INVESTIGATION OF MIRROR-LIKE SURFACE FINISH IN OPTICAL GLASS (BK7) LAPPING

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ABSTRACT

Surface quality of optical glass is crucial for application in high precision products. This paper aim to investigate the surface roughness improvement and the limit surface roughness of the BK7 optical glass for mirror-like surface finish. Due to the brittleness of workpiece, lapping pressure need to be controlled diligently to prevent crack and brittle fracture from occurring. At first, the new lapping tool is installed on the collect chuck of the CNC milling machine and lapping is performed by the table movement in X and Y direction by NC control. Then, suitable lapping parameters are carefully selected for ductile mode machining in mirror-like finishing process. According to results, the mirror-like surface is achievd with proposed lapping method especially in low lapping pressure of 25MPa.

Keywords—lapping pressure, ductile mode machining ,surface roughness, optical glass

1. INTRODUCTION

In general, glass has high hardness but low fracture toughness. This results in poor machinability of glass. Under loading, for a brittle material like glass, crack initiation might occur from a flaw in the structure of glass that propagates under continuous loading. This may cause brittle fracture after reaching the critical value of the crack size. Since glass has low fracture toughness, the critical size of crack for brittle fracture to occur is very small because of its low fracture. In addition, if in the cutting zone high cutting stresses is developed, brittle fracture can happen easily.

On the other hand, loose abrasives are used in lapping for finishing the surface. Slurry containing abrasive grain is introduced between worpiece and lapping head. Then, the workpiece is moved under pressure which come from the pressing of lapping head onto the surface of workpiece. Since glass is a brittle material, for obtaining a very smooth surface finish, fracture must be avoided. Even microfracture could lead to the degradation of the performance of the optical glass especially one that has a very specific function such as lens used in camera and microscope. Therefore, in order to avoid brittle fracture from occurring during the machining process, the glass workpiece must be machined in ductile machining mode. In this mode, material removal happens mainly by plastic deformation and any cracks are prevented from extending into the machined surface.

This research aim to predit the lapping parameters for mirror-like surface finish on the optical glass (BK7) using proposed lapping method. At first, three lapping pressure is proposed and their effect on limit surface roughness is examined. Other suitable parameters are applied form previous research [1 to 6]. The relationship between surface roughness improvement and lapping time is investigated experimentally.

2. MACHINING OF BRITTLE SURFACES

Theoretically, to make cutting possible in this lapping process, abrasive grain must be harder than workpiece it need to cut. However, the lapping head hardness can be lower than that of the abrasive grain. However, due to the brittle nature of the glass, machining parameter must be carefully selected so that brittle fracture will not occur. In brittle machining mode, material removal occur by brittle fracture which involve radial cracking and lateral cracking. In addition, the larger and harder the abrasive grains, the rougher will be the finish [7]. On the other hand, the finer the abrasive grains, the smoother will be the finish [8].

There is a limit to the smoothness that can be obtained by lapping, even when very fine abrasive grains are used. This limit is called the limit surface roughness. Below the critical depth of cut, brittle to ductile transition occur and result in the ductile machining mode. In ductile machining mode of brittle material, material removal occur mainly by plastic deformation [9]. Most of the material removal occur due to shearing stress between the rolling abrasive and surface of the material. Thus, fracture and micro-fracture is avoided. Material breakdown behaviour due to localized loading for ductile and brittle materials [10] is as shown in Table 1. On the same surface of brittle material, ductile and brittle modes of deformation can happen and by changing the machining parameters, the transition between them can be controlled [11]. For ductile mode machining, the regime in which the deformation takes place in the form of simple plastic flow is favourable [12]. Besides that, process condition and crystallographic directions have effects on ductile mode machining of brittle material. In addition, for ductile mode grinding of hard and brittle materials, the critical depths of cut changed depending on the machining directions and coolant fluids used [11].

2.1. Brittle to ductile mode machining

The challenge faced in machining brittle material such as glass is how to ensure that the material removal occur by plastic deformation rather than characteristic brittle fracture [13]. Generally, all materials including glass are able to be machined in a ductile manner under a specific value of depth of cut. This cutting depth is called critical depth of cut. This is because below its critical depth of cut, transition occur from brittle to ductile machining region for glass material. Since, fracture need to be avoided, glass have to be machined in ductile machining mode. In this mode, the chip formation process is comparable to that of metal grinding. It mainly involves plowing, scratching and chip formation. Hence, to avoid micro-fracture and subsurface damage, ductile machining mode is required for the lapping process and material removal occur mainly by plastic deformation. Thus, in order to machine brittle material in ductile mode machining, suitable parameters for machining and appropriate cutting tool need to be selected.

2.2. Critical depth of cut

Critical depth of cut is defined by equation shown below. Based on the equation, there are several factors that affect the value of the critical depth of cut which are fracture toughness, Kc, material hardness, H, and mcodulus of elasticity, E. It is also called as critical penetration depth for initiation of fracture. Below this critical value, brittle material will undergo transition from brittle to ductile machining mode. This transition can be described in terms of energy balance between surface and strain energy. Since fracture is to be avoided when machining brittle material such as glass, the depth of cut must be ensured to be below its critical depth of cut.

$$d_c = b\left(\frac{K_c}{H}\right)^2\left(\frac{E}{H}\right) \quad (1)$$

2.3. Two body and three body abrasive wear

Wear can be defined as progressive loss of material from a solid surface. This is due to relative motion between contacting substances and the surface in contact. There are five main types of wear which are fatigue wear, fretting, erosion, adhesive and abrasive, which are commonly observed in practical situations [14]. Among the five, abrasive wear is the most important due to it contribution which accounted about 63% of the total cost of wear [15]. It happens when hard particles or hard protuberances are forced onto a solid surface and and move along it .Generally, abrasive wear is divided into two groups which are two-body and three-body abrasive wear [16].In lapping process which use free abrasive there are two-body and three-body mechanisms as shown below in figure 3.

This mechanism describes whether the abrasive particles are free to slide or roll (three-body) or bound (two-body).

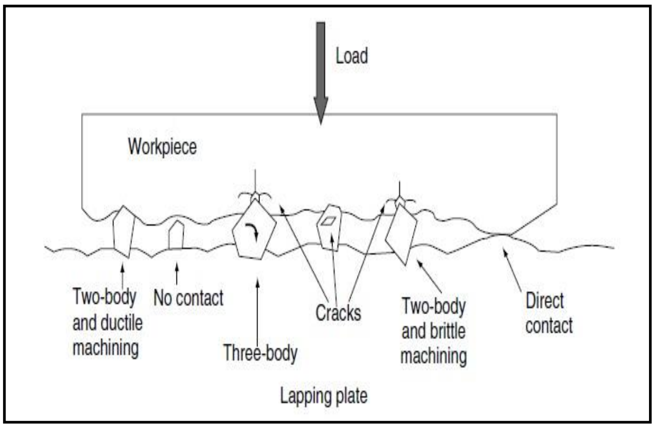

Figure 1. Three-body and two-body abrasive wear model

Wear in two-body abrasion is caused by abrasive grains which are embedded in the second body. On the other hand, three-body abrasion refers to wear caused by free and loose abrasive particles existing in between a lapping plate solid and workpiece. Hence, more stock removal would be seen in two-body mechanism than that of three-body.

3. LAPPING SYSTEM USING CNC MACHINE

The lapping tool used was installed on 25mm chuck of the CNC milling machine. Workpiece, BK7 glass cylinder, was fixed on the table of the milling machine by using lathe machine chuck. This is done to ensure that the glass cylinder can be hold firmly in secure position during the lapping process. Basically, the lapping system consist of lapping tool and nozzle for supplying the lapping slurry. After each cycle finished, the lapping head need to be dressed with lapping slurry and cleaned again alternately.

The lapping tool was hold stationary at the spindle of milling machine without any rotation. The table that was holding the workpiece only moved in translational motion in X and Y axes direction of the milling machine and cover a lapping area of 100mm^2. Lapping speed was produced by the table movement in X and Y axes direction. Material removal occurred due to rubbing action between the pressed lapping tool head and area of contact on the workpiece which resulted in the cutting of material. The lapping system used is as shown in figure 2.

Milling machine used has the positioning of 5 micrometres which is very good in terms of the repeatability of the lapping process inside the lapped area. Moreover, this machine work table has the stability and capability of conducting rapid movement in X and Y axes direction. This feature is really important for the experiment to generate the lapping speed.

While spindle rotation was not needed during the experiment, movement of the stationary spindle in Z axis.

was indeed important to move the lapping tool downward. This movement will cause the spring on the lapping tool to compress and thus created the pressure for the lapping process

Table 1. Material properties of workpiece

Mechanical properties BK7		
E	Modulus of elasticity	82GPa
γ	Poisson ratio	0.206
HV	Vickers hardness	535 (5247N/mm^2)

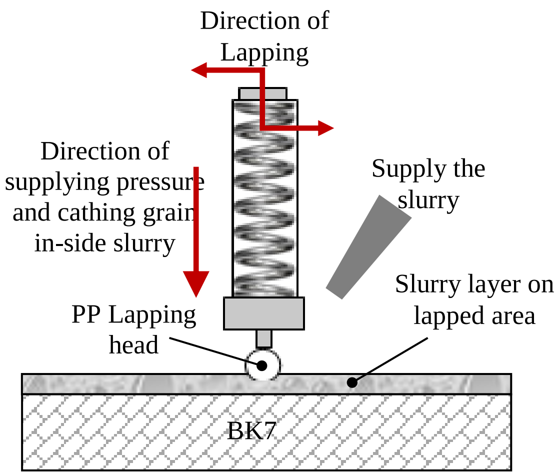

Figure 2 Lapping tool setup on CNC milling machine

Table 2. CNC milling machine specification

Machine brand	BRIDGEPORT
Machine model	VMC 2216xv
Machine dimension (mm)	2460 x 2500 x 2600
Machine weight (kg)	2993
Positioning accuracy (µm)	+/- 5.0
Table Load (kg)	341
Machine travels X,Y,Z (mm)	560(X) x 406(Y) x 508(Z)
Main motor (hp)	12

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4. EXPERIMENTAL DETAIL

In this experiment different diamonds grain size which are #320, #1200 and #2500 are used. After reaching the limit surface roughness, the grains size is changed. Polypropylene was selected as lapping head material for

Table 3. Experiment parameters for lapping process

Lapping slurry	0.5% (PEO) and 99.5% distilled water (wt%)
Grain size	#320, #1200, #2500
Workpiece material	BK7 Glass
Lapping head material	Polypropylene (PP)
Lapping speed (mm/min)	3500
Lapping pressure (MPa)	25, 30, 35
Grain catching pressure (MPa)	35
Lapping pitch (mm)	0.1
Lapping area (mm^2)	100

long time and high precision lapping. When the static spindle of CNC milling machine move downward, lapping force was generated from the compression of the spring onto the contact area between lapping head and workpiece. By using this arrangement, lapping force could be controlled easily. Since the contact made between the 10mm spherical lapping tool head and the flat surface lapped area are point contact, it was analysed based on Hertzian contact mechanics. Besides that, Hooke's Law equation is also used for determining the required spring compression value. The soft 87 mm long coil spring with a spring constant of 1.5 N/mm was used for generating lapping pressure.

Since, it is easier to control the minimum spring compression at 1 mm, 25 MPa was selected as the minimum lapping pressure used for the lapping process. Three different lapping pressure were selected to observe how it affect the surface of workpiece after lapping. Area selected for lapping measures 100mm^2. It is in this area that the diamond grain was catched by the lapping head and rubbed against the surface of glass. During lapping process, removal of material was done by the active grain which located in between the lapping head and workpiece.

Lapping speed is a result of relative motion between the lapping head and workpiece. It is also the feed rate used for machining and depends on the tool and workpiece motion. Therefore, for this experiment, lapping speed is generated from the table movement. The table speed was set to 3500 mm/min in the CAD/CAM program both for X direction and Y direction lapping. Each program took 45 seconds to complete. Slurry was dressed or pour on the BK7 glass workpiece before a complete cycle of lapping program was run. After the cycles completed, the remaining slurry were cleaned completely from the lapped area.

In order to cover the lapping area, the table was moved by a pitch value of 0.1mm in a direction perpendicular to the rubbing direction. This pitch value was used because the lapping tool has ball shape lapping head. lapping head is 10mm in diameter and form a point contact when pressed against the lapped surface. Due to its spherical shape, it can reach uneven surface better and lapping can be done more

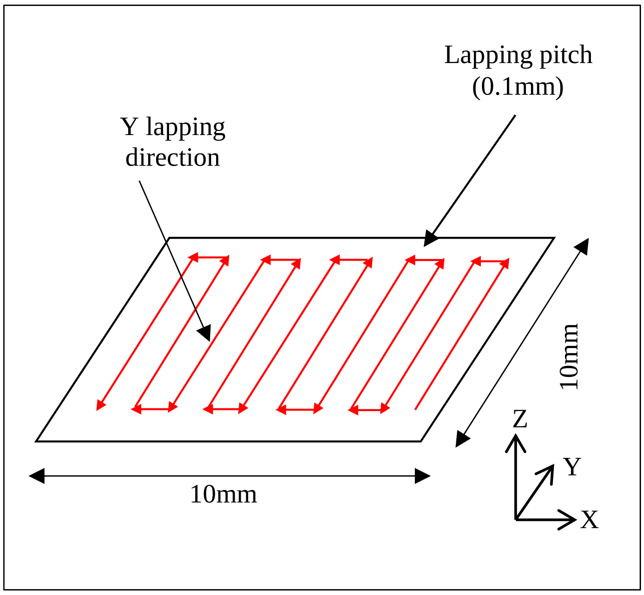

Figure 3. Lapping tool pass on work surface

effectively. Figure 3 below shows the lapping path travelled by the tool during lapping process in y direction. Another lapping path is in x direction which is perpendicular to the path depicted in the above figure. This path also has the same pitch and travel through the same distance which is 10mm. After each cycle finished, the lapped area was measured to obtain the value of the roughness of the surface. Measurement was done using Mitutoyo Surface Roughness Tester. This roughness tester measure the surface by using probe. Reading was taken at fives different places in X and Y lapping direction. In addition, the lapped area was observed under Keyence 3D microscope to study how the lapping pressure affect the BK7 glass surface and the surface nature after lapping.

5. RESULTS AND DISCUSSIONS

5.1. Rate of material removal

Rate of material removal depends on the diamond grain size. Theoretically, when lapping is done with bigger diamond grains, the rate of material removal should be high. As the surface roughness of the lapped area improves, a smaller size of diamond grain need to be used to machine the surface, the rate of material removal gradually decrease. It is assumed that for the same grain size, the rate of material removal is the same until the lapped area reaches its limit surface roughness.The removal rate is also affected by the number of active grain, which is the grain that actually involve in cutting whether through rolling or sliding mode. This is because there might be grains which are smaller in size than the average grain size that are moving freely in between the lapping head and lapping areas and thus do not involve in cutting.At the beginning of lapping process, bigger grain size, #320, was purposedly

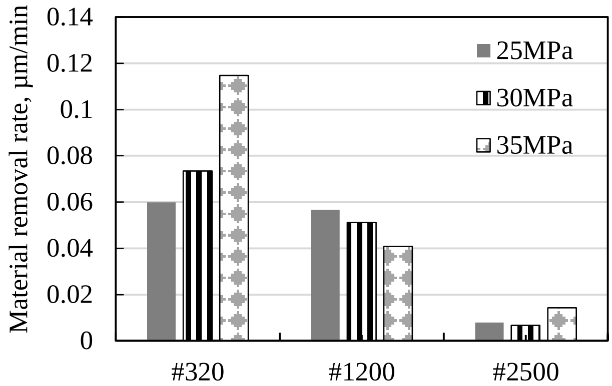

Figure 4. Material removal rate of different grain size at different lapping pressure

used for removing the cutting lines and groove that had formed previously during the cutting of glass cylinder. After that, a smaller grain size, #1200 was used to get a smoother surface and repaired the lines left behind by #320 diamond grain. Then, lapping process was continued using #2500 in order to achieve smoother surface and thus lower the surface roughness. In this experiment, the rate of material removal is calculated for every diamond grain size used. It is obtained by dividing the difference between surface roughness value at the beginning of lapping until it reaches the limit surface roughness value with time taken for lapping using that grain size. The material removal rates are as shown in figure 4. According to the results, material removal rate is higher for higher lapping pressure and bigger grain sizes.

5.2. Limit surface roughness

If a surface reaches its limit surface roughness, increasing the lapping pressure and the friction distance will not cause the processing surface roughness to improve. Generally, grain properties and lapping pressure have direct effect on the surface roughness value.

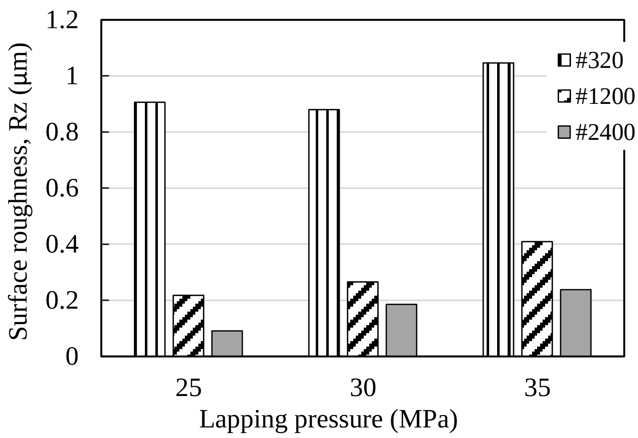

Figure 5. Limit surface roughness vs lapping pressure

Limit surface roughness is observed at every diamond grain size. The surface roughness value is accounted as limit surface roughness. when it does not change even after lapping process is continued. In this experiment, three limit surface roughness are identified for #320, #1200 and #2500. Figure 5 shows the limit surface roughness value for all grainsa sizes and different lapping pressure.Limit surface roughness for #1200 and #2500 are lower especially in smaller grain size and able to reach the mirror-like surface finish at 25MPa lapping pressure. Moreover, the limit surface roughness value under 30 and 35 MPa can not achieve the mirror-like surface finish. It can be seen that different lapping pressure results in different limit surface roughness for each grain size under same experiment conditions. This result might have been affected by the vibration of lapping tool during process as the lapping pressure is increased, the surface roughness value increased.

5.3. Surface roughness improvement with lapping time

Lapping condition for mirror-like surface finish is listed in Table 4.As shown in the figure 6,7,8, for each grain size, the surface roughness continue to decrease as the lapping time increase. Roughness improved until the limit surface roughness for the specific diamond grain size is reached.

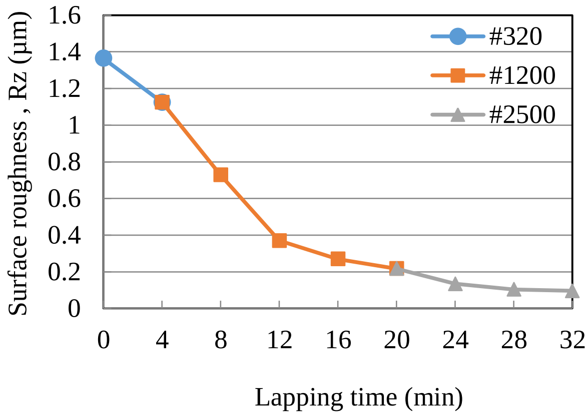

Figure 6. Surface roughness improvement with lapping time for 25MPa lapping pressure

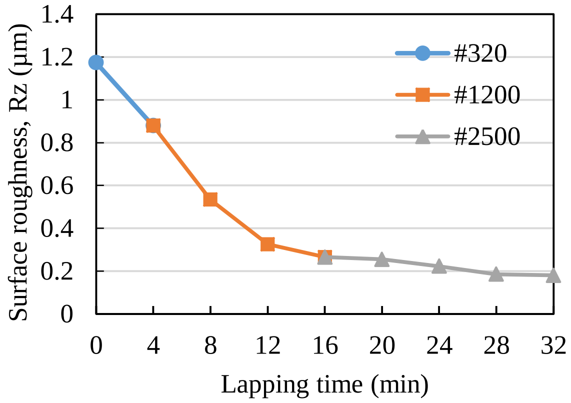

Figure 7. Surface roughness improvement with lapping time for 30MPa lapping pressure

After reach the limit surface roughness, even lapping process is continued using diamond grain of the same size, the surface roughness value will not decrease any more. One can get an accurate estimation of the thickness of the damage layer that need to be removed by subsequent lapping operations from the measurement of surface roughness.

In addition, the results reveal the ability of achieving the intended surface roughness for that particular lapping pressure used. Only, 25MPa lapping pressure can achieve mirror-like surface finish with developed lapping system. Higher lapping pressure may not be a good option at the mean time as it has some possibility of damaging the glass surface. Compare with the other work materials study for mirror-like surface finish [1 to 6] , to achieve the roughness value (Rz) lower than 0.1 μm is more challenging in glass lapping process. It may be many other influencing factors that are needed to be considered and examined.

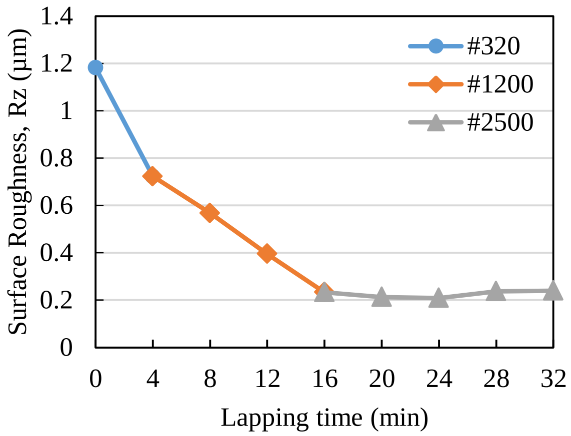

Figure 8. Surface roughness improvement with lapping time for 35MPa lapping pressure

Table 4 Lapping condition for mirror-like surface finish

Lapping pressure	25MPa		
Lapping speed	See table 3.		
Lapping pitch (mm)	0.1		
Lapping slurry (wt%)	Water 99.5% + PEO 0.5%		
Diamond grain (wt%)	2%		
Grain size	#320	#1200	#2500
Lapping time (min)	4	16	12
Total time (min)	32		

6. CONCLUSIONS

In conclusion, mirror-like surface finish is possible to be obtained using the proposed lapping process for optical glass (BK7). Since this experiment was conducted to pre determine the lapping parameter for mirror-like finish. Optimization of the lapping process by the suitable combination of all lapping parameters are needed to be claried in future experiments.

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