



Selective unidirectional median crack propagation in glass achieved by mechanical scribing

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Abstract This work reports a selective median crack propagation phenomenon in glass, leading to a novel glass cutting process. We found that by scribing a glass sample to the extent of plastic deformation with a deformation depth of 100–400 nm, followed by inducing an initial crack, a subsurface crack with a depth of $\sim 10 \mu\text{m}$ was propagated backward along the centerline of the scribed region with a speed of 1 $\mu\text{m/s}$ order. The crack depth and propagation speed were increased by increasing the scribing load. We

conclude that the propagation direction was determined by the effect of the shear stress caused by a scribing tip sliding motion.

Keywords Glass cutting · Median crack · Subcritical crack propagation · Plastic deformation · Mixed mode fracture

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1 Introduction

Crack formation is one of the fundamental phenomena in brittle materials, including glass, and has always been a complex matter. Various types of cracks, such as median, lateral, and radial cracks, typically appear when hard materials are indented into glass surfaces (Lawn and Swain 1975; Cook and Pharr 1990; Sglavo and Green 1995). The nucleation and propagation mechanisms have been intensively researched (Hagan 1979; Rouxel 2015; Yoshida 2019). Controlling these crack formations is difficult because the indentations include elastic/plastic deformation, densification, and shear flow (Peter 1970; Hagan 1980), followed by the unloading process, leading to the change of the stress distribution resulting in multiple types of crack formation. Moreover, the crack formation can be three-dimensional, which becomes further complicated, as shown in the fundamental studies on scratching and grinding-related tests. For example, Qiu et al. (2016) investigated the surface flaw and

subsurface behavior when scratching glass–ceramics to elucidate crack propagation and material removal mechanisms of grinding. Yu et al. (2016) studied the effect of machining parameters, and Li et al. (2016) analyzed the subsurface damage using an analytical model. Matsuoka et al. (2017) reported the influence of scratching speed and normal load on the crack morphology in glass by changing the environment. Bandyopadhyay and Mukhopadhyay (2013) predicted the shear stress distribution and experimentally validated these values after scratching glass. Some of the research applied progressively increased loads to evaluate scratch resistances (Le Hou erou et al. 2003; Gu and Yao 2011; Ming et al. 2019). In summary, the scratching or grinding motions can form these cracks into lines instead of one point. Although a median crack line is the most important for the glass cutting process, other types of cracks are formed as well when median cracks are formed, as shown in glass cutting via wheel scribe (Swain 1980; Swain et al. 1980; Cook 1994; Kopchekchi and Shitova 1996; Tomei et al. 2018).

In this study, we report the phenomenon that only the median crack lines are successfully formed into glass by a simple mechanical method, which includes two steps, the introduction of plastic deformation by using a diamond tip and followed by initial crack formation. As a primary objective, this study discusses the crack formation and propagation mechanisms, which is essential for the future application of these cracks based on this phenomenon.

2 Materials and methods

Figure 1 shows the schematic of the experimental procedure for the median crack initiation and propagation. Alkali-free glass substrates (AF45, Schott AG) with a thickness of 500 μm were scribed via diamond tip (SOLID-D, Mitsubishi Diamond Industrial Co., Ltd.) with a speed of 30 mm/s (“1st scribing”). The glass surface was contacted with the point at the diamond tip, where three diamond surfaces intersected, and one of the surfaces was faced front in the scribing direction, as shown in Fig. 1. The diamond tip was attached to a tip holder connected to a linear servo guide through an air cylinder to control the scribing load ranging from 0.26 to 0.76 N. After the 1st scribing, to initiate the crack propagation, another

scribing line (“2nd scribing”) was formed orthogonally to the 1st scribing line via scribing wheel (Micro-Penett, Mitsubishi Diamond Industrial Co., Ltd.). The scribing wheel had a periodically patterned structure with a pitch of $\sim 18 \mu\text{m}$ along its circumference. The scribing wheel rolled on the glass surface and initiated the crack propagation caused by the indentation of each pattern onto the glass surface along the scribing line, as shown in Fig. 1. The scribed glass was observed by a confocal microscope (LEXT OLS4000, Olympus Co., Ltd.), including the measurement of surface profiles. Crack propagation speed was measured by monitoring and plotting the location of the crack tip in the air at $\sim 70\%RH$ in the case of 0.26, 0.38 and 0.51 N. In the case of 0.63 and 0.76 N, the crack propagation speeds were measured by observing the glass sample at a specific angle using a standard camera due to the difficulty of locating the crack tip via microscopic view. The sectional view of the median crack was also captured using a scanning electron microscope (SEM, JSM-IT200, JEOL Ltd.). Breakability along the median crack line was checked by breaking along the 2nd scribing line to expose the crack initiation point, followed by breaking along the 1st scribing line by hand.

3 Results and discussion

Figure 2 shows the photographs nearby the crack initiation point by changing the scribing load from 0.26 to 0.76 N. As an additional remark, the micrographs only when the cracks were formed were shown, because there was some instability in the crack initiation and its propagation direction. As shown in Fig. 2a, cracks were propagated backward compared with the 1st scribing direction. The crack origins were considered as radial cracks caused by the 2nd scribing. From the origins, the cracks propagated from the slight left or right side compared with the centerline of the 1st scribing area. Then, the crack propagated towards the centerline (in the case of 0.63 N, the cracks were initiated both on the left and right side, and only the right side propagated because of the earlier initiation than the left one). It is noted that the crack also propagated forward along with the 1st scribing direction, as shown in Fig. 2b. However, the cracks, in turn, started to deviate away from the centerline and stopped with a length of 20–100 μm .

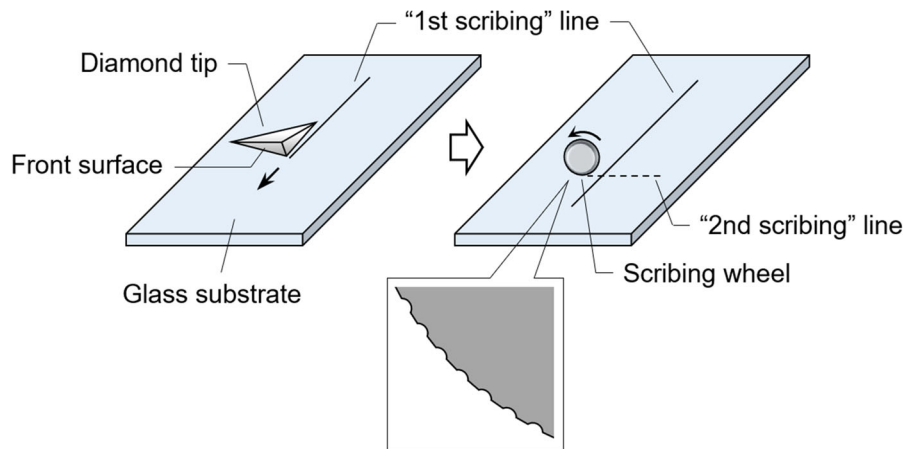


Fig. 1 Schematic of the experimental procedure for the median crack initiation and propagation

Fig. 2 Micrographs nearby crack nucleation areas. Cracks propagated **a** backward and **b** forward and stopped. In **a**, crack initiation parts are marked, and in **b**, whole cracks are marked by broken enclosures

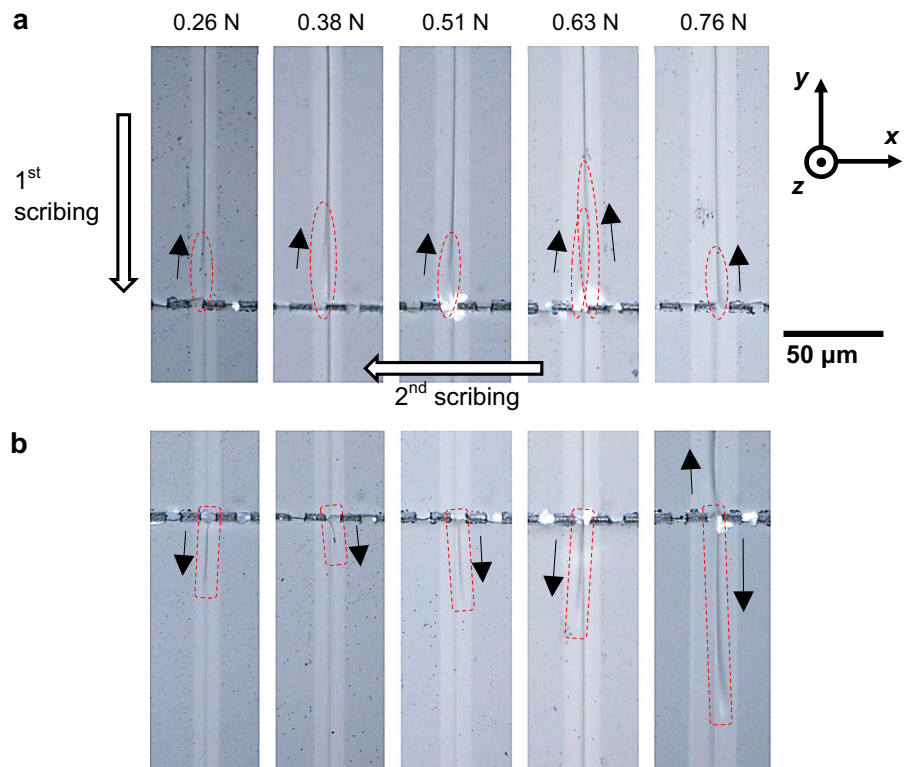


Figure 3a and b represent the cross-sectional micrographs (x - z plane) of cracks in the glass after its propagation taken by the microscope in the case of 0.26–0.76 N and by the SEM in the case of 0.63 N, respectively. Figure 3c shows the schematic of the cross-section near the crack-formed area, including the definition of the measured values in this paper. As shown in Fig. 3a, median cracks with a depth of

9.7–18.9 μm measured from the glass surface were observed. According to Fig. 3a and b, the surface layer depths were ~ 2 μm (E.g., 1.7 μm in the case of 0.63 N, confirmed by the SEM image). Figure 4 shows the surface profiles along the x -axis, revealing that the glass was deformed at a 200–500 nm depth. This deformation was considered the plastic deformation of the glass. By increasing the scribing load, the

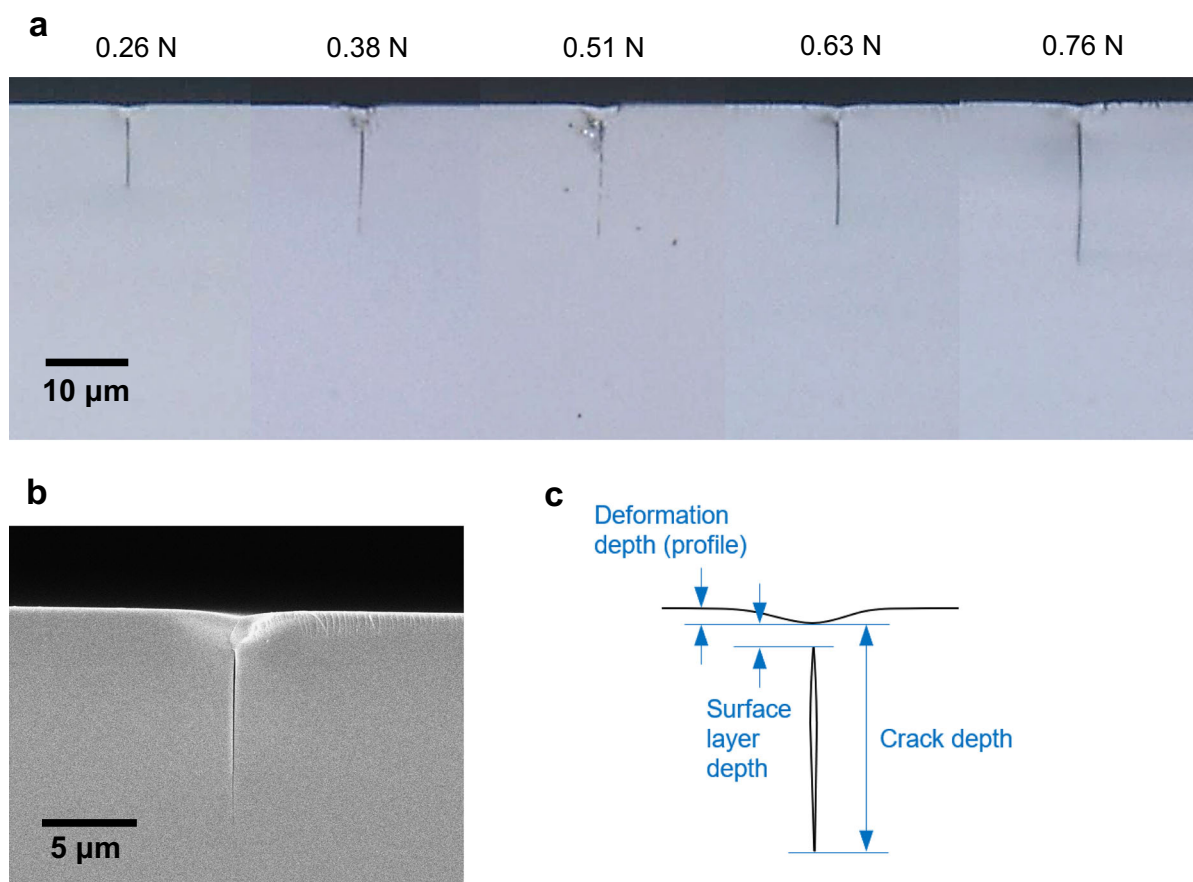


Fig. 3 Cross-sectional images taken by **a** the microscope in the case of 0.26–0.76 N and **b** the SEM in the case of 0.63 N. **c** Schematic of the cross-section near the crack-formed area

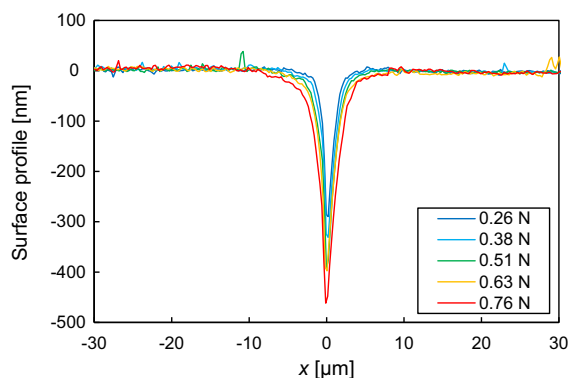


Fig. 4 Surface profiles in each scribing load

deformation depth was also increased. Then, internally applied tensile stress will increase, leading to deeper crack depths. Regarding the surface profile of the centerline of the scribed area along the scribing

direction (y -axis), no significant irregularities were detected. Furthermore, we confirmed that the samples having these cracks were breakable only in the backward direction by applying tensile stresses after breaking along the 2nd scribing line.

Figure 5a shows the time-lapsed crack propagation length plotted every 10 s, where the slope of the graph shows the crack propagation speed. The measurement start point was located at ~ 1 mm apart from the crack nucleation point. The crack propagation speeds were 1.6, 1.9, and 2.4 $\mu\text{m/s}$ at a scribing load of 0.26–0.51 N. Although, on average, the propagation speed was constant, in a microscopic view, the crack propagation randomly and repeatedly accelerated and decelerated with each periodic propagation length of a few μm order. As the profile irregularities were not observed along the 1st scribing direction (y -axis), we consider that this periodic propagation behavior is

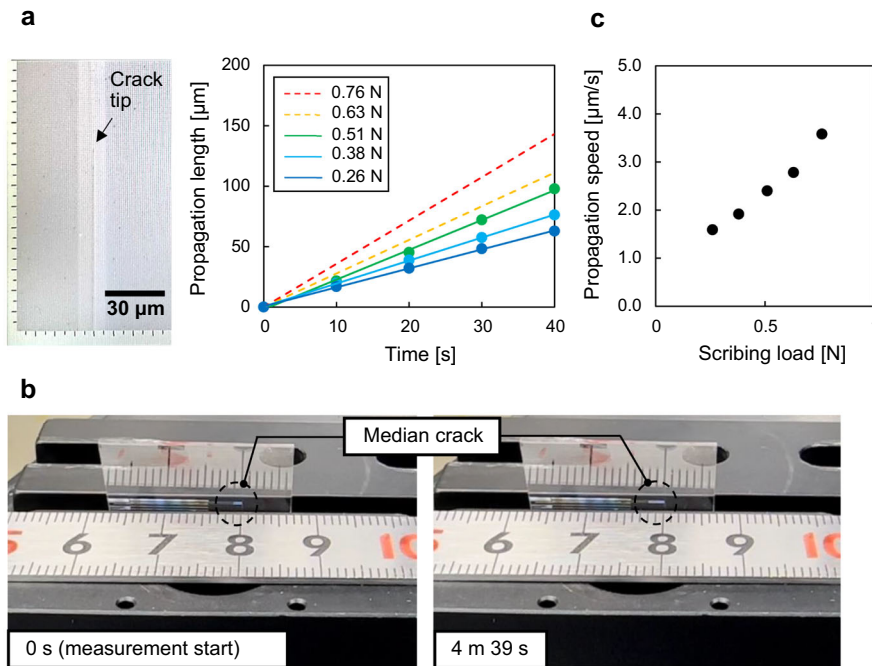


Fig. 5 **a** The time-lapsed crack propagation length (Snapshot example is shown in the left photo. Supplemental videos in the scribing load of 0.26 N (0_26N.mp4), 0.38 N (0_38N.mp4), and 0.51 N (0_51N.mp4) are available. Supplemental video (0_26N_water_drop_test.mp4) is another video file, which

was captured when the water drop test was conducted in the scribing load of 0.26 N. **b** Photographs of the median crack captured at 0 s (measurement start) and 4 m 39 s in the scribing load of 0.76 N. **c** The relation between the scribing load and propagation speed

caused by the cyclic behavior of the accumulation and concentration of crack opening force at the crack tip and release of the force by crack opening. Figure 5b shows photographs of the median crack captured at 0 s (measurement start) and 4 m 39 s in the scribing load of 0.76 N. The median crack propagated towards the left in the photo, and the propagation speed in the scribing load of 0.63 and 0.76 N was 2.8 and 3.6 $\mu\text{m/s}$, respectively (broken lines in Fig. 5a), calculated via propagation distance and time. Figure 5c represents the relation between the scribing load and propagation speed. The measured speed values are similar to those of subcritical crack propagation, a kind of crack propagation phenomenon driven by chemical reaction and minor applied stress, reported by Wiederhorn (1967). Simple confirmation can be done by breathing onto these glass samples to increase the humidity, and then the propagation speeds increased. We note that the median crack propagated only inside the glass and did not open into the air, except for the initial crack point, confirmed by a water drop test. In the case of

0.26 N, the crack propagation speed was 1 $\mu\text{m/s}$ order, which was increased to $\sim 200 \mu\text{m/s}$ when the water was dropped onto the initial crack point (Supplemental video (0_26N_water_drop_test.mp4) is available). Therefore, we conclude that the moist air entered through the initial crack point.

Regarding the unidirectional crack propagation mechanisms, the crack was always driven into the centerline during backward propagation, while deviating away from the centerline during forward propagation, as shown in Fig. 2a. Figure 6 shows the schematics of the crack propagation phenomena. Crack patterns were shown in curved solid and broken arrows. We consider that the key driving force is shear stress in the x - y plane caused by scribing glass via diamond tip. It is considered that the glass surface moves toward the scribing direction via shear flow when the glass is scribed. Then, an internal force is applied to the subsurface part in the $-y$ direction (depicted as the red arrow in Fig. 6). Simultaneously, the reaction force is applied to the surrounding area in the $+y$ direction (the

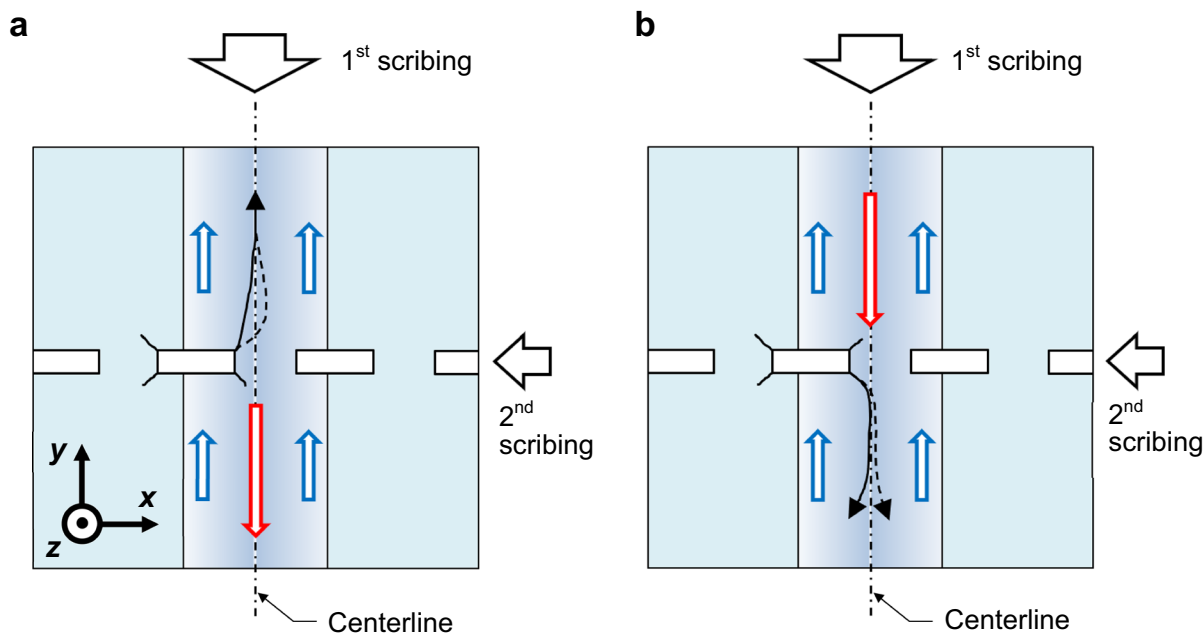


Fig. 6 Schematics of the crack propagation phenomena in **a** backward and **b** forward directions

blue arrows). As a result, the shear stress is applied to the scribed area. Thus, the crack propagates under the mixed stress field on the tensile and shear stresses. According to the study on crack propagation under the mixed loads (K_I and K_{II} modes) (Erdogan and Sih 1963), the propagation angle can be described as

$$\theta(A) = 2 \tan^{-1} \left\{ \frac{1}{4} \left[\frac{K_I(A)}{K_{II}(A)} \mp \sqrt{\left(\frac{K_I(A)}{K_{II}(A)} \right)^2 + 8} \right] \right\}, \quad (1)$$

where K_I and K_{II} are stress intensity factors on each fracture mode, and θ is the crack propagation angle to the centerline. Equation (1) is only valid for small θ values. According to Fig. 2, crack propagation angles in both cases of backward/forward propagations were 3–5°, corresponding to $K_{II}/K_I = 0.026$ –0.044. The result implies that even a small value on K_{II} is enough for this phenomenon.

4 Conclusions

This study demonstrated the median crack propagation phenomenon in glass by mechanical scribing. By the reported method, subsurface cracks were propagated backward with a crack depth of $\sim 10 \mu\text{m}$ and

propagation speed of 1 $\mu\text{m/s}$ order. The sample was breakable only in the backward direction toward the scribing direction. The crack propagation speed was exponential to the applied load, and then we concluded that the crack propagation was similar to the subcritical propagation reported in the past. The shear stress is considered the key driving force for the crack to be propagated along the centerline only in the backward direction. This crack propagation phenomenon is essential and fundamental to studying a new mechanical glass cutting process without unfavorable cracks.

Author contributions SI: Conceptualization (lead); Resources (equal); Visualization (lead); Writing — original draft (lead); Writing — review & editing (equal). SM: Resources (equal); Supervision (equal); Writing — review & editing (equal). HH: Resources (equal); Supervision (equal); Writing — review & editing (equal). KM: Conceptualization (supporting); Resources (equal); Writing — review & editing (equal). MK: Resources (equal); Writing — review & editing (equal).

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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