Experimental Investigation of the Surface Roughness in Grinding of BK7 Optical Glass in Brittle Mode

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Abstract
Surface roughness is a significant parameter which determines the efficiency of optical components. Surface damages induced by grinding strongly influence the mechanical strength and optical quality of optical glasses. It is meaningful to rapid evaluate the surface roughness through the measurement of different grinding parameters. In this study, a cup diamond wheel (D64) is used in grinding process of the specimens made of BK7optical glass to investigate the influences of grinding parameters on the surface roughness. The grinding parameters used in this study are depth of cut, cutting speed, tables speed and feed rate; and effects of these parameters are studied. The dependence of surface roughness on grinding parameters was systematically analyzed. The experimental results indicate that feed rate, depth of cut and cutting speed have the most significant effect on surface roughness, respectively. By increasing feed rate and depth of cut, the surface roughness increases and increasing cutting speed results in a decrease in surface roughness.

Keywords
Grinding, Cup Diamond Wheel, Optical Glass BK7, Surface Roughness

1. Introduction

Optical lens in the optic industries are very important components that are widely used to the applications of digital cameras, scanner, projector, etc [1]. As a type of high-quality optical materials, optical glass BK7 enjoys high linear optical transmission, good wear resistance and colorless appearance, and is often used as a standard of comparison for other glass materials [2]. Compared with the lapping process, the grinding process has been considered as a promising "rough" machining technology for BK7 manufacturing because of its high efficiency and low cost. However, the grinding process of BK7 with aggressive machining parameters (e.g., high feed rate, big depth of cut) is easily led to serious surface roughness (SR) due to the brittle and hard nature of BK7. This SR influences the service life, optical performances and mechanical properties of optical components [3, 4].

For products, surface roughness is an important index of product quality and technical requirement [5]. Consequently, the investigation on prediction of surface roughness in brittle modes grinding is significant and necessary in order to control the desired surface roughness of product in a fast and effective manner. Many researchers are interested in the prediction of surface roughness and research in this field has yielded some useful findings along with successful experience through the use of approaches based on machining theory, experimental investigation and artificial intelligence [6-8].

In order to improve the performance for the grinding of the hard brittle materials (BK7), some studies have been conducted. The contributions in this field have been systematically reviewed by Malkin and Hwang [3]. It was found that indentation and scratch processes in brittle mode usually involve two principal crack systems: (I) lateral cracking responsible for material removal and surface formation, (II) radial/median cracking for strength degradation. Lateral crack leads to surface roughness (SR) and median crack leads to subsurface crack (SSD) on the surface of optical material. Based on malkin's studies, Lateral cracks are generated under the plastic deformation area and parallel to ground surface. (See Figure 1) In brittle mode grinding, materials can be removed without extensive fracture damage oreven with ductile flow, so a high surface quality, ultra-precision accuracy and low subsurface damage component will be obtained [3, 9].

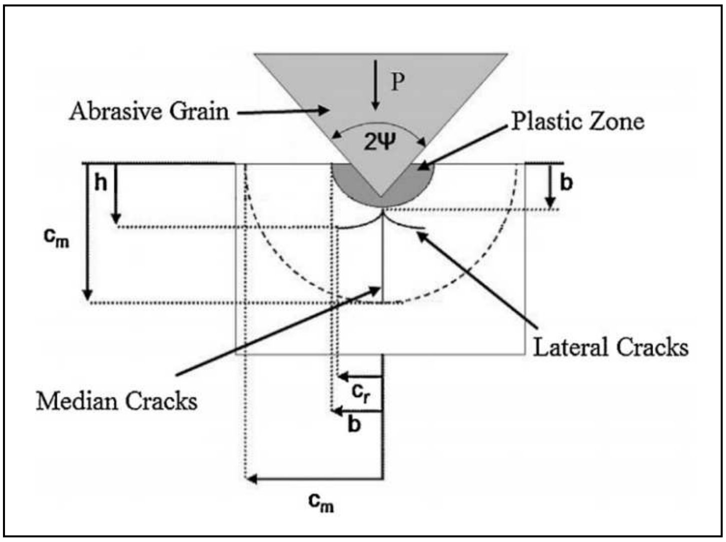

Figure1. Lateral and median crack systems in grinding process [3]

Chen et al. [5] presented an improved method to evaluate the actual relative tool work vibration. By using this method, the vibration information obtained is more credible, as it contains the components caused by machine tool error, grinding force, material property and changing of grinding parameters. Moreover, the swelling effect is analyzed using a new evaluating method and taken into account for predicting surface roughness. Shiou et al. presented surface roughness improvement of Zerodur optical glass using an innovative rotary abrasive fluid multi jet polishing process. In addition, the influence of significant factors on surface roughness improvement has been discussed by them. For that purpose, a tool for executing ultra-precision polishing was designed and manufactured. Taguchi’s experimental approach, an L18 orthogonal array was employed to obtain the optimal process parameters. The experimental results show that a finished surface achieved can satisfy the requirements for optical-quality surface (Ra < 12 nm) [10].
Even though several studies on the performance of the grinding hard and brittle materials had been investigated. However, studies about relating the cup grinding parameters on surface roughness of BK7 glass were not reported. In this paper, the effect of cup grinding parameters on surface roughness of BK7 optical glass in brittle mode is being discussed.

2. Material and methods

2.1 Material

In this research, the grinding process is conducted on BK7 optical glass, a glossy, engineered optical glass material based on a Silicon oxide-Boron oxide formulation with the crystalline phase consisting of meta stable solid solutions of high quartz structure. BK7 is 70 to 78% by weight crystalline phase with crystals generally 50 to 55 nm in size. The material composition and mechanical properties are given in Tables 1 and 2, respectively [11].

Table1. Chemical composition of BK7 [11]

BK7 Chemical composition	SiO_2	B_2O_3	BaO	Na_2O	K_2O	Others
%Wt	68	15	6	6	4.9	0.1

Table2. Mechanical properties of BK7 [11]

Mechanical properties	**Value**
Modulus of elasticity (E, Gpa)	85
Poisson's ratio (υ)	0.203
Density (ρ, g/cm^3)	2.51
Hardness, knoop (H, GPa)	520
Strength (MPa)	85

Because of its extraordinary properties, BK7 has priorities in hi-tech applications described in a number of researches and manufacturing processes, such as: stages and mirrors for IC and LCD lithography equipment, mirror substrates for segmented and large monolithic astronomical telescopes, rocket launching pads, high accelerating objects, high precision mechanical parts and reference standards for precision measurement technology [11].

Samples' dimensions are 25 mm in diameter and 10 mm in thickness. The grinding wheel was metal bond cup diamond wheel manufactured by Winter Diamond Tools. Diameter of 50 mm and grid size of D64 and grinding diamond wheel concentration code was C50. Surface roughness was measured by HOMMELETAMIC T8000 RC (JENOPTIC AG Co.) machine over a roughness evaluation length of 12.5 mm and roughness sampling length of 2.5 mm, according to IS 15263:2003.

2.2 Methods

The experimental design is one of the important approaches for exploring multifactor opportunity spaces where the effect of individuals and the combined interaction between the factors could affect the target. Moreover, improve quality without controlling or eliminating causes of variation are studied altogether. The DOE provides full insight in turning all standard designs into forms which are robust. Taguchi techniques for quality engineering are one of the contemporary methods used in many specific fields to enhance the quality of products and processes.

Table3. Grinding parameters and their levels

Parameters	Level 1	Level 2	Level 3	Level 4
Cutting Speed (m/s)	15	20	25	30
Feed rate (mm/rev)	0.005	0.01	0.015	0.02
Cutting depth(μm)	20	40	80	100
Tables Speed (rev/min)	100	200	300	500

The Taguchi method mainly uses a possible combination of experimental trials making use of a Latin square. The combination of Latin squares shows the property of orthogonal array representation. Based on the number of the control factors, the Taguchi’s L18 mixed type orthogonal array was selected. As Taguchi has pointed out, the interaction information can be obtained without sacrificing any other column, and the interactions between four-level columns are distributed more or less evenly to all other four-level columns. As a result, enough space for investigation of main effects can be achieved. Consequently, it is suitable to use the L16 for this study. Optimal parameters and their levels have been determined according to the experimental results (See Tables 3, 4). The ranges and levels of control factors have been estimated based on preliminary trials executed for each of them. Varying one control factor randomly at a time and keeping the others unchanged has been applied to estimate the range of a level so that promising output can be achieved. Hence, suitable ranges of parameters were selected and categorized for further optimization process.

3. Experimental procedure

To measure the SR after grinding test, the samples must be properly prepared before the grinding process. Sample preparation consists of five general steps: cutting the samples, milling the samples, lapping the samples, washing the samples in ultrasonic bath and adhesion. At first, the samples are cut by circular diamond saw. Then the surfaces of samples are being milled by D91 diamond cup grinding wheel. In this case all the samples have equal heights. Then, the test surface is refined by lapping. The lapped surface should also remain flat and perpendicular to the machined surface. Then the samples are washed in ultrasonic bath for 15 minutes. And finally, the samples and holder are bonded face-to-face with a suitable adhesive. In this step, a clamping pressure was used to push the two parts tightly together. After achieving a proper bonding between the two parts, the samples are ground according to Table 4. After the grinding process, the specimens were separated by melting the glue and cleaned with acetone in an ultrasonic bath.

Figure2. Specimens are glued and prepared for milling with D91 diamond cup grinding tool

Finally, the surface roughness is measured by HOMMELETAMIC T8000 RC. Each specimen is tested for three times due to repeatability in three different paths. The average of surface roughness for each experiment is shown on Table 4.

Figure3. Grinding test in brittle mode with D64 cup grinding tool

4. Result and Discussion

In brittle mode, the ground surface is relatively rough and no ductile streaks are observed. This means that brittle fracture and chipping are induced mainly by lateral cracking dominated the grinding process and extended below the ground surface plane which is illustrated in Figure 1.

Table4. Average of surface roughness and grinding parameters for Taguchi designed experiment

No	Cutting Speed (m/s)	Feedrate (mm/rev)	Cutting depth(micron)	Tables Speed (rev/min)	Ra (micron)	Rz (micron)
1	10	0.005	100	100	1.13	8.93
2	10	0.01	80	200	1.183	9.18
3	10	0.015	40	300	1.243	10.34
4	10	0.02	20	500	1.85	16.25
5	15	0.005	80	300	1.09	9.43
6	15	0.01	100	500	1.426	8.84
7	15	0.015	20	100	0.97	8.91
8	15	0.02	40	200	1.106	9.56
9	25	0.005	40	500	0.973	9.47
10	25	0.01	20	300	1.24	12.29
11	25	0.015	100	200	0.996	8.8
12	25	0.02	80	100	0.92	7.34
13	30	0.005	20	200	0.65	5.105
14	30	0.01	40	100	0.68	5.805
15	30	0.015	80	500	0.983	7.603
16	30	0.02	100	300	0.976	7.75

4.1 Effect of cutting speed on surface roughness

As shown in Figure 4, the increase of cutting speed causes a decrease on surface roughness. Cutting speed means the speed of disporting the chip from the cup grinding tool edges. Based on the graphs, ideal surface roughness is reached on higher cutting speeds.

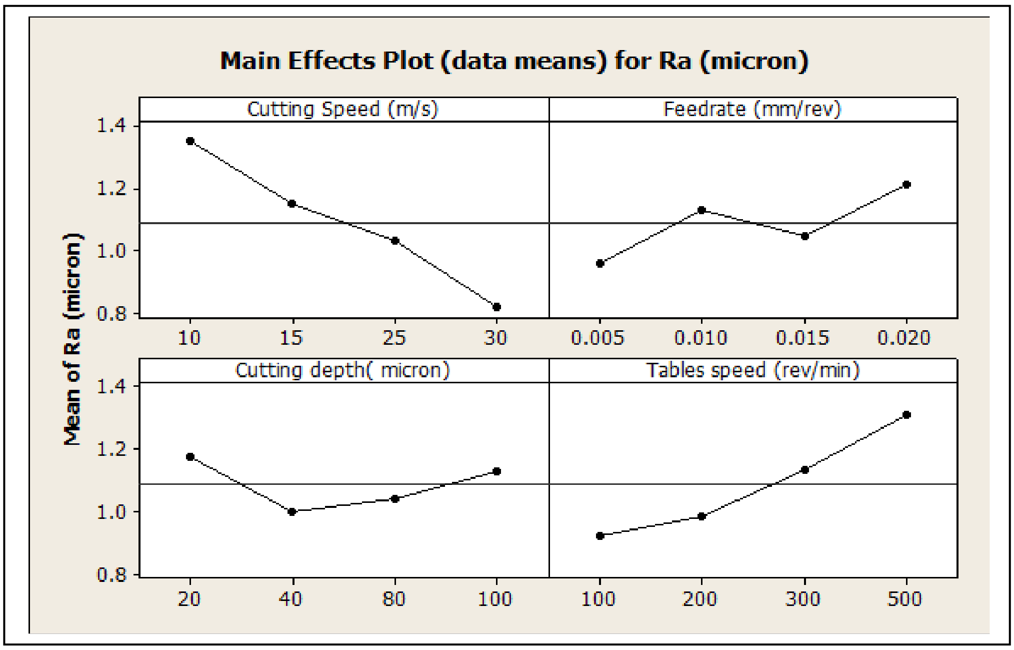

Figure4. Variation of R_a with respect to cutting speed, cutting depth, tables speed and feed rate in experimental results

The surface morphology profile of two specimens in two different cutting speed is shown in Figure 5. While all the other grinding parameters are the same. Based on the profile, the specimen (a) has higher peak to value number while specimen (b) has a better surface roughness with lower peak to valley value.

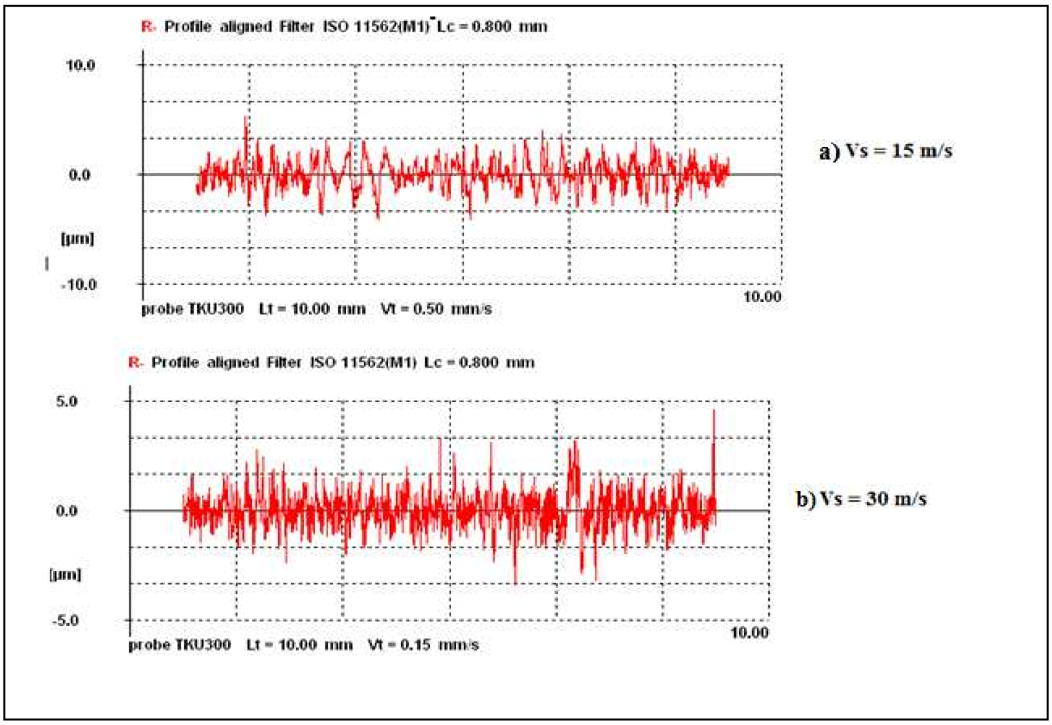

Figure5. Surface morphology profile when $f=0.005$, $a_p=80\mu m$, $V_w=200$ *rev/min* (a) V_s =15 m/s, (b) V_s =30 m/s

4.2 Effect of feedrate on surface roughness

Based on the experimental investigation done by Yao [12] and Zhao [13], feedrate is the most effective grinding parameter on surface roughness and subsurface crack. Feedrate is a harmful parameter on surface roughness in grinding optical glasses. This means that the ideal surface roughness reaches at lower feedrates. The experimental achieved data proves those investigations. The dependence of surface roughness on grinding parameter is shown in Figure 4.

4.3 Effect of cutting depth on surface roughness

Based on the experimental investigation done by Chen et al [14], cutting depth has weak effect on surface roughness, but because of its effect on contact time between abrasive grain and work piece, when the cutting depth increases subsurface cracks increase too. Because of that, the graphs of dependence of surface roughness on cutting depth are influenced by the other grinding parameters. (See Figure 4)

In high cutting depths, grinding fluent chips increase and also the porosity on the surface of cup grinding wheel decreases. So the surface roughness increases due to grinding fluent chips and porosity. The cutting depth has an effective influence on the number of active grains on the surface of grinding wheel, so the effect of cutting depth on subsurface damage (SSD) is more impressive than surface roughness.

4.4 Effect of tables speed on surface roughness

Based on the experimental investigation done by Chen et al. [14], by the increase of tables speed (work piece speed), the maximum unformed chip thickness increases too and furthermore the surface roughness increases. However the increase of tables speed causes humdrum surface with lower peak to valley value. (See Figures 4, 6)

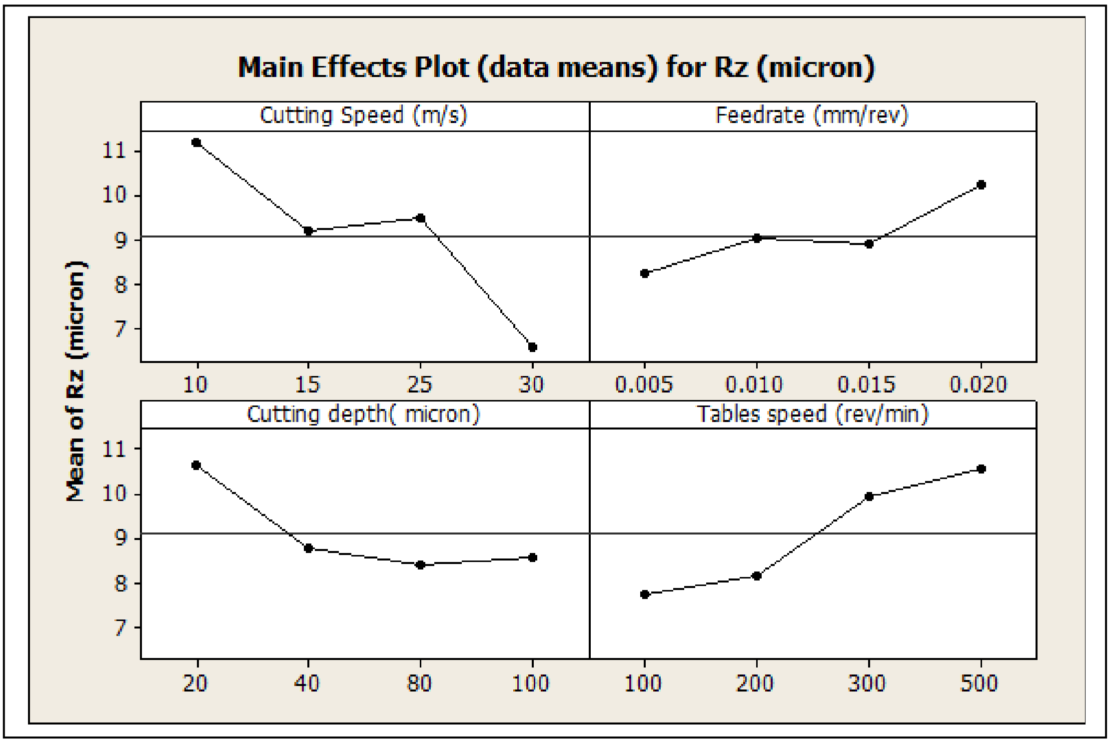

Figure6. Variation of RZ with respect to cutting speed, cutting depth, tables speed and feed rate in experimental results

5. Conclusion

The main objective of the present study was the experimental investigation of the grinding mechanism and the effect of grinding parameters on surface roughness in the grinding process of BK7 optical glass using cup diamond wheel. In this regard, based on the studies and conducted experiments, the following conclusion can be made.

As a result, surface roughness decreases with the increase of wheel speed and the decrease of feed rate. It is shown that the effect of grinding depth on surface roughness as well as subsurface crack depth is weaker than those of wheel speed and feed rate. This is because that although the maximum penetration depth and surface crack depth increases with grinding depth, larger value of grinding depth causes greater distance between the grain tip to the ground surface plane. One of the important parameters in the surface roughness is maximum unformed chip thickness which is in direct relation with surface roughness. An increase in maximum unformed chip thickness leads to an increase in surface roughness.

6. Reference

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