The Basic Study About the Effect of Single Point Grinding on the Bending Strength of Brittle Material

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Single point grinding was investigated by using a sliding indentation apparatus. Sharp indenter sliding against brittle solid produces a scratch with a median crack. The size of the crack depends on the applied indenter load and the sliding speed. The effect of the crack size and its orientation on bending strength of glass is investigated experimentally. It is shown that the tested glass has high bending strength when the indenter load is low, bending direction is parallel to the scratch, and sliding speed is low. The results of bending test are predictable by fracture mechanics analysis including residual stress effect. This study makes it possible to understand the influence of grinding conditions on the bending strength of ground ceramics.

Key Words : Single Point Grinding, Sliding Indentation, Bending Strength, Ground Ceramics

1. Introduction

Ceramic components are being increasingly used in many industrial applications. Machining of electronic and structural ceramics is often required to meet stringent tolerance and surface finish requisites. Among the various machining processes, grinding, lapping, and polishing are widely used to generate fine finishes on ceramics. Grinding and lapping processes utilize abrasives as the principal tools to accomplish material removal. The material removal is carried out by relative motion and force traction imposed at the abrasive particle-workpiece contacts (Ahn and Park, 1997). The abrasive machining introduces contact damage such as microcracking and plastic deformation on the near surface of ground ceramics. These flaws include median, radial, and lateral cracks along the scratches which are caused by abrasive particles on ground surface (Evans, 1981). The residual stresses are also induced by the differential elastic-plastic deformation in the damaged and undamaged layers (Chandrasekar, 1987).

The machining-induced flaws and residual stresses have a significant effect on the mechanical properties of the machined component. For example, the bending strength depends on grinding conditions (Inasaki, 1987 and Richerson, 1982). When the orientation of grinding is parallel to bending direction, ceramic materials withstand more toughly in bending test than they do when orientation is perpendicular. The abrasive size also has an influence on the strength. The bending strength of ground ceramics decreases with an increase in the abrasive size of a grinding wheel. Mechanical strength of ceramic materials may be dominantly governed by the median crack among the surface flaws (Matsuo, 1987). The feed rate among the grinding conditions also has an effect on the strength of material. As the feed rate gets higer, the bending strength becomes lower (Yui, 1989). If compressive residual stesses exist in grounded surface, the strength of ground ceramics increases (Samuel, 1989).

The main objective of this paper is to understand the effect of surface damage on the bending strength of ground ceramics based on a single-point grinding. Grinding can be thought to be occurring through the repeated application of hard, rigid sliding indenters (abrasives) to the

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surface of solid. In this study a single point grinding (scratching) was made on the surface of soda-lime glass by sliding indentation with a sharp indenter and the bending strength of the indented glass was measured in various indentation conditions. The bending experiments are interpreted by fracture mechanics analysis with respect to the size and orientation of scratching-induced crack, and the residual stresses near the crack.

2. Experimental Details

Commercially available microscope slide made of soda-lime glass was used as specimen. The glass slide has a dimension of 76.2mm×25.4mm ×1.0mm and surfaces of the glass slide are highly polished. The typical properties of the soda-lime glass are shown in Table 1.

A single point grinding (scratching) on the specimen was made by the formal experimental equipment used for sliding indentation study (Fig. 1, see Ref. of Ahn, Choi and Park, 1997 for details of equipment). Pyramidal diamond Vickers indenter was used for single point abrasive. The normal load applied on indenter was controlled between 0.5N and 2.5N with a resolution of 5×10^{-3}N by using a strain gauge device. Linear stage (Newport PM500) was used to generate constant speeds within the range from 32.0 to $25\times10^{3}\mu$m/sec. A single scratch is made on the center of specimen. The length of the scratch is 2.0cm and is oriented with 5 different angles of 0°, 22.5°, 45°, 67.5°, and 90°, as shown in Fig. 2(a). Several experiments of static indentation were carried out to be compared with those of sliding indentation. The static indentation can be thought to be the basic material removal model for free abrasive grinding. A single static indentation with normal load of 9.8N or 49.0N was made on the center of specimen and arranged so that one of indenter diagonals is parallel to the bending direction (Fig. 2(b)). The standard Vickers hardness tester (Leco V-100A) was used for static indentation. Fig. 3 shows typical flaw types used when soda-lime glass is indented by quasi-static (Fig. 3(a)) and sliding (Fig. 3(b)) Vickers indenter (Cook, 1990 and Ahn, Choi and Park, 1997).

Some indented specimens are annealed before bending test in order to investigate the residual stress effect on the bending strength. Annealing of glass was done by heating the sample at the temperature of 520℃ for 1.5 hours and by slow cooling in the furnace. At least one hour after the annealing process, specimens were broken by four-point bending fixture along the indented surface on the tensile side. The cross head speed was 5m/s.

Table 1 The typical properties of the soda-lime glass.

Hardness	5.5 GPa
Young's modulus	70 GPa
Poisson's ratio	0.25
Fracture toughness	0.75 $MPa\sqrt{m}$

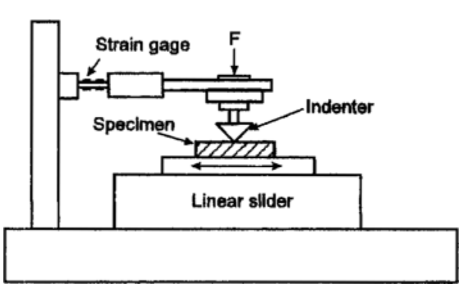


Fig. 1 Single point grinding apparatus configuration.

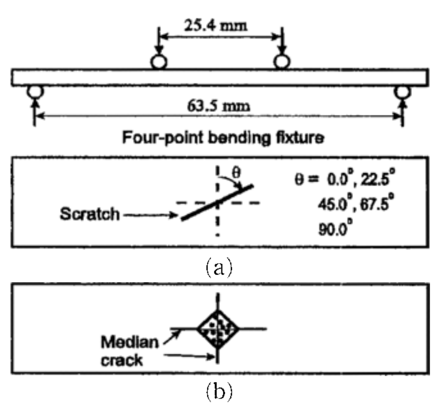
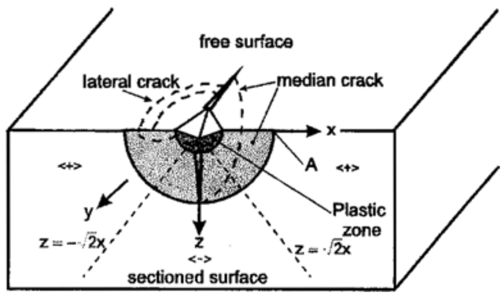
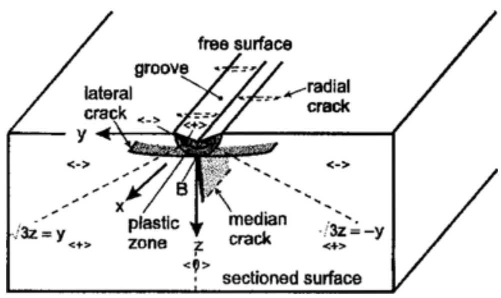


Fig. 2 Schematic drawings of (a) scratch orientation of sliding indenter and (b) orientation of static indentation in four-point bending test.



(a)



(b)

Fig. 3 Schematic views of (a) quasi-static indentation and (b) sliding indentation showing cracking, plastic zone, and residual stress. (⟨+⟩ : σ_y is in tensile, ⟨−⟩ : σ_y is in compressive, ⟨0⟩ : σ_y is zero).

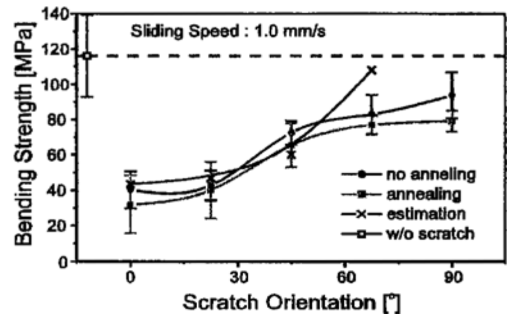


Fig. 4 Influence of scratch orientation on bending strength at indenter load of 1.0N.

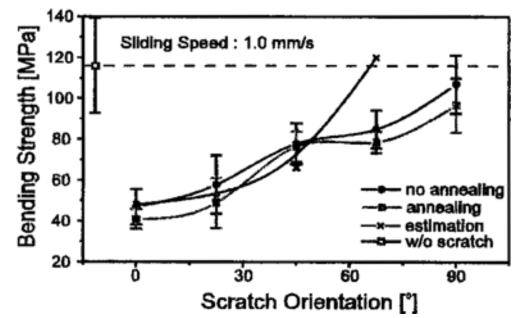


Fig. 5 Influence of scratch orientation on bending strength at indenter load of 2.0N.

Cylindrical bearing steel shafts of which diameter was 6mm were used for loading and supporting the test specimen. The bending force was measured by piezoelectric force transducer (made by Kistler Instrument Corp.). The indentations and bending tests were accomplished in a laboratory at room temperature of 25℃. In all experiments we used at least 8 specimens for one test. The bending strength of soda-lime glass without any grinding(indentation) was also measured.

To measure the size of subsurface median crack caused by the sliding indentation, some scratched specimens were cut perpendicular to the sliding direction of the indenter. The cross-sectioning was accomplished based on the fact that the bending fracture of specimen with static indentation flaws produces very smoothly sectioned surface by the propagation of median crack. At first, the center of the specimen was static indented with a Vickers indenter at applied load of 49.0N. Then sliding indentation is made perpendicular to bending direction in the pre-indented surface of the specimen and near the outside of median/radial crack tip of the static indentation. In the last stage, the specimen is fractured by the four-point bending fixture.

3. Experimental Results

The variation of bending strength with respect to five different scratch orientations is shown in Figs. 4 and 5. The sliding speed is 1. 0mm/s and the applied loads are 1.0N and 2.0N, respectively. From both figures it is revealed that the bending strength increases as the scratch orientation changes from 0° to 90° regardless of the annealing of the samples. As the bending strength increases, there is a rapid increase around at scratch orientation of 45°. Finally, when scratch orientation is close to 90°, the strength is close to that of glass without any indentation flaws on surface. The lowest strength occurs when the scratch is oriented perpendicular to the bending force while

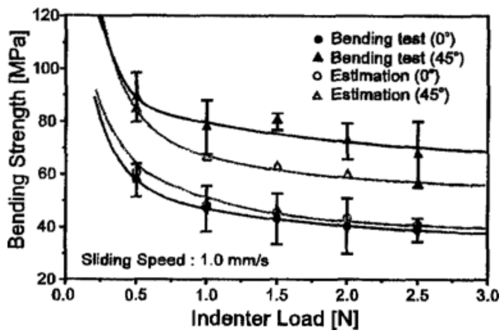


Fig. 6 Influence of indenter load on bending strength.

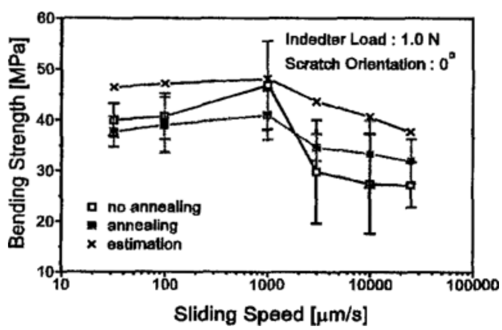


Fig. 7 Influence of indenter sliding speed on bending strength.

the highest does at parallel scratch orientation.

Bending test for various indenter load ranges from 0.5N to 2.5N was tried using indenter sliding speed of 1.0mm/s. Figure 6 shows that the bending strength decreases as the indenter load increases. The scratch orientations were 0° and 45°. The bending strength is close to the maximum when an indenter load is very low and it drops exponentially as the indenter load are raised. In Figs. 4 and 5 the bending strength for applied load of 2.0N is greater than that for 1.0N for all scratch orientations regardless of the annealing process. Thus it is thought that the effect of indenter load on bending strength is independent of scratch orientations.

Figure 7 shows the bending strength variation of glass according to the sliding speed of Vickers indenter when indenter load is 1.0N and the scratch orientation is 0°. The bending strength is almost constant as the scratch speed increases from 32μm/s to 1.0mm/s. However when the

Table 2 Bending strength of glass with static indentation flaws.

Indenter load	Strength of no-annealed glass	Strength of annealed glass
9.81 (N)	73.6$\pm$4.22 (MPa)	94.0$\pm$5.78 (MPa)
49.05 (N)	53.7$\pm$4.15 (MPa)	61.7$\pm$2.91 (MPa)

sliding speed of indenter is faster than a critical speed of 1.0mm/s, the bending strength is reduced and becomes smaller than those at low sliding speeds ($\leq$ 1.0mm/s).

The bending strength of annealed glasses is different from that of non-annealed glasses. The bending strength of annealed glass is a little smaller than that of non-annealed one for all scratch orientations when scratch speed is 1.0mm/s and indenter loads are 1.0N and 2.0N (Figs. 4 and 5). From figures it looks as if the effect of annealing treatment on bending strength is independent of indenter load and scratch orientation. However, the influence of annealing on bending strength is dependent of sliding speed (Fig. 7). The bending strength is diminished after annealing at low scratch speed ($\leq\sim$ 1.0mm/s), but when the scratch speed is greater than the critical speed of~ 1.0mm/s the annealing treatment enhances the bending strength.

Table 2 gives fracture strengths measured from four-point bending test of statically indented glasses. The bending strength for an indenter load of 9.81N is greater than that of 49.05N. Annealed glasses have more strength than non-annealed glasses for both indenter loads, but the strength of all glasses with a static indentation flaw on the surface is lower than that (116$\pm$23.205MPa) of glass without any indentation flaw. For statically indented glass, the bending strength decreases as the indenter load increases, and the annealing treatment raises the bending strength.

4. Fracture Mechanics Analysis

Sliding indentation by a sharp indenter usually produces deep median crack as shown in Fig. 3 (b). If the bending fracture is assumed to be generated by the median crack, the fracture

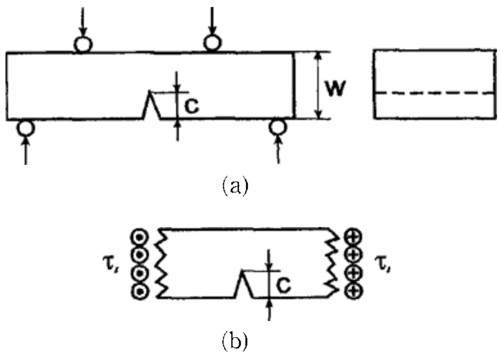


Fig. 8 Schematics of idealized median crack for (a) Mode Ⅰ and (b) Mode Ⅲ.

mechanics can be applied with a combination of mode Ⅰ and Ⅲ. The schematics of idealized median crack for fracture mechanics analysis are shown in Fig. 8. When the scratch orientation of median crack is θ, the bending stress (σ_B) is transformed to the tensile stress ($\sigma_B \cos^2\theta = \sigma_t$) and shear stress ($\sigma_B \cos\theta \sin\theta = \tau_t$) with respect to median crack. It is assumed that the median crack intersects a free surface through plastic zone and the shear stress (τ_t) is constant along the depth direction of specimen.

For the idealized crack as shown in Fig. 8 the stress intensity factors of mode Ⅰ and Ⅲ are quoted from the handbook (Murakami, 1987) and are

$$K_I \cong 1.122\sqrt{\pi c}\ \sigma_t (\text{when } \frac{c}{w} \ll 1.0),$$
$$\sigma_t = \sigma_B \cos^2\theta \quad (1)$$
$$K_{III} = \sqrt{2w \tan\left(\frac{\pi c}{2w}\right)}\tau_t, \quad \tau_t = \sigma_B \cos\theta \sin\theta. \quad (2)$$

The stress field near median crack can be assumed as a plane strain if the scratch is long enough to ignore the longitudinal displacement. The strain-energy release rate for plane strain with mode Ⅰ and Ⅲ is (Hellan, 1984)

$$G = \frac{K_I^2(1-\nu^2)}{E} + \frac{K_{III}^2(1+\nu)}{E} \quad (3)$$

The strain-energy release rate (G_c) when the glass is fractured by bending force is equal to K_{Ic}^2/E and this value can be calculated from the mechanical properties of glass. Therefore, the

Table 3 Measured depth of median crack in sliding indentation

Indenter Load	Depth at sliding speed of 1.0 (mm/s)
0.5 (N)	41.7±9.45 (μm)
1.0 (N)	71.2±30.71 (μm)
1.5 (N)	77.1±25.14 (μm)
2.0 (N)	85.8±35.96 (μm)
2.5 (N)	98.7±45.60 (μm)
Sliding speed	**Depth at indenter load of 1.0 (N)**
0.032 (mm/s)	74.1±18.71 (μm)
0.1 (mm/s)	71.9±16.56 (μm)
1.0 (mm/s)	71.2±30.71 (μm)
10.0 (mm/s)	98.4±17.70 (μm)
25.0 (mm/s)	116.9±10.20 (μm)

bending strength (σ_B) which is at $G = G_c$ can be calculated from the Equations, (1), (2), and (3) if the depth of median crack (c) is known.

The bending strengths (σ_B) are analytically estimated for various scratch orientations (θ) with the measured median crack depth in Table 3. In estimation, the residual stress effect is not considered. These results are shown in Figs. 4 and 5. At low angles of 0° and 22.5° the estimated strengths agree well with experimental data. The bending strength of analytical model goes up exponentially with the increase of scratch orientation and diverges from bending test data when scratch orientation is greater than 45°. It approaches the maximum limit when the scratch orientation is about 67.5°. The analytical estimations are also plotted as a function of indenter load in Fig. 6 and of sliding speed in Fig. 7. A comparison of the prediction by fracture mechanics model with the experimental measurements shows reasonable agreement.

5. Discussion

Median and radial cracks of scratch are potential flaws that can initiate bending fracture. The fracture mechanics model was developed based on only median crack because the depth of radial crack is much smaller than that of median one. As shown in Figs. 4 and 5, when sctach orientation (θ) is less than about 45°, reasonable agreement between the results of bending test and analytical estimation validates the assumption that the longitudinal median crack is the major flaw causing fracture. However, the prediction deviates from the experimental results when scratch orientations is about 60°∼90° at which radial crack is subjected to tensile stress by bending force, because the real bending strength is a little reduced by radial crack when the scratch orientation is parallel to the bending force, while the influence of radial crack is not considered in analytical estimation. Grinding process produces many grooves on the workpiece surface with longitudinal median cracks and transverse radial cracks along the grinding direction (Evans, 1981). From our experimental outcome it is thought that the strength of ground ceramics is controlled by the median crack rather than radial crack. Therefore the bending strength is the weakest perpendicular to grinding direction and is the strongest parallel to grinding direction.

As the bending force is applied to a specimen, stress concentration will take place at the tip of a median crack. It would be expected that the bending strength of glass be reduced with the increase of depth of a median crack because the stress concentration is higher for a deep crack than a shallow one. It is found that high load applied on sliding indenter produces deeper median crack than low load does (Table 3). Peter also observed the increment of the depth of median crack as the indenter load increases when sliding speed is ranged from 2.5 to $1\times10^4 \mu m/s$ (Peter, 1964). In consequence, the bending strength decreases as the higher load is applied on sliding indenter. In grinding process, the larger abrasive grain size is used, the fewer abrasive particles are active in machining process. Thus the average load per active abrasive particle becomes high and produces large median and radial cracks on ground surface. Accordingly, the bending strength of ground ceramics is reduced as the grain size increases.

The variation of bending strength as a function of sliding speed is well predictable from the measured depth of median cracks. In Table 3, the depth of median crack is almost constant at low sliding speeds ($\leq$1.0mm/s) but the depth increases greatly as the speed increases beyond the critical speed (∼1.0mm/s). It seems that as the sliding speed of indenter is increased the strain rate of indented solid gets higher. The solid could behave more brittle with the increase of strain rate so that the cracks under the indenter become much bigger. This change of crack depth well explains why the bending strength is varied with the sliding speed of the indenter. The bending strength is not much changed at low sliding speed ($\leq$1.0mm/s) because of small variation of the crack depth. When the sliding speed of indenter increase more than ∼1.0mm/s, the strength is reduced rapidly due to the increment of depth of the median crack. Holland and Turner (1937) found the same result with a cutting diamond. In grinding process, the sliding speed of abrasive grain against a workpiece becomes faster as the feed rate is increased. Thus, the median cracks under the ground surface get deeper and then the strength of workpiece gets weaker.

The bending strength is also affected by the residual stress around a crack. The analytical model of residual stress is described by Ahn (Ahn, 1994) and coordinates systems for the analysis are shown in Fig. 3. From the analytical model the distributions of normal residual stresses which are parallel to bending force are shown in Fig. 3(a) for static indentation and in Fig. 3 (b) for sliding indentation. The maximum stress concentration in statically indented flaws occurs at the crack tip where a median crack intersects the surface, the point A in Fig. 3(a). It is found analytically that the residual stress around this crack tip is tensile. The bending strength has to be reduced by this tensile residual stress. If the specimen is annealed before bending test so that residual stresses are removed, the strength will increase. Same results have been also found for soda-lime glass (Lawn, 1985) and for silicon nitride and silicon carbide (Petrovic, 1979).

In sliding indentation the median crack does not intersect the surface. When scratch orientation is perpendicular to bending direction the maximum stress concentration caused by bending force takes place at the crack tip in elastic-plastic boundary, the point B in Fig. 3(b). Analytically, the compressive residual stress is found near the crack tip (the point B). This compressive residual stress is expected to prevent the propagation of median crack to the surface so that the bending strength increases. The annealing of sliding indented specimen will reduce the bending strength by removing of compressive residual stress near the tip of median crack. Stress concentration occurs at radial crack when scratch orientation is parallel to bending direction. Similar analytical inspection has been carried out and it is discovered that the residual stress at tip of radial crack is compressive. Thus it is expected that the annealing effect on bending strength for radial crack is same as that for median crack.

As it can be seen from Figs. 4 and 5 the bending strength decreases after annealing regardless of scratch orientation. However, if the scratch speed increases high enough to produce very deep median crack, the bending strength increases after annealing (Fig. 7). It seems that when median crack is very deep compared to plastic zone, the influence of tensile residual stress existing along the crack surface becomes superior to that of compressive residual stress existing at the crack tip in the elastic-plastic boundary. Consequently the crack opening that is caused by tensile residual stress acting on the crack surface decreases the bending strength. Kirchner and Isaacson have found similar result that strength of steatite and H.P. Si_3N_4 were reduced by residual stresses in single point grinding at the grinding speed of 13m/s (Kirchner, 1981). They attributed this to the fact that the tensile residual stresses acting on the wedge open the median crack.

Samuel et. al. (1989) found that compressive residual stresses existed on the surface of the most ground ceramics and annealing treatment reduced the bending strength of ground ceramics, which was different from experimental results of single point grinding at high speed. The grinding process can be thought of repeated action of single point grinding. Hence the residual stresses in ground surface can be produced by the superposition of residual stresses from each single point grinding. It seems that residual stresses at the vicinity of median cracks in grinding process are compressive. The experimental result of single point grinding is not enough to explain the effect of residual stress in grinding process. The scratching speed of single point grinding in this study is not fast enough to resemble the cutting speed of typical grinding process. In order to understanding the residual stress effect on ground ceramics more detail, sliding indentation study will have to be carried out at as high sliding speed as that of typical grinding process is required. In future work, various ceramic materials besides glass are to be examined to get the more reasonable understanding about single point grinding.

6. Conclusion

The bending strength of single point ground glass is controlled by longitudinal median crack. Therefore,

(1) The perpendicular orientation of scratch against bending direction results in lower bending strength than the parallel orientation.

(2) A higher indenter load results in lower bending strength because of deeper median crack.

(3) Increasing the sliding speed of a sharp indenter produces a deeper median crack and so results in lower bending strength.

In addition the residual stress near the median crack has an influence on bending strength.

These results well correspond to the effects of grinding direction, abrasive grain size, and feed rate on the bending strength of ground ceramics. This indicates that the median cracks caused by abrasive particles in grinding process are the main factor controlling the strength of ground ceramics. In order to control the strength of ground ceramics it would be useful to study for the better prediction of median crack depth and for the understanding of its interaction with a residual stress.

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