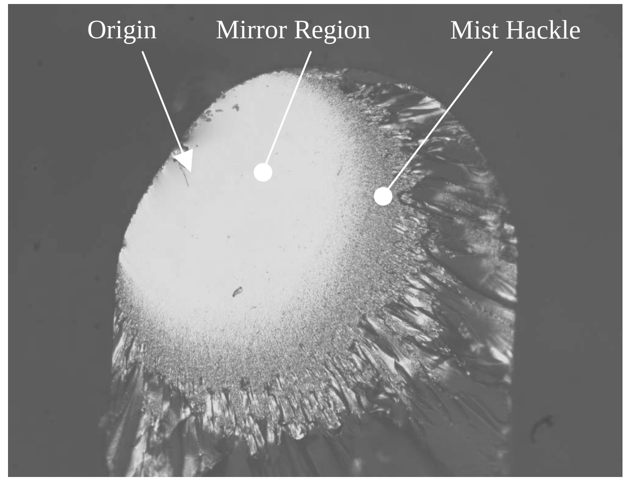

Fig. 6 Fracture surface around origin. Origin is surrounded with mirror region, which is covered with mist Hackle mark. Failure stress can be estimated using radius of the mirror region.

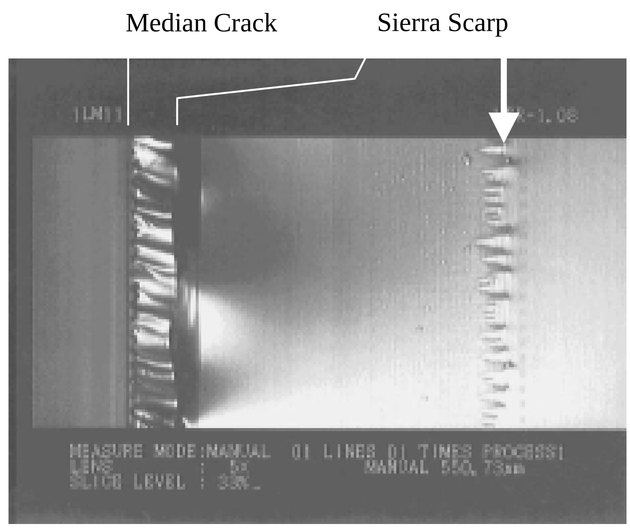

Fig. 7 Sierra Scarp appears on a fracture surface created by scribe/break process. Water was present during median crack propagation.

Sierra scarp: When water exists at crack front during the crack propagation, Sierra scarp appeared.

Actual Step of Fracture Analysis

Procedure of the fracture analysis when a breakage is reported is explained using a typical case [12]. This case is that breakage on three substrates was found when the sheets were unloaded from the film deposition chamber. In all cases, the cracks separated the sheets into two pieces. The crack shape of three sheets is shown in Fig. 8.

(1) Collect all broken pieces

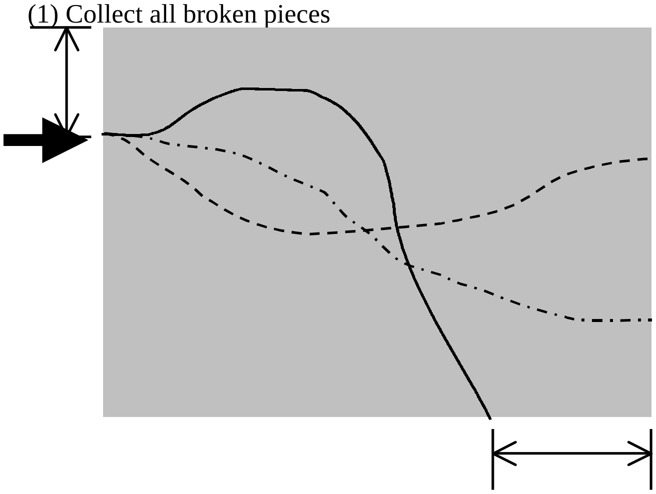

Fig. 8 Crack map of three broken sheets.

All important information is on the broken pieces. It is very important for the fracture analysis that the fracture surface be kept from any additional mechanical damages to retain information. Additional damage such as chipping by friction can erase the information easily. In this case, a sheet was separated already, so two pieces were separately kept.

(1) Make crack maps

Mapping the crack running feature is important to make the analysis easily. It is important to note that you don't play jig-saw puzzling of broken pieces, because the puzzling causes secondary damages. A rough sketch of the crack forking is enough. Also, the distance between the crack end crossing an edge and the nearest corner is important information for identifying the contact point on the edges in the processes.

In this case, the crack map of three broken pieces was obtained as shown in Fig. 8. One of two cracks ending on each broken sheet were located at the same position (arrow mark). This information indicates that the probability of existing origin at this point is high. If a machine creates damage, its location is precisely the same due to its high repeatability compared to a manual process.

(3) Identify crack propagation direction

The crack propagation direction is identified with observation of the Wallner lines or hackle marks to look for a location of origin of the breakage. Not only the crack propagation direction, but also the type of applied stress can be identified from the results of this observation. In this case, Wallner lines which are almost perpendicular to the surface are seen in the middle of the fracture surface as shown in Fig. 9. These Wallner lines indicate two things, (1) that the thermal stress possibly contributed to propagation of this crack and (2) the crack runs right to left.

Fig. 9 Wallner lines on fracture surface Thermal stress is one stress that can generate this shape of Wallner lines. The crack runs right to left.

(4) Identify origin

By following the opposite direction of crack propagation, the origin should be found. The way to identify the origin is three:

1. Find the defect at the center of the mirror region, which is surrounded by a mist hackle mark
2. Find the defect at the center of hackle marks running radial
3. Find the defect at the center of semicircle Wallner lines

Fig. 10 shows around the origin. Origin can be identified at the apex of round edge (arrow mark) by (1) center of radial hackle marks and (2) center of semi circular Wallner lines. This point was the same as the point that the mapping result indicated was a potential location of origin.

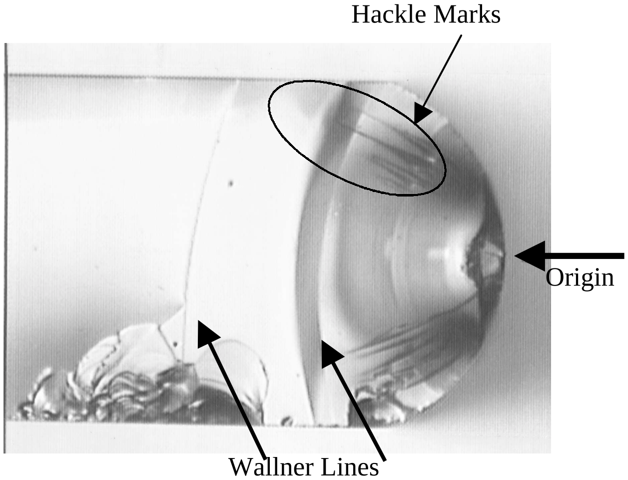

Fig. 10 Fracture surface around origin. Radial hackle marks, symmetrical Wallner lines with Arrest lines are present.

(5) Identify root cause of origin creation

After the identifying the origin, observation around the origin is performed to obtain the information related to origin creation. If residue exists, material identification should be done using SEM/EDX or FTIR. Small cracks by mechanical damage become visible after appropriate etching.

In this case, the ground edge around the origin was observed, and the result is shown in Fig. 11. Obtained information was:

1. There is residue, which shines brightly at the apex near the origin.
2. Due to the residue position, only at apex, it is assumed that the sheet rubbed a bar or pin, and its direction is perpendicular to the edge direction.
3. The shape of origin is curved, and hidden cracks having same shape as that of the origin was confirmed (it is difficult to see in this picture). This information implies that the origin was one of Chatter marks, created by friction. Rubbing direction was identified parallel to the edge by the shape of the chatter mark.

Generally, metallic material will appear shiny in an optical microscope with a reflective light source. The residue was analyzed with SEM/EDX to identify its material. The result indicated that the metallic material was stainless steel. Preliminary summary of the mechanism of origin creation is that something made of stainless steel rubbed apex of the ground edge, created a Chatter mark and left metal residue. The chatter mark became the origin of breakage when thermal stress was applied.

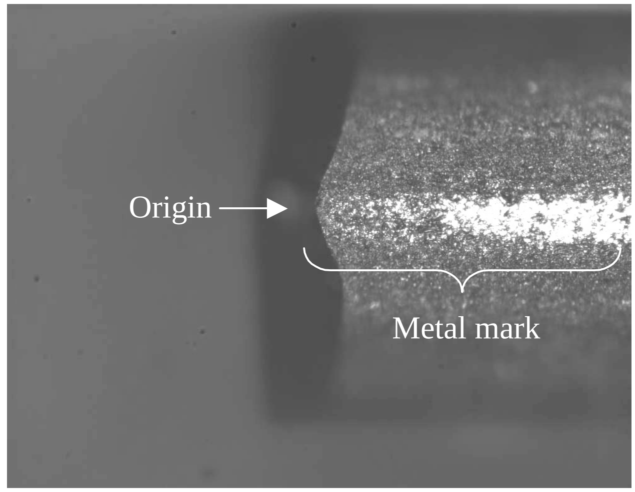

Fig. 11 Around the origin. This picture was taken from apex of the ground edge. Vertical axis in this picture is thickness direction.

(6) Combine with process information

From the preliminary summary of the mechanism of the breakage, other necessary information for the analysis was acquired, such as:

1. The position of the contact point(s) which is pointed out by mapping
2. Contact was initiated mechanically, not manually, as indicated by the high repeatability
3. Contacted material is likely stainless steel
4. The shape of the metal is a pin or bar
5. The contact happened before the CVD cooling process

From these conditions, the customer found a process where a stainless steel pin was used for alignment of the sheet. The surface of the pin was abraded by the ground edge.

(7) Identify the mechanism of the breakage

Finally, information obtained from the broken piece and processes is considered to identify the breakage mechanism. In summary of this case, damage was generated by the glass edge rubbing with the alignment pin when the substrate was pushed toward the pin as shown in Fig. 12. After the film deposition, the crack propagated from the origin by tensile stress, which was created parallel to the edge when the substrate cooled down from 200-300°C to room temperature.

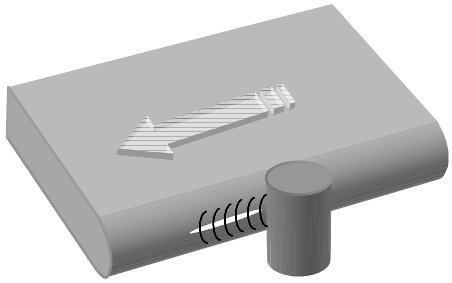

Fig. 12 Schematic illustration of the identified mechanism of origin creation on the case. The glass sheet slides in the direction of the arrow against the fixed pin, and the relative rubbing direction by the pin is in the opposite direction (left to right in this figure).

Application of the Fracture Analysis for the Cutting Process Optimization

The fracture analysis also can be applied to the optimization of cell/glass cutting process. Scribe/break method is widely used as a glass cutting method. The glass sheet was first scribed to create a median crack with a tungsten carbide wheel. Tensile stress is then applied with a force on the back side of the scribed surface, or, bending to separate the glass sheet by propagation of the median cracks.

Therefore, the glass cutting process using scribe/break method is a controlled breakage, where the crack propagates only along the scribe line. Cracks of the glass sheet cutting is the controlled breakage shown in Fig. 13. The scribe line is an origin of the breakage, which crack propagation along with the scribe line is an origin of separation of the sheet. The fracture analysis is a useful tool for the optimization of the process, and/or to analyze the cause of faulty cutting, where cracks run uncontrolled.

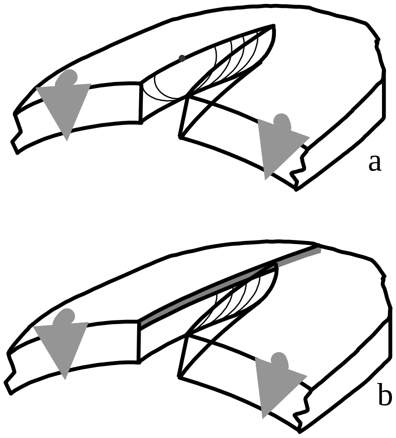

Fig. 13 Schematic illustration of (a) breakage and (b) cutting. The only difference between (a) and (b) is the origin of crack propagation. Irregularly created damage as origin for breakage (a) and median cracks created with scribing as controlled origin for the cutting (b).

The typical fracture surface by good cutting (called "Cut surface") is shown in Fig. 14. Median crack, approximately 100μm in depth is uniformly created, and the median crack propagated portion was smooth, due to low and stable breaking force.

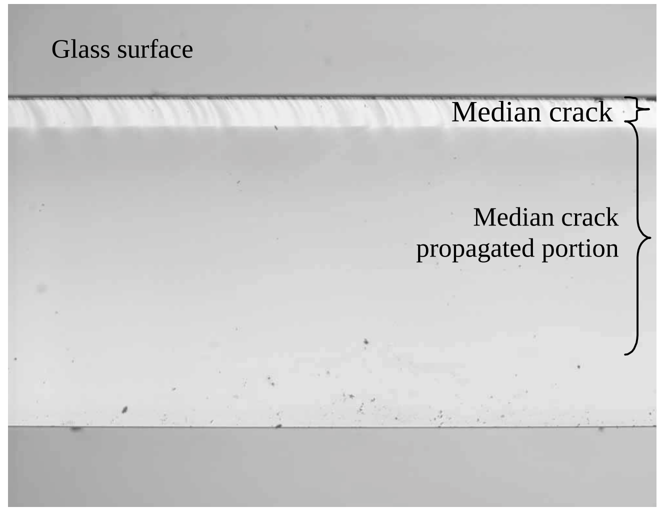

Fig. 14 Typical fracture surface by good cutting. Median crack depth is stable, and the median crack propagated portion is smooth.

In contrast to that, Figs. 15 and 16 show some faulty cut surfaces [13]. When individual FPD cells are separated in the final stages of FPD manufacture, the fracture plane sometimes deviates from the score-line. Even when scoring is done properly, i.e., the median crack is deep enough, this break failure is (also called mis-break) can result from inappropriately applied stress during separation. In Fig. 16, although the median crack is deep enough, the fracture surface deviates from the median crack. This fact shows that the tensile stress on the opposite surface of the scribed side is higher than that on the scribed side. The mechanical stress of impact during the cell separation process could also provide sufficient additional stress to cause mis-break.

Fig. 16 shows how insufficient median cracks are often created when the scribe wheel becomes worn or the scribe force is too low to maintain the median crack. Left side median cracks were created uniformly, but on the right side, radial cracks were created. The radial cracks are created just in front of the scribe wheel contact portion. They are shallower than median crack depths at the same scribe load, and have a wavy surface. This crack easily deviates from the scribe line. The scribe wheel runs from left to right.

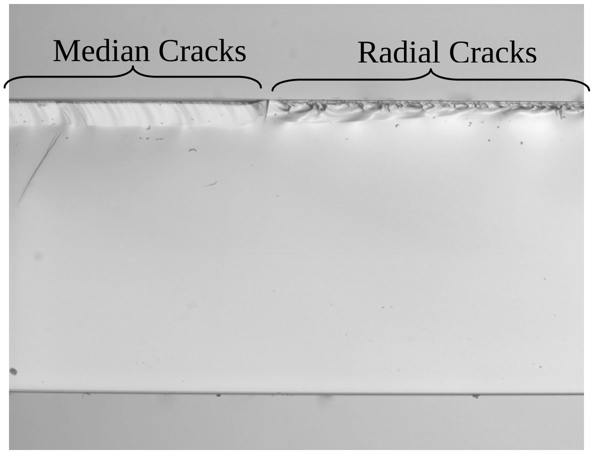

Fig. 16 Cut surface where the median crack stopped. Scribe wheel runs left to right.

Key information for the optimization of the cutting process are Wallner lines and hackle marks at the median crack propagated portion, as well as median crack feature.

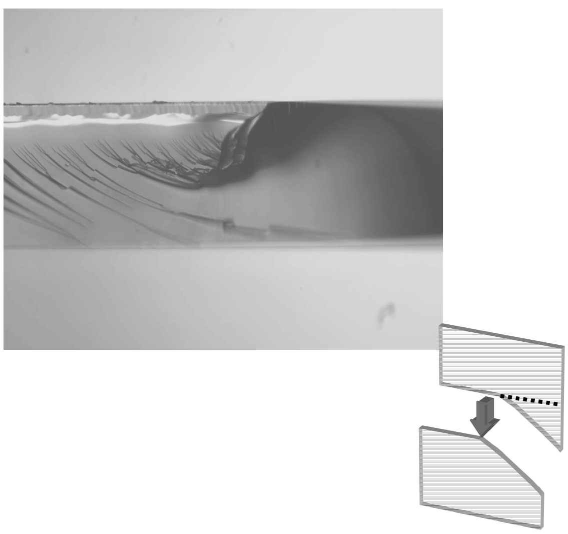

Fig. 15 Fracture surface of miss-breaking sheet by inappropriate separation [13].

Conclusion

1. Fundamentals and applications of fracture analysis, the effective tool to solve the breakage problem, is explained. The fracture analysis can bring reliable evidence of breakage from broken pieces. Once the mechanism of the breakage can be identified with the collected evidence, an appropriate solution can be secured.
2. Also, the effectiveness of the fracture analysis for the cutting process optimization is explained. Fracture analysis is applicable for the optimization, because the cutting process using scribe/break method is a controlled breakage.

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