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ORIGINAL ARTICLE

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Laser cutting with controlled fracture and pre-bending applied to LCD glass separation

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Abstract In this study, a laser beam, a water jet coolant and a pre-bending device were used to produce tensile stress along the cutting path that causes the material to separate along the moving path of the laser beam. The fracture mechanism and the machining parameters of laser cutting with controlled fracture were studied. The specimen materials were LCD glass substrates and the laser source was a CO_2 laser. The relationships between laser power, cutting speed, and bending deflection were obtained from experimental analyses. The separation of glass substrates is similar to crack propagation. The extension of the crack tip lags behind the laser spot at a non-uniform lagging distance. The acoustic emission signals generated during the fracture process were analyzed to obtain the stages of fracture growth. It was found that the three types of breaking, namely delay breaking, nick breaking, and ahead breaking, are all dominated by the moving speed of the laser beam. The breaking surface shows no micro-cracks and the surface quality is much better than that obtained by mechanical breaking.

Keywords Controlled fracture · Glass substrates · Laser cutting

1 Introduction

The conventional cutting technique for liquid crystal display (LCD) glass substrates uses a diamond wheel to scribe a deep groove, which then extends through the glass for complete separation by mechanical bending. Many chip defects are found in the product edge when scribed with a diamond wheel and broken with a mechanical force.

The controlled fracture technique, proposed by Lumley [1], has great potential for cutting glass with lasers. The laser energy is absorbed in a local area on the glass, producing mechanical stress that will cause the material to separate along the moving path of the laser beam. Similar to crack extension, the material separates and the fracture growth can be controlled. Grove et al. [2] proposed a related method of controlled fracture for cutting glass that used a higher cutting speed. The quality of the surface separated by laser cutting is much better than that broken by mechanical breaking.

Kondratenko [3] improved the controlled fracture technique using a water jet coolant to produce tensile stress on the surface along the cutting path. This improvement of the controlled fracture method has been recognized as having good prospects in the cutting of glasses. Here, the surface of a glass plate is heated using a CO_2 laser, closely followed by a quenching jet. This rapid quench creates tensile stress along the applied laser path to form a blind crack or through crack. This method can increase the cutting accuracy and speed, and also allow precise scribing depth.

In the patent proposed by Hoekstra [4], an initial mechanical or laser scribing device creates a micro-crack in the substrate. A helium coolant stream follows closely the scribing laser beam. Two breaking laser beams are applied on both sides of the separation line, following the coolant stream. To facilitate separation, an additional mechanical force applicator may be used to provide a bending moment at the separating line. Choo et al. [5] modified the conventional method for cutting LCD glass substrates, in which a pre-scriber is used to form a pre-cut groove at the starting edge and at the end of cut. Combining the laser heat and the coolant stream generates great tensile stress to separate the glass.

In the studies by Tsai and Liou [6] and Tsai and Chen [7], the fracture mechanism of laser cutting with controlled fracture technique for alumina was thoroughly investigated. In the laser cutting for alumina, the high temperature induces creep deformation, which generates a highly compressive stress through the substrate thickness. The creep deformation is limited to a thin surface layer. After the laser beam

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passes, the temperature decreases and the compressive stress at the surface layer is released and induces tensile stress. The tensile stress causes the main crack to extend unstably. The fracture grows stably along the moving path of the laser spot.

The laser cutting technique with controlled fracture for the alumina substrate does not require a coolant stream, prescribing or mechanical bending. Because the LCD glass is more ductile than the alumina ceramic, the crack extension of LCD glass is more difficult than that of alumina ceramic. Therefore, water coolant and pre-bending are needed to help enhance the thermal stress for the separation of glasses, unlike the cutting of alumina. The softening point of LCD glass substrates is low, about 985°C. The laser spot must be large enough to decrease the temperature and prevent the softening effect.

According to the idea of pre-bending proposed by Hoekstra [4], the method of cutting glass using a laser for controlled fracture was investigated. In this study, a water jet coolant and a pre-bending device were designed to produce tensile stress along the cutting path that causes the glass to separate along the moving path of the laser beam. The key point of this method is the design of a pre-bending mechanism. In the patent proposed by Hoekstra [4], the discussion of the effect of pre-bending was less than the current work. Hoekstra only proposed the idea of a bending technique, but had neither presentation of experimental results nor any discussion on the crack propagating process. In this paper, the fracture extension process and the machining parameters have been discussed in detail.

The fracture mechanism of laser cutting for alumina has been well studied [6, 7]. However, only a few studies have examined the fracture extension mechanism for LCD glass. The controlled fracture mechanism for glass is different from that for alumina. In this study, the mechanism by which the fracture is controlled was proposed according to observation of the fracture extension and experiments of acoustic emission. At the same time the micro-structure of fracture surface was observed by scanning electron microscopy (SEM). The relationships between the machining parameters, i.e., laser power, cutting speed, and cutting quality were also discussed.

2 Principle of controlled fracture with pre-bending

2.1 Materials and cutting process

The experimental specimens are TFT-LCD Eagle^{2,000} glass substrates produced by the Corning Company (Taiwan). The glass substrates are cut to the size of 100 × 100 × 0.63 mm^3. Figure 1 illustrates the laser-cutting system, which is composed of a laser system, a coolant system, and a bending device. The laser is a continuous output voltage CO$_2$ laser, in which the minimum diameter of the focal spot is about 135 μm. The glass is bent to a curve using a three-point-bending device. The defocused laser beam is applied along the desired separation path and the coolant water jet follows the laser spot. Great tensile stress is generated along the separated plane and induces substrate separation.

The coolant water is emitted from a nozzle. It flows at a constant rate in a direction opposite to that of the moving laser. The coolant water must be applied behind the laser spot. The cooling area is influenced by the coolant flow rate and the blow speed.

2.2 Defocused laser beam

Because the softening temperature of the glass is low, the temperature increase due to the applied laser energy must be low enough. If the laser beam is focused on a narrow spot, the laser energy will concentrate on a local area and induce a high temperature. Therefore, the laser spot size must be large enough to limit the temperature and prevent the softening effect.

The focal plane of the CO$_2$ laser was placed at a defocused distance of 30–45 mm, at which the diameter of the laser spot was about 3.5–4.5 mm. The laser spot size is the dominant parameter for the controlled fracture technique. For constant laser power output, a larger laser spot size could prevent the melting effect and create large thermal stress. However, if the laser spot is too large, the energy diverges greatly and does not induce the required stress. The optimal laser spot diameter is about 4.0 mm.

According to the foregoing study on the laser cutting for alumina [6], the crack propagation speed for the smaller laser spot was slower than that for the larger laser spot at the same laser power output. When reducing the laser power and laser spot size, the melting effect could be prevented, but thermal stress will also be decreased and not sufficient to separate the substrate. In general the thermal stress and the cutting speed obtainable for the small spot size with small laser power is less than that for large spot size with large laser power.

2.3 Pre-bending technique

It is difficulty to obtain a high cutting speed and good surface quality when only employing a defocused laser to separate the LCD glass substrates. In order to improve the surface quality and the cutting speed, a bending moment is required to increase the tensile stress along the separation path. The bending moment is applied using a three-point bending device as shown in Fig. 1. The bending deflection δ can be regulated by a bolt screw. The relationship between the bending moment M and the deflection δ along the cutting path can be expressed as $M = Lt^3E\delta/W^2$, where L, W, and t are the length, width, and thickness of the substrate, respectively. The corresponding maximum bending stress is $6Et\delta/W^2$ on the top surface of the substrate.

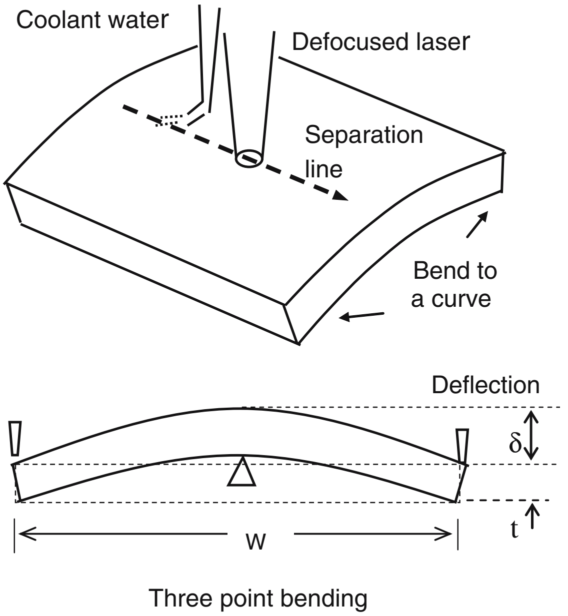


Fig. 1 Illustration of laser cutting LCD glass with bending moment

3 Experimental results

3.1 Cutting speed, laser power, and bending deflection

For a laser spot diameter of 4 mm and the pre-bending deflections (δ) value of 0.18 mm and 0.43 mm, the experimental results of the cutting speed and the required laser power to separate the substrate are shown in Fig. 2. The symbols represent the experimental data for successful glass separation. The solid lines and dashed lines represent the maximum cutting speed attainable at different laser power outputs. The results have been proved by repeated tests. The cutting speed represents the laser moving speed, which can make the crack tip follow the moving of the laser spot.

It can be seen that the higher the bending deflection, the higher the maximum cutting speed is. With a laser power of 50 W, the maximum cutting speed that can be attained is 115 mm/s and 50 mm/s for a pre-bending deflection of 0.43 mm and 0.18 mm, respectively.

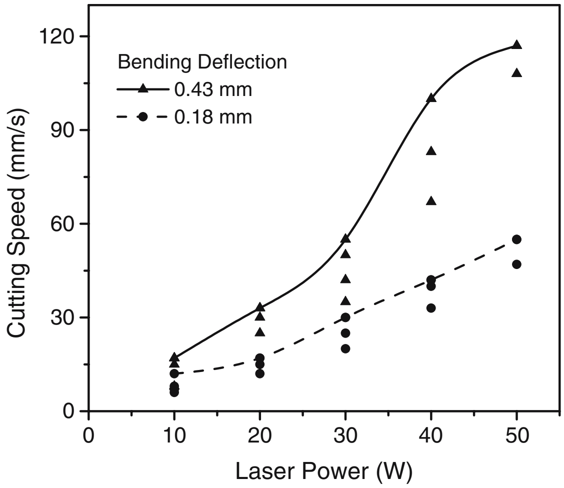


Fig. 2 Relationships between cutting speed, laser power, and bending deflection

3.2 Breaking surface

To understand the mechanism of laser cutting with this controlled fracture technique, a cross section along the cutting path was investigated. When using a CO_2 laser to cut a LCD glass substrate, the laser beam traversed a distance but did not go completely through the material. The specimen was then stripped into two pieces along the cutting path. Photographs of the breaking surfaces obtained at a cutting speed of 35 mm/s and a laser output power of 30 W are shown in Fig. 3.

The photograph in Fig. 3 shows two regions: the controlled fracture region, throughout the thickness, and the unfractured region. The dashed line, i.e., crack edge, indicates the boundary between the fractured region and the unfractured region. The curves indicated by the arrows on the photographs are Wallner lines, which have been extensively employed in the analysis of glass breaking [8]. The direction of the fracture extension is along the normal direction of the Wallner line. The crack edge does not penetrate through the thickness during the cutting process. The crack extends top-down from the surface and will stop extending when it approaches the bottom. At the end of material separation, an unstable fracture of the crack edge causes the glass substrate to split completely into two pieces.

3.3 Non-uniformly separation

Material separation is similar to crack propagation. An image processing system of crack detection was employed to obtain a crack image continuously during the laser-cutting process. The images of the crack tip were grabbed by the camera and computer, and analyzed by an image processing program. Figure 4 shows the positions of the crack tip and the laser spot. The separation frontier can be recognized due to the inflection of the light in the material separation region. The crack tip is extending behind the moving laser spot during the cutting process. The lagging

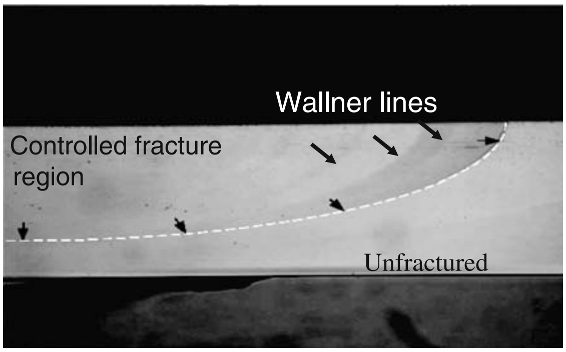


Fig. 3 Separation surfaces along the cutting path. The arrows denote the wallner lines and the crack propagating direction

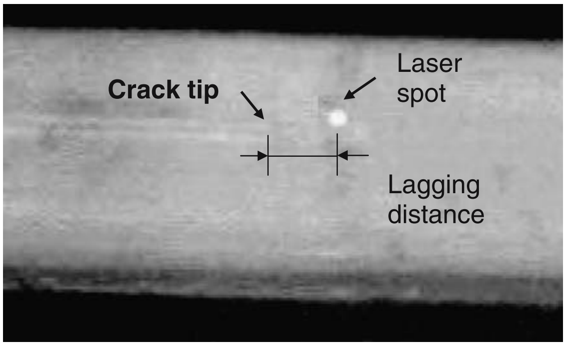


Fig. 4 Measurement of the lagging distance of the crack tip to the laser spot

distance between the crack tip and the laser spot can be measured using the crack detection system.

Figure 5 shows the lagging distance for the cutting condition of laser power 30 watts and cutting speeds 17, 25, and 35 mm/s. The experiment was repeated twice, but no repetition of the lagging distance distribution could be concluded. Most of the time, the crack tip lags behind the laser spot. Only near the cutting end, the crack propagation may overtake the moving of the laser spot. An interesting phenomenon is that the crack does not propagate at a constant speed. In general, the distance between the crack tip and the laser spot fluctuates about 2 mm with amplitude of about 2 mm. It can be seen that the lagging distance is random with no obvious behavior. The phenomenon is very different from laser cutting in alumina [6], in which the higher the cutting speed, the longer the lagging distance is.

The crack propagating speed is not a constant even at the condition of constant moving speed of laser beam. The propagation of the crack tip always follows the laser spot within a finite distance. The higher the laser moving speed, the higher the crack propagation speed is. However, if the laser moving speed is too high, the crack extension will not initiate.

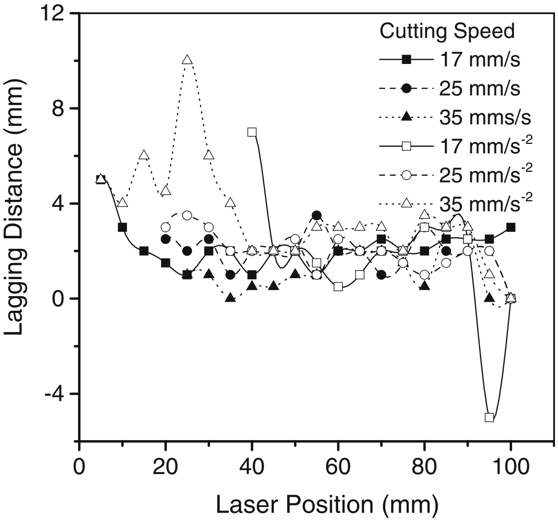


Fig. 5 Lagging distance of the crack tip to the laser spot

3.4 Acoustic emission

The acoustic emission (AE) sensing technique was employed to investigate the crack propagation process during the laser-cutting process with controlled fracture. The acoustic emission system comprises an AE sensor, a signal processor, and software. The AE sensor can detect a signal when a crack is initiated or propagates. The acoustic emission signal provides useful information about crack growth in the cutting process, in which stress waves are emitted from cracking. The investigated AE signal parameters were peak amplitude and energy. They could be useful for monitoring the crack initiation and propagation process.

Consider a glass of size 100 × 100 × 0.63 mm^3. A laser beam was applied to the glass edge, moving at a constant speed of 17 mm/s. The laser beam had a power output of 40 W and a defocused spot diameter of 2 mm. The peak amplitudes of the transducer voltage and energy during the laser-cutting process are shown in Fig. 6.

At time t=0, the laser was applied at the edge of the substrate and moved along the desired cutting path, thus emitting a signal. At time t=0.55 s and 6.5 s, two large signals of amplitude and energy due to acoustic emission were received. Between t=0.55 s to 6.5 s, the acoustic emission signals occurred continuously and uniformly. It means that after the laser had moved for 0.55 s, a crack was initiated suddenly at the edge of the substrate and then the crack extended steadily along the moving path of laser beam. At the end of cutting, t=6.5 s, the laser spot arrived at the opposite edge of the substrate and an unstable breaking

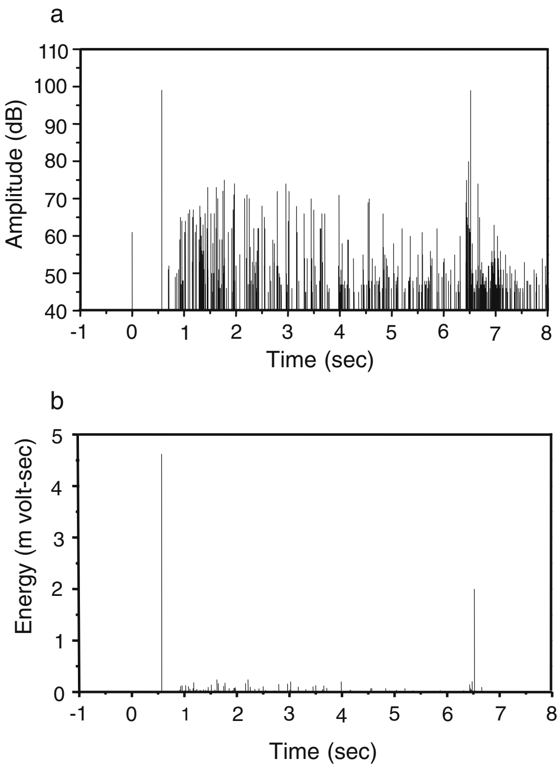


Fig. 6 (**a**) Amplitude and (**b**) energy of acoustic emission signal during the stable fracture cutting process

occurred. At the final stage, the unfractured region was breaking unstably, and a great AE signal was emitted.

If the moving speed of the laser beam is 10 mm/s, the acoustic emission signal occurrence as shown in Fig. 7 is very different from the one mentioned above. At time t=0, the laser was applied at the edge of the substrate and moved along the desired cutting path. At time t=0.6 s, when the laser had moved for a short distance, i.e., 6 mm, a large acoustic signal was emitted and a crack was initiated suddenly at the edge of the substrate. However, at time t=3.5 s, another large signal was emitted and the substrate was split into two pieces, when the laser spot had just arrived at the distance of 33 mm from the starting point of the cutting. Because the laser is moving very slowly, a large stress will be induced causing the substrate to break unstably before the cutting is completed. Under this condition, good straightness cannot be achieved.

Laser cutting without cooling or pre-bending yields poor cutting quality and many cross cracks distributed uniformly along the laser-applied path. For cuts made with laser spot speed of 5 mm/s and without cooled and pre-bending assistance, the peak amplitudes of the transducer voltage and energy during the laser-cutting process are shown in Fig. 8. There is no signal jump during the whole laser cutting process, the time interval between 0 and 20.8 s. This phenomenon is very different from the cases shown in Figs. 6 and 7. The amplitude of the AE signal is larger and denser than that emitted from the cutting with cooled and pre-bending assistance as shown in Figs. 6 and 7. This signal indicates that many cross cracks uniformly initiate at the laser spot path. The photo of cross-cracks distribution is shown in Fig. 8.

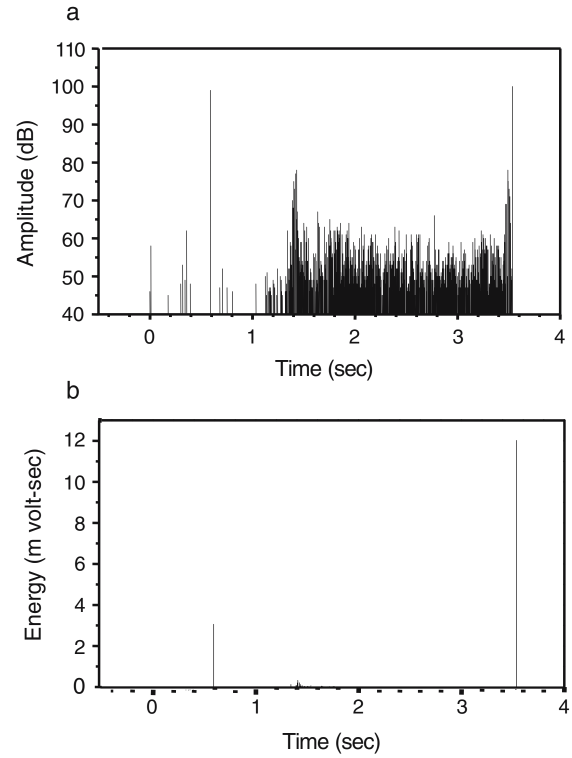


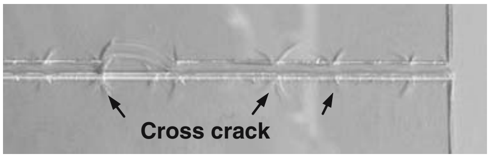
Fig. 7 (**a**) Amplitude and (**b**) energy of acoustic emission signal during the unstable fracture cutting process

3.5 Three stages of fracture extension

From the acoustic emission experimental results, it can be concluded that the whole cutting process can be divided into three stages as shown in Fig. 9. Stage I is the fracture initiation, with time t=0~t_i, when the initiation of the fracture occurs due to the tensile stress at the edge of the glass substrate. When the laser has been applied at the edge of the glass substrate and is moving along the desired cutting path, the substrate will not crack immediately. After a short delay time, i.e., t=t_i, cracking is initiated at the edge of substrate. In general the lagging distance is about 1 to 10 mm at this stage.

Stage II is the stable fracture growth, from time t_i to t_f, when the fracture frontier follows the moving path of the laser beam. The distance between the fracture frontier and laser spot is non-uniform during this stage, even though the fracture extension is always stable.

Stage III is the unstable fracture, at time t=t_f, in which the stress near the crack tip is totally a tensile stress through the



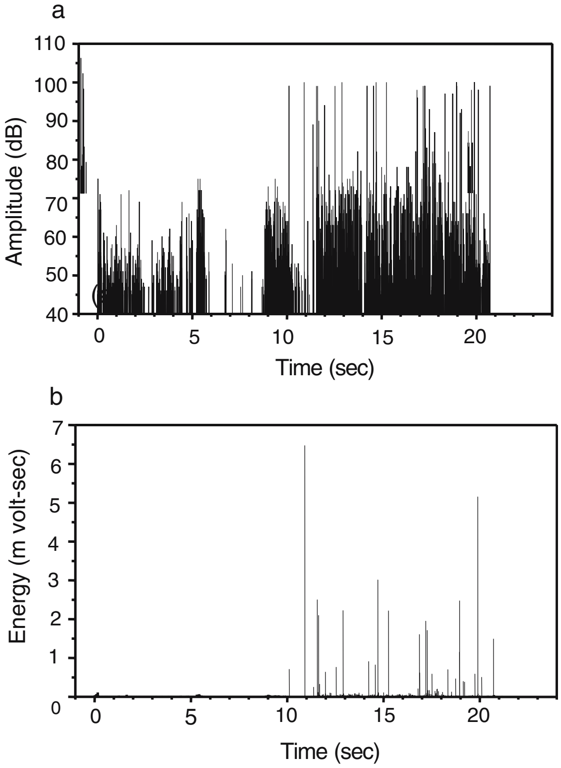


Fig. 8 (**a**) Amplitude and (**b**) energy of acoustic emission signal during the cutting process without pre-bending

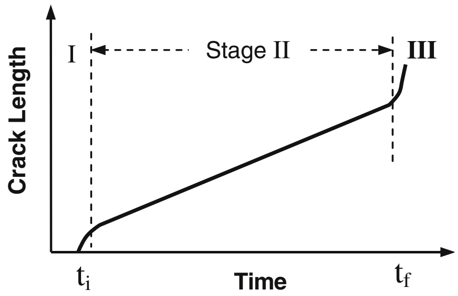


Fig. 9 Configuration of the three stages of fracture extension

thickness direction, so that the crack will extend unstably. The blind crack will penetrate through the thickness direction suddenly and extend through the whole desired cutting path.

3.6 Three types of unstable fracture

From the analysis of acoustic emission signals and the image processing of separation frontier during the cutting process, it is obvious that there are three types of unstable fracture: (1) delay breaking, (2) nick breaking, and (3) ahead breaking. The configurations of the three types are shown in Fig. 10. Dashed lines represent the position of the laser spot while solid lines represent the position of the crack tip. Delay breaking occurs after the laser completes the whole cutting path, with a short delay. At high cutting speed, the occurrence of the unstable fracture is usually delayed. In the case of nick breaking, when the laser spot moves near the substrate edge, the unstable fracture occurs immediately and the crack tip overtakes the laser spot. The third type is ahead breaking, in which the unstable fracture occurs before the laser spot moves close to the substrate edge.

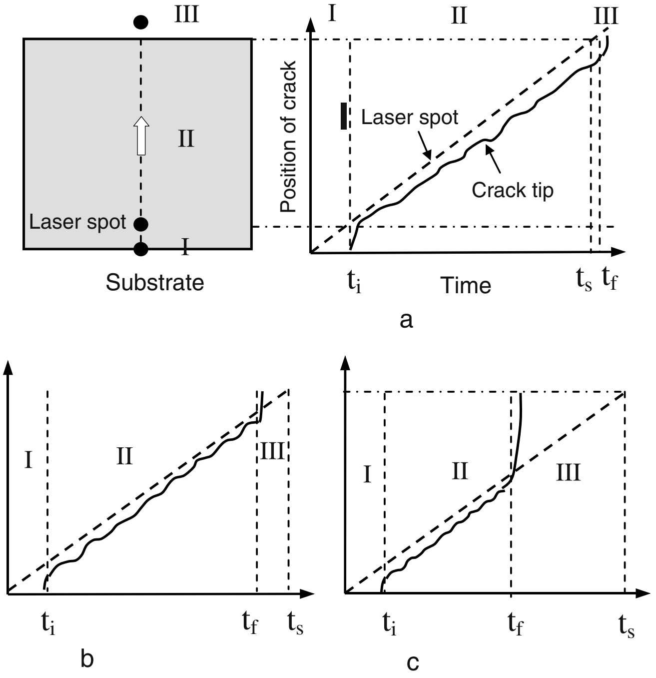
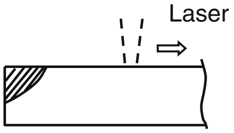


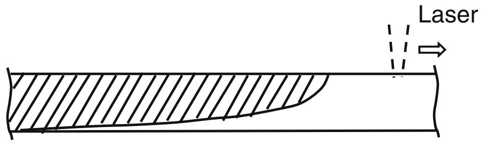
Fig. 10 Configuration of fracture extension stages for the (**a**) delay breaking, (**b**) nick breaking, and (**c**) ahead breaking

The illustrations of the breaking mechanism for the three types of unstable fracture are shown in Fig. 11c. It shows the relative locations of laser spots and crack tips before the instance of unstable fracture occurrence. For delay breaking, the blind crack is formed during the cutting process. After the laser moves through the cutting path, the blind crack penetrates through the substrate and complete separation occurs at the end of the cutting process. For nick breaking, the through-cut of substrate grows stably following the motion of laser spot. For ahead breaking, the unstable fracture occurs at one-third to one-half of the length of the cutting path.

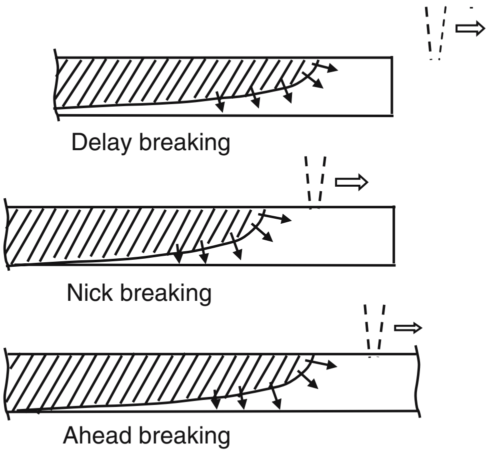
The moving speed of laser beam is the dominant factor for the three breaking types. If the cutting speed is fast, the unstable fracture forms by delay breaking. The top-down crack extension will be stopped before cutting through the thickness direction. Therefore, the blind crack is formed and the occurrence of unstable fracture will be delayed. If the laser beam is moving at medium speed, the unstable fracture forms by nick breaking.



a Stage I –Fracture Initiation



b Stage II –Stable Fracture Growth



c Stage III –Unstable Fracture

Fig. 11 Configuration of fracture extension stages. The black arrows denote the crack extending direction

If the moving speed is slow, the unstable fracture stage will occur early. For a cutting speed of 10 mm/s, the acoustic emission signals are shown in Fig. 7. It is obvious that the unstable fracture occurred at the time of 3.5 s, in which the laser passed one-third of the length of the whole cutting path.

3.7 Fractograph and surface quality

SEM Photographs of the cutting surface are shown in Fig. 12. As can be seen, the surface quality obtained by laser cutting using controlled fracture combined with a coolant jet and pre-bending was very smooth and showed no significant micro-cracks. Three alternative methods were compared. Figure 13a is the SEM photograph of the LCD glass surface separated using laser cutting without bending. Because the laser-cutting speed is slow, the surface quality is poor due to the melting effect. Figure 13 (b) shows the traditional cutting of diamond scribing and mechanical breaking. As can be seen, many chips exist in the breaking surface. Figure 13c is the SEM photo of surface broken by a diamond through cutting, in which some chips exist in the breaking surface.

The roughness profiles of the separation surfaces are shown in Fig. 14. The arithmetic averaged surface roughness R_a calculated is 0.4 μm for a laser power of 40 W, cutting speed of 30 mm/s, and bending deflection of 0.18 mm. R_a is 0.2 μm for a laser power of 40 W, cutting speed of 80 mm/s, and bending deflection of 0.43 mm.

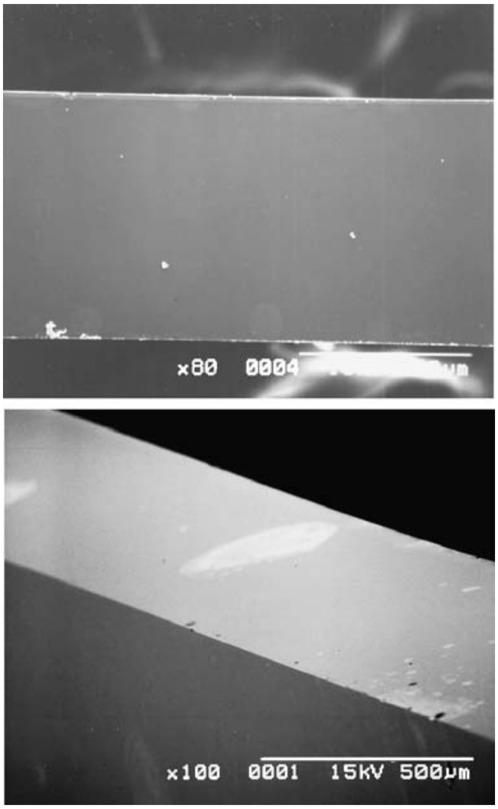


Fig. 12 SEM photographs of the separation surfaces of the LCD glass using the method of controlled fracture with bending moment

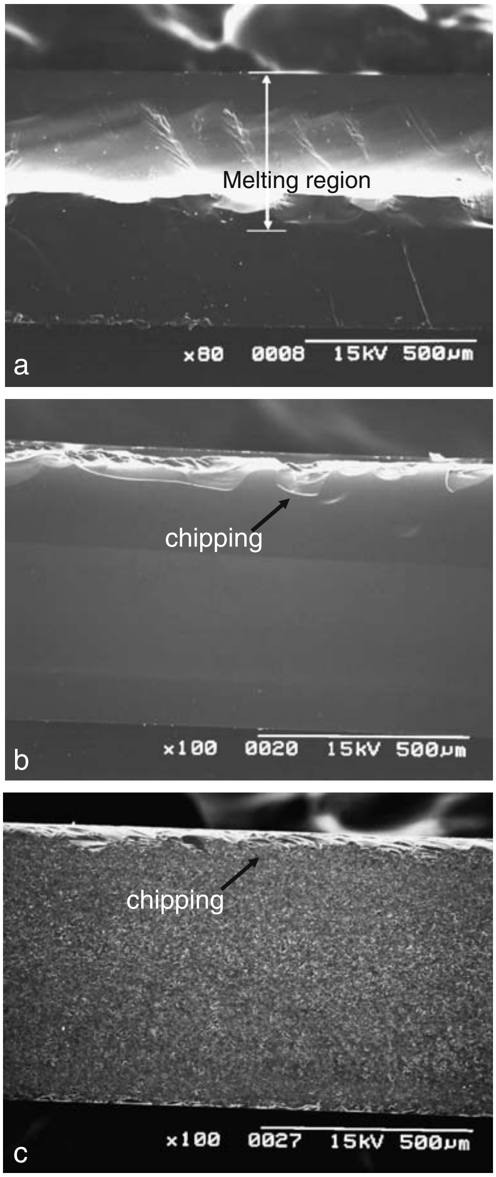


Fig. 13 SEM photographs of the separation surfaces of the LCD glass using the method of (**a**) laser cutting without bending, (**b**) diamond scribing and breaking, and (**c**) diamond through cutting

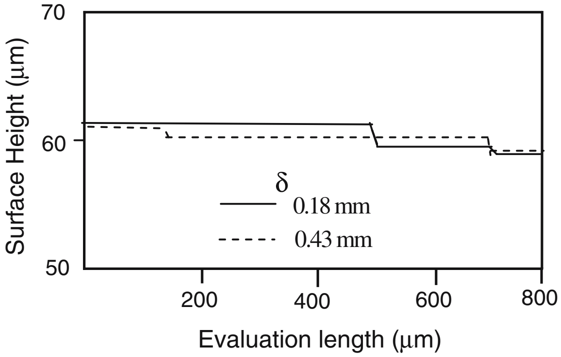


Fig. 14 Roughness profile of the separation surface for bending deflection of (**a**) 0.18 mm and (**b**) 0.43 mm

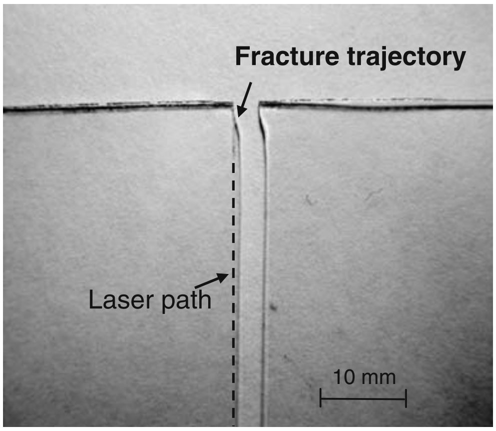


Fig. 15 Fracture trajectory deviates from the applied laser path for cutting an asymmetrical line

3.8 Asymmetrical cutting

The crack extension in laser cutting using controlled fracture technique is attributed to the thermal stress induced by the laser heat. In order to ensure accurate splitting, it is essential that the stresses must be distributed symmetrically with the crack. However, for most cutting conditions the cutting path is asymmetrical, so the crack extension trajectory will deviate from the desired cutting path.

Cutting a line that is straight but not along the median plane is asymmetrical cutting. The stress state at the crack tip is not symmetrical with the crack, so the actual fracture trajectory will deviate from the desired cutting path. The photograph of straight line cutting is shown in Fig. 15, where the specimen size was 100 × 100 × 0.63 mm^3, the bending deflection was 0.18 mm, the laser power was 40 W, and the cutting speed was 33 mm/s. The laser-cutting path denoted by the dashed line was one quarter of the way along the specimen edge. The actual fracture trajectory deviated from the straight line of the laser-cutting path.

The bending device is difficult to implement along a curve-cutting path. Furthermore, the bending moment will cause the crack to branch away from the curve-cutting path due to the mixed mode stress concentration. Therefore, the bending technique can not be successfully applied to curve cutting.

4 Conclusion

The controlled fracture technique with pre-bending was successfully applied to the cutting of LCD glass substrates. The mechanism of the controlled fracture technique has been thoroughly examined in this study. It was found that the unstable fracture growth mode can be divided into three types: (1) delay breaking, in which the blind-crack is formed during the cutting process and complete separation occurs at the end of the cutting process; (2) nick breaking, in which the through-cut of substrate grows stably following the moving laser; and (3) ahead breaking, in which the unstable fracture occurs in the middle of the cutting path.

The surface quality along the cutting path is very good, and is better than that from the diamond scribing and breaking. The pre-bending operation can enhance the cutting speed that can be attained.

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References

1. Lumley RM (1969) Controlled separation of brittle materials using a laser. Am Ceram Soc Bull 48:850–854
2. Grove FJ, Wright DC, Hamer FM (1970) Cutting of glass with a laser beam. US Patent 3,543,979
3. Kondratenko VS (1997) Method of splitting non-metallic materials. US Patent 5,609,284
4. Hoekstra BL (2002) Method for separating non-metallic substrates. US Patent 6,252,197
5. Choo DH, Kim BI, Jung SU, Lee WS, Kim BS (2002) Laser cutting apparatus and method. US Patent 6,407,360
6. Tsai CH, Liou CS (2003) Fracture mechanism of laser cutting with controlled fracture. ASME J Manuf Sci Eng 125:519–528
7. Tsai CH, Chen CJ (2003) Formation of the breaking surface of alumina in laser cutting with a controlled fracture technique. Proc Inst Mech Eng, B J Eng Manuf 217:489–497
8. Ono T, Tanaka K (2001) Effect of scribe-wheel dimensions on the cutting of AMLCD glass substrate. J Soc Inf Display 9:87–94