Effects of the tool inclination and edge serrations on the brittle fracture in the micro milling of the optical glass

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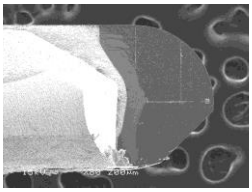
Abstract. Effects of the tool inclination and edge serrations on the brittle fracture in the micro ball endmill process on the soda-lime glass are discussed. Cutting tests are carried out by edge serrated SCD (Single Crystal Diamond) micro ball endmills they are redressed the micro structure by the Focused Ion Beam (FIB) milling process to observe the changing of the crack propagation by features of serrations and tool inclination. In the cutting tests, characteristics of the crack propagation were changed by a tool inclination angle, especially, cracks were reduced at the angle of 45 degrees.

Background

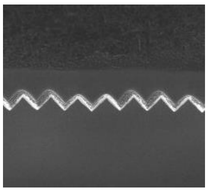
Recent years, optical glasses are widely used not only the conventional optical applications. For examples, glass chemical inspection plate is used in the chemical engineering and medical and pharmacy fields because of its excellence thermal and chemical characteristics. Normally, this inspection plate is constituted by micro scale grooves for a flow channel or a chemical reaction of chemicals. And these grooves are made by the chemical etching process. However, the brittle fracture is caused on the machined surface by the inadequate cutting conditions for example the excess cutting depth with the irregular cutter engagement. An avoidance of the brittle fracture is the most important issue because they make deterioration of surface quality and decrease the stiffness.

Based on this background, author has tried to observe the brittle cracking in typical micro cutting processes by diamond tools they are fabricated periodic serrations on their cutting edge [1-2]. In previous experiments, milling tests were performed on the soda-lime glass by the serrated SCD (Single Crystal Diamond) ball endmills as shown in Figure 1 to observe the characteristics of the fracturing [1]. In the milling test, a crack propagation on the machined surface is changed by vertex angle of the edge serrations as shown in Fig. 2. At the vertex angle of 90 degrees, the fracture is reduced than that of 120 degrees. According to these results, it can be considered that the shape of the serration and a cutter locus effect on the brittle cracking. In the ball endmill process, the cutter locus is changed by the tool attitude. If periodic (uniform) serrations are formed on the cutting edge, characteristics of the cutter engaging, for example the cutting depth, the engaging direction, the cutting force, etc. are changed by change in the tool attitude. And characteristics of the brittle fracture also may be changed by change in the cutter engaging. However, the mechanics of this changing have been not cleared.

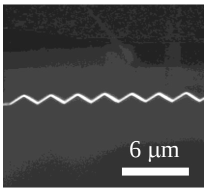
To solve this problem, the milling tests were performed by change in the tool attitude. In cutting tests, the shaping is performed on the soda-lime glass by the serrated ball endmills. Uniform triangular serrations are produced by the Focused Ion Beam (FIB) process. Thus, milling tests are performed with change in the tool inclination angle to observe its effect on the brittle fracture.



(a) Tool nose

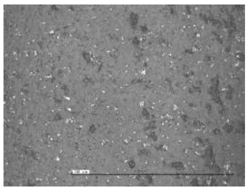


(b) Vertex angle, 90 deg.

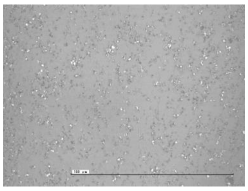


(c) Vertex angle, 120 deg.

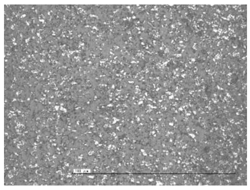
Fig. 1 Serrated SCD ball endmill [3]



(a) No serrated



(b) Vertex angle, 90 deg.



(c) Vertex angle, 120 deg.

Fig. 2 Machined surface [3]

Cutting conditions: material cut, soda lime glass; feed rate, 0.12 mm/min; rotational speed, 20000 rpm; feed rate per edge, 12 nm/edge; cutting speed, 62.8 m/min; depth of cut, 0.02 mm; and lubrication, water.

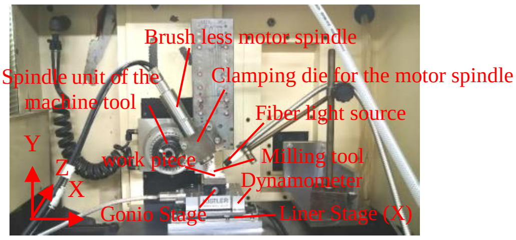
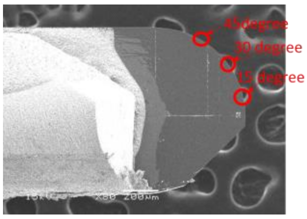
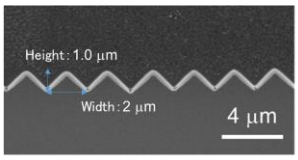


Fig. 3 Machine tool in the milling test



(a) Tool nose



(b) Tool shape

Fig. 4 R0.5 SCD ball endmill in the milling test

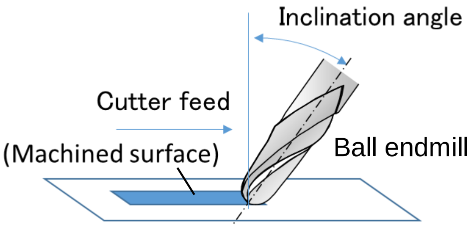


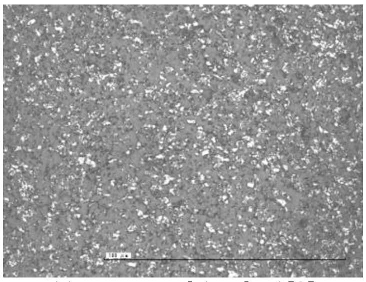
Fig. 5 Schematic of the slotting oparation

Table 1 Cutting conditions

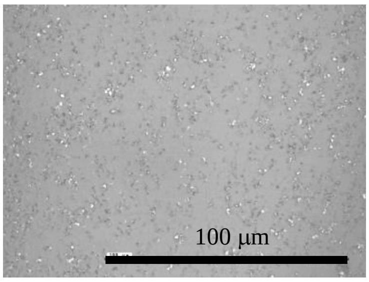
Material cut	Soda lime glass
Cutting tool	R0.5 SCD ball endmill
Tool inclination angle deg.	15, 30, 45
Feed rate per an edge nm	6
Cutting velocity m/min	62.3
Depth of cut in Z axis mm	0.02
Feel length mm	0.6
Lubrication	Distilled water

Milling tests

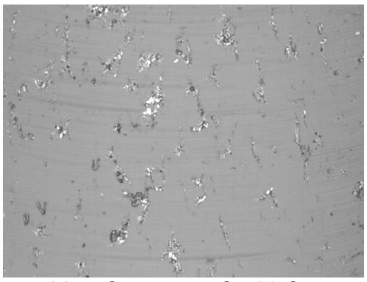
Figure 3 shows the machine tool in the milling tests. Slotting operations are performed by the three-axis controlled horizontal CNC machine tool. A milling tool is clamped on a brushless motor spindle. The motor spindle is mounted on the spindle head of the machine tool by the clamping device to change the tool inclination angle that respect to the cutter feed. In this experiment, the slotting is performed at the inclination angle of 15, 30 and 45 degrees respectively. A specimen of the soda-lime glass is clamped on piezo dynamometer by a clamping jig on the X stage to observe not only a cutting tool but also observe a contact of the cutting edge and the material cut. Also, the cutter engaging can be observed by a CCD microscope. during the milling tests. Figure 4 shows the serrated SCD (Single Crystal Diamond) ball endmill in cutting tests. Its nose radius of curvature of 0.5 mm, rake angle of 0 deg. and relief angle of 7 degrees, respectively. And it is observed that the its edge roundness of less than 100 nm by the observation with SEM (Scanning Electron Microscope) images. Edge serrations are fabricated as the symmetry triangular its vertex angle of the 90 degrees by the FIB process. In the FIB process, the ion beam is exposed on the rake face of the cutting tool with the inclination angle of 2 degrees from a nominal direction of the rake face to makes the relief



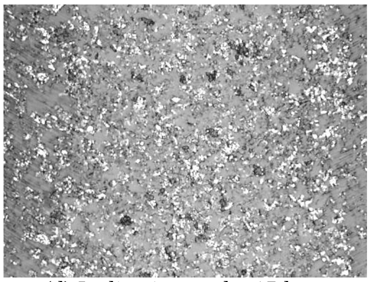
(a) No serrated (45 deg.)[3]



(b) Inclination angle: 45 deg.



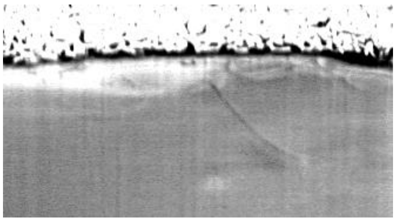
(c) Inclination angle: 30 deg.



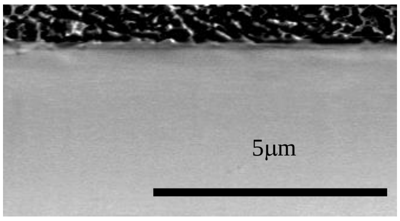
(d) Inclination angle: 15deg.

Fig. 6 Machined surface

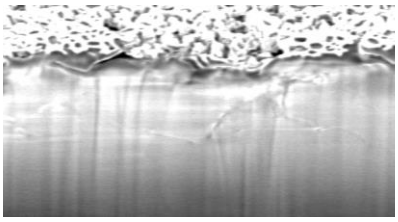
Cutting conditions: Tool, R0.5 single crystal diamond ball endmill; material cut, soda lime glass; feed rate, 0.24 mm/min; rotational speed, 20000 rpm; feed rate per edge, 12 nm/edge; cutting speed, 62.8 m/min; depth of cut, 0.05 mm; and lubrication, water.



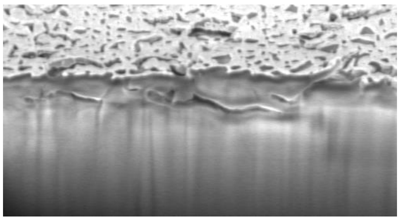
(a) No serrated (45 deg.)



(b) Inclination angle: 45 deg.



(c) Inclination angle: 30 deg.



(d) Inclination angle: 15deg.

Fig.7 Cross section under the machined surface

Cutting conditions are same as those in Fig. 6.

surface. Figure 5 shows the schematic of the milling process in milling tests. The slotting is performed with the tool inclination it is respect to the cutter feed as shown in this picture at the constant depth of cut in Y (Vertical) axis. Table 1. illustrates the mainly cutting conditions. The slotting is performed with the distilled water lubrication.

Figure 6 shows the machined surface they are observed by the Scanning Electron Microscope (SEM). In this figure, the machined surface which fabricated by the no serrated milling tool at the inclination angle of 45 degrees in previous experiments is also shown as the reference. In the case of the no serration edge is shown in Fig. 6(a), many cracks leave over the machined surface at random. On the other hand, the fracture is suppressed with the serrated edge despite with the same inclination as shown in Fig. 6(b). And at the inclination changes of 30 degrees as shown in Fig. 6 (c), the fracture is almost reduced but large cracks leave on the specific position (center of the surface). At the inclination of 15 degrees, the small cracks are leave over the surface like the case of the no serrated as shown in Fig. 6(d).

Figure 7 shows cross sections at the center of the machined surface respect to the cutter feed. These cross sections were cut by the FIB process and observed by the SEM at the inclination angle of 53 degrees from the FIB expose direction. In all pictures, the cutter feed respects to the right side. As shown in Fig. 7(a), in case of the no serrated edge, large cracks propagate at depth of 2-3 micrometer. On the other hand, in case of the serrated edge with tool inclination angle of 45 degrees, the crack propagation is not observed correctly as shown in Fig. 7(b). However, at the inclination angle of 30 degrees, the cracks leave under the surface at random as shown in Fig. 7(c) like the case of no serrated edge. At the inclination of 15 degrees, lamenter cracks observed, a depth of the propagation is reduced (less than 1 micrometer) compare with the case of the no serrated edge as shown in Fig. 7(d).

Discussion

In the milling tests, the brittle cracking was changed by change in the tool attitude. The one cause of this experimental result is considered that the effective cutting thickness on the engaging side of the serration ridge is changed by its position, the cutter locus and tool attitude, respectively. During the milling process, the milling cutter is moved on the helical locus. In this process, the cutter engagement is also changed, the "up cut" to the "down cut" manner. However, when the cutting edge has the periodic triangular serration like this experiment, the angle between the engaging side of the serration ridge and cutter feed direction is not only changed by the cutter locus, but also changed by the serration geometry. In the cutting process, the stress distribution on the cutting edge is changed by the cutter engagement because the chip deformation is affected by the relationship between the edge roundness and the cutting depth.
However, it is only the presume. Especially, effects of the vertex angle and a roundness of the cutting edge have not been cleared yet in this experiment. Thus, the author has started the following projects, 1. milling tests are performed by change in the various vertex angles of the edge serration with tool inclinations, 2. edge sharpening by ion milling apparatuses (with penning type and ECR type ion sources) [5].

Conclusion

In this research, the glass milling was performed by the edge serrated SCD tools to observe the effect of the edge serrations and tool inclination angles on the brittle cracking. As the result, characteristics of the crack propagation were changed by a tool inclination angle, especially, cracks were reduced at the angle of 45 degrees.

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