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Procedia CIRP 45 (2016) 143 – 146

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3rd CIRP Conference on Surface Integrity (CIRP CSI)

Surface roughness in ultra-high precision grinding of BK7

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Abstract

Borosilicate (BK7) is widely applied in the automotive and optics industries for the production of a number of critical optical components. In normal manufacturing practice, the surfaces of BK7 components undergoes a series of manufacturing operations, such as grinding, polishing and lapping, in order to obtain nanometric finish with high optical quality. In this study, we used an ultra-high precision grinding spindle mounted on ultra-high precision machine tool to machine flat surfaces from BK7. The process was observed by monitoring its acoustic signals which were acquired at a high sampling rate. Three grinding parameters, depth of cut, feed rate and wheel speed, were varied in this study. The results obtained from this experimental work indicate the strong independence of surface roughness of the ground samples on feed rate. It was found that the effect varying the feed rate was more noticeable than that of depth of cut and wheel speed. Also, it was observed that the amplitude of the acoustic emission events changed significantly with the variation in the grinding parameters. The result indicates that acoustic emission sensing technique has the potential to be adopted as an effective monitoring method for the ultra-high precision grinding of BK7 glass.

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)

Keywords: Ultra-high precision grinding, acoustic emission, surface roughness, BK7

1. Introduction

Surface integrity is one of the most important parameters of any machined surface and it is a deciding factor when assessing the success of optical lens grinding especially when high surface integrity requirements need to be met for some critical applications [1]. Out of the existing surface integrity parameters, the average surface roughness value is the most widely measured parameter in precision optics production [2]. The surface roughness value of a machined BK7 glass depends on its materials properties, machining system and combination of grinding parameters. It has been observed that brittle materials with higher fracture toughness still could deliver relatively good machinability if machining parameters were carefully selected [3]. Since the goal in precision grinding of brittle materials is to realize the best surface roughness value within the minimum machining time while maintaining good form accuracy and minimum subsurface damage, it is necessary to carefully select determining factors like machining systems and parameters in order to achieve the best surface finishes in precision optics.

Several techniques have been applied to monitor the performance of grinding of precision optics. This can be achieved for example with use of acoustic emission (AE), grinding force, and vibration signals [4]. Furthermore, surface roughness prediction techniques in machining include numerical scheme and feedback control [5], response surface modeling technique, genetic algorithm and machine learning techniques [6].

Currently, there is little research reports on the performance evaluation ultra-high precision grinding of BK7 glass in terms of surface roughness, and its independence on the grinding parameters. The study has used an efficient design of experiment based on response surface modeling technique to predict and optimize the surface roughness values in the ultra-high precision grinding of BK7 glass. Also, the study employed acoustic emission monitoring technique to monitor the grinding process. In conclusion, this study will serve as a guide and provide database for future research in ultra-high precision grinding of BK7 glass.

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doi:10.1016/j.procir.2016.03.023

2. Ultra-high precision grinding

Good surface finishes cannot be achieved without highly reliable ultra-high precision machining systems that can repeatedly generate precise small scale dimensions. The development in current ultra-high precision machining systems has improved on the areas of thermal stability, stiffness and dampness of motions, and ultra-high precision grinding spindles. Similar ultra-precision machining systems used for diamond turning are applicable in precision grinding. With the evolution of conventional grinding techniques to precision and ultra-precision grinding (UHPG), UHPG process can now compete with ultrahigh precision diamond turning [1].

AE is a physical phenomenon which consists of high frequency elastic waves originating from structural lattice dislocation. AE sensing technique has been employed for grinding condition monitoring processes including: wheel-workpiece contact detection, spark-in, spark out [7], grinding burn detection [8], grinding wheel wear monitoring [9], surface and sub-surface properties. Its reliability as a sensing technique stems from its superior signal/noise ratio and high sensitivity at the ultra-precision scale [10]. Another advantage of AE is its ability to propagate frequencies in the megahertz range above natural structural vibrations frequencies therefore reducing the influence of the usually noisy machining environment.

A number of researchers have used AE in monitoring precision grinding operation when machining glass. Zhao et al. [3] applied AE sensing technique to monitor surface integrity of quartz and fused silica and observed that smaller amplitudes and RMS of the raw AE signals corresponded to better surface integrity. Zhang et al. [4] concluded that extracted features from AE signals have significant correlation with ground surface roughness of optical glasses. Also, Stephenson et al. [11] investigated the performance of resin and cast iron bond diamond wheels on the surface of optical BK7 glass using AE.

Grinding is a complex machining process with a lot of independent parameters fused into the wheel-workpiece interaction. Furthermore, one of the major desirability in the grinding of precision optics is to ensure a high rate of reproducibility therefore it is necessary to optimize the response surface which is determined by the various independent process/machining parameters. Response surface methodology (RSM) has been utilized as a technique to achieve efficient modeling of precision grinding surfaces [2]. RSM is a collection of statistical and mathematical models which are used for analyzing and modeling engineering problems to quantify the relationship between the response surface and the control parameters.

RSM technique in grinding involves: adequate design of experiment for reliable measurement of the response variable, development of second order response surface mathematical model with the best fit, optimization of grinding parameters that may achieve minimum response surface value, analyzing direct and interactive effects between the machining parameters through 2D and 3D plots [2].

3. Experimental setup

3.1. Design of experiment

Box-Behnken design found broad application in RSM classes because of its simplicity as it requires only three levels and is based on a combination of factorial with incomplete block design for each independent variable(2). Furthermore, BBD helps to achieve a design of experiment with only a fraction of the experiment required for the three-level factorial as a result reduces experimental errors and facilitate easy analysis and realization of result thereby saving time and cost.

The parameters of feed speed and cutting depth have been investigated in relation to the surface roughness using 3x3 Box-Behnken design with three center points to yield a total of 15 experimental runs. Surface toughness has been found to be dependent on wheel speed, cutting depth and feed rate. Furthermore, it is suggested that high wheel rotation, low feed rate and low cutting depths are necessary conditions for precision grinding of brittle materials [2] . Hence the low, medium and high points of the respective machining parameters were selected as shown in Table 1.

Table 1. Design of experiment.

Level of grinding parameter	-1	0	1
Grinding depth (μm)	2	5	8
Feed rate (mm/min)	1	3	5
Wheel speed (rpm)	15000	30000	45000

3.2. Machining setup

A four-axis Precitech Nanoform 250 ultra-high precision lathe machine (Fig. 1) coupled with a 50,000 rpm ultra-high precision grinding spindle was employed in this study. A fine grit resin bond diamond wheel was used to grind the BK7 surface. This grinding spindle was mounted on the Nanoform lathe in such a way that a single point inclined axis (SPIA) grinding configuration was realized (Fig. 2). To achieve the SPIA configuration, the grinding spindle was rotated 359° on the B-axis to enable only the tip of the wheel to make contact with the workpiece surface. The SPIA is advantageous as it enables easy chip removal therefore preventing wheel loading occurrence while working with small grits. The SPIA set up is such that the feed travels in a direction perpendicular to the rotation direction of the wheel speed.

The 1200-grit resin bond diamond grinding wheel was manufactured by Braemer USA, with a diameter of 0.625 inches. The wheel was dressed on the machine at it peripheral and cylindrical surfaces in the perpendicular directions. Intermediate grinding speed of 1500 surface meter per minute was selected as recommended by manufacturer. The surface speed was converted to rpm as follows:

Cutting parameters of 30000-rpm cutting speed, 3-mm/min feed and 5-μm depth were selected as the centre points for the parameters in the design. With the help of Precitech's DIFFSYS software interphase, the work spindle was balanced at 1000 rpm clockwise direction thereby achieving a spindle run out error of only 0.003μm P-V. This balancing was done to ensure the spindle chuck was well positioned hence preventing unwanted oscillation patterns on the surface of the workpiece which could deteriorate the surface roughness of the workpiece and to ensure even contact at all points the through workpiece surface and wheel tip. Wheel dressing was done using a wheel dresser.

Fig. 1. Precitech Nanoform 250 Ultra-high precision lathe

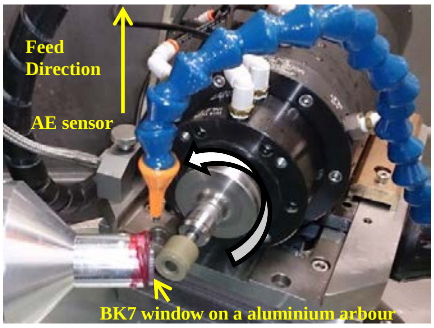

Fig. 2. SPIA grinding setup with AE sensor

The BK7 glass is characterized by its low acoustic impedance, high fracture toughness, Knoop hardness of 610 and elastic modulus of 82GPa. The workpiece was attached to the work spindle mount using a fast cooling wax. A water soluble grinding fluid with coolant ratio of 50:1 was used to reduce heating effects and prevent thermal damage to the workpiece surface during grinding.

Kistler piezoelectric AE sensor was mounted close to the workpiece (Fig. 2) and the sensor output was channeled through a coupler for pre-processing using band pass filter (50 KHz-1000 KHz) and to NI PIC 6110 card through NI LabView interphase. The AE signals were acquired at rate of two million samples per second during each grinding pass.

An initial pass was done to clean the surface of the workpiece and ensure an evenly flat surface while the work spindle was rotated at 100 rpm at a feed rate of 6mm/min for the initial pass. Subsequently the work spindle speed was reduced to 50 rpm such that the grinding was done on the entire surface of the workpiece with each selected parameter combination from the experimental design.

After each pass, the ground surface was cleaned and placed under Taylor-Hobson optical profiler for surface roughness measurement. Three consecutive average roughness measures parallel to feed direction were taken and the average was recorded.

4. Results and discussion

Table 2 shows significant variation of the surface roughness depending on the grinding parameter combination. A highest surface roughness values value (Ra) of 320 nm and lowest value of 130 nm were recorded. One can easily notice that these values correspond to the high and low conditions of feed rates respectively.

The significance of the grinding parameters on the response variable was analyzed using ANOVA. To further monitor the interaction of the different machining parameters, a response surface model was developed.

In order to determine the best polynomial function for the model, sequential sum of square test (Table 3) was employed to select the highest order polynomial where the additional terms are significant without having an aliasing effect while a lack of fit test (Table 4) was employed to determine the suitable terms in the response model without significant lack of fit. The results of the test reveal that a quadratic and two factor interaction model should well represent the surface roughness as follows:

$$\check{R} = B_o + B_1d + B_2f + B_3s + B_4d^2 + B_5f^2 + B_6s^2 + B_7df + B_8ds + B_9fs$$

Table 2. Surface roughness measurements

Run Order	Depth, *d* (µm)	Feed, *f* (mm/min)	Speed, *s* (rpm)	Ra (nm)
1	5	1	15000	130
2	8	3	15000	300
3	2	1	30000	150
4	2	3	15000	180
5	8	3	45000	220
6	5	3	30000	240
7	5	5	15000	320
8	5	1	45000	180
9	5	3	30000	230
10	8	1	30000	180
11	5	5	45000	210
12	2	5	30000	220
13	5	3	30000	240
14	2	3	45000	215
15	8	5	30000	260

Table 3. Percentage contribution of the surface roughness model terms

Source	Model	*d*	*f*	*s*	$f * f$	$d * s$	$f * s$
Contri-bution (%)	96.38	12.12	46.52	3.75	6.8	8.9	17.4
F-value	35.53	35.83	70.73	39.10	15.05	19.88	38.49

Insignificant terms of the model were eliminated and the developed model indicates interaction effects between speed and depth, feed and depth, with the influence of the feed being the highest as indicated by the standardized coefficients of the model below and the percentage contribution of the F-test table 3

$R_a = -125.699 + 27.292d + 101.964f + 0.006s - 6.473f^2 - 0.01ds - 0.001fs$

The p-value of the model from the ANOVA test (Table 4) reveals that the model is extremely significant when compared to the 0.05 threshold. The adjusted R^2 value indicates that the model explains 93.7% of the variation in the surface roughness. Hence the developed response surface model is valid. Furthermore, F-value of 35.53 implies the model is significant hence there is 0.01% chance that the model could occur due to noise.

Table 4. ANOVA analysis

	df	*SS*	*MS*	*F*	*P-value*
Model	6	35452.98	5908.83	35.53	0.000024
Residual	8	1330.36	166.29		
Total	14	36783.33			

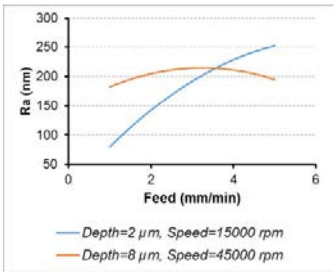

Fig. 3. 2D profile plot of surface roughness at different levels of machining parameters

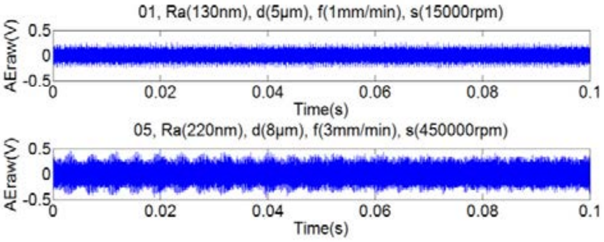

Fig. 4. Raw AE voltage levels

2D profile plot (Fig. 3) shows that better surface finishes can be achieved at low cutting parameters. However at 45000 and 8μm, surface roughness can be improved by increasing the feed rate. Optimization from the response model reveals that the lowest achievable surface roughness from the experimental design domain is 80 nm which occurs at a combination of cutting depth of 2μm, feed of 1 mm/min and speed of 15000 rpm.

A significant change in the raw AE amplitude level is observed with the increase in the surface roughness value (Fig. 4). The results show that the raw AE amplitude voltage values increased with the increase in the surface roughness values for most of the values observed. At 220nm AE voltage levels were above 0.3nm while the voltage level as below 0.3V at 130nm. Further studies have been carried out involving feature extraction which shows good correlation with the surface roughness. It was found that extracted time-frequency domain features were more consistent in monitoring surface roughness in UHPG of BK7 glass compared to raw AE amplitude levels.

5. Conclusion

Good surface finishes can be realised with ultra-high precision machining systems and the right combination of machining parameters. A minimum value of 80nm has been achieved from optimization with developed response surface model. Hence better surface finishes can be achieved by using low values of feed rate, cutting depth and high wheel rotation.

The feed rate has been observed to be the most influential parameter on the surface roughness of BK7 glass. Therefore increased feed yields poor surface finishes. However, at high feeds and cutting depth, surface roughness can be slightly improved by increasing the wheel speed. Furthermore, influence of the feed is dependent on the interaction effect with the speed.

Finally, the raw AE signals could be a reliable means for monitoring the surface roughness in the ultrahigh precision grinding of BK7 glass.

Acknowledgements

The financial support given by the National Research Foundation of South Africa is highly appreciated.

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