APPLICATION OF TAGUCHI METHOD TO INVESTIGATION OF OPTIMAL ABRASIVE JET POLISHING PARAMETERS

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Abstract - The surface finish of N-BK7 optical glass is improved by abrasive jet polishing (AJP) process. Taguchi's method is employed to investigate optimal AJP parameters. The important parameters that influence the N-BK7 surface finish are determined by Analysis of variance (ANOVA). The optimal parameters are found based on Taguchi's experimental results and signal noise ratio (S/N). These optimal parameters are: polishing time of 45 min, pump pressure of 5 kgf/cm^2, standoff distance of 12 mm, abrasive grain type of Al_2O_3, abrasive grain concentration of 20%, and impact angle of 40°. The surface finish (Ra) of the N-BK7 is improved significantly from 0.350 µm to 0.018 µm.

Key words - Abrasive jet polishing; ANOVA; surface finish; Taguchi; N-BK7 specimen

1. Introduction

Many research projects have been conducted to amend surface roughness of optical materials in the past decades. Fähnle [1] studied fluid jet polishing (FJP) method to improve BK7 surface finish. Booji [2] analyzed FJP method on glass optical material and showed advantages and disadvantages of this technology. Simulations of FJP process for BK7 materials were studied by Li et al. [3]. A machining center is usually used to conduct the FJP process [4-6]. Materials that polishing process usually apply are optical materials, steels for moulds, stainless steels and ceramics [7, 8]. FJP method has many advantages over other traditional methods such as: less corrosive system, no need to contact the sample surface, capability of polishing complex surfaces, cooling tool and less environmental costs [7-9]. However, survey studies show that very few people have studied abrasive jet polishing (AJP) on NBK-7 optical glass material. Hence, this study uses Taguchi's method to investigate optimal AJP parameters for the N-BK7 materials. A tool-head was machined and clamped on a CNC milling machine for AJP process. Six factors and three levels were chosen for polishing experiment. After the experiments were completed, the optimal parameters were investigated by the signal-to-noise (S/N). Based on the optimal parameters, confirmation experiments were conducted. The important parameters that affect AJP process include: impact angle (α), abrasive material, abrasive concentration, aperture of nozzle (d), polishing time and standoff distance (S) (Figure 1).

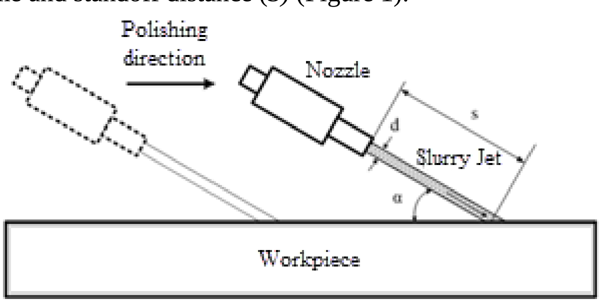

Figure 1. *The parameters of the AJP process*

2. Experimental Work

2.1. Fabrication of polishing Tool-head

An polishing tool-head is designed and machined to polish N-BK7 optical glass, as shown in Figure 2. This tool-head includes the key components as follows: a nozzle, a nozzle fixture, holes, a holder and a clamping shank. This clamping shank is clamped on a CNC milling machine. The impact angle is adjusted by screws. The standoff distance is adjusted by the nozzle fixture. Hence, The polishing tool-head can easily adjust the impact angle from 20^0 to 90^0 and alter value of standoff distance from 5mm to 30mm.

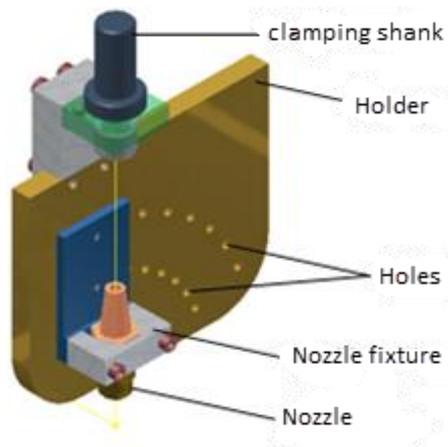

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Figure 2. *CAD model of the AJP tool Posmodifier*

2.2. Experimental materials

Experimental material is N-BK7 optical glass. Before AJP process, experimental specimens are ground. Table 1 shows chemical composition of NBK-7 optical glass and Table 2 shows mechanical characteristics of this material [10]. A color 3D laser scanning microscope instrument is used to measure the surface roughness of N-BK7 specimen. The ground specimens have a initial surface roughness of 0.35 µm.

Table 1. *The N-BK7 chemical properties [10]*

Properties	Value
Specific Heat Capacity	858 J/KgK
Thermal Conductivity	1.114 W/mK
Apparent Elastic Limit	63.5 MPa
Young's Modulus (E)	82 GPa
Poisson Ratio	0.206
Hardness of material	610 Knoop

2.3. Design of Experiments

Design of experiments for AJP process is illustrated in Figure 3. The clamping shank is connected to a CNC milling machine. The N-BK7 specimen is clamped tight on the fixture. The slurry includes abrasive particles and water.

The slurry is pumped from a tank to the nozzle through a hose. As this slurry impacts on specimen surface and guided back to the tank for reuse. Experiments on the N-BK7 specimen are performed on a CNC milling machine. The NC code is created by MaterCAM software and transmitted to a CNC milling machine.

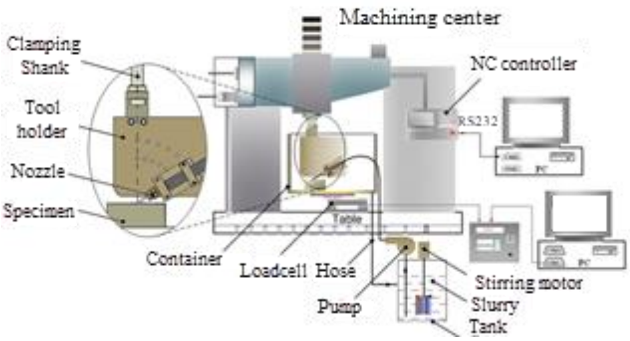

Figure 3. *Experimental setup of AJP process*

Table 2. *The N-BK7 mechanical characteristics [10]*

Composition	Chemical formula	Percentage
Silicon dioxide	SiO_2	60-70
Boron Oxide	B_2O_3	10-20
Potassium oxide	K_2O	5-15
Sodium oxide	Na_2O	1-15
Barium Oxide	BaO	1-10
Antimony Trioxide	Sb_2O_3	<1
Calcium Oxide	CaO	<1
Titanium Oxide	TiO	<1
Zinc Oxide	ZnO	<1

2.4. Experimental Parameters

Matrix experiments are carried out to determine the effect of polishing parameters [11]. The AJP parameters selected for experiments includes polishing time, abrasive material, impact angle, abrasive concentration, standoff distance and pump pressure. Taguchi's experiments and analysis of variance (ANOVA) are used to determine these parameters. Fixed factors for AJP experiments are shown in Tables 3. Control factors and their levels in the AJP experiments are shown in Tables 4. Eighteen samples are selected separately for experiments to determine optimal AJP parameters.

Table 3. *Fixed factors in Taguchi design experiments*

Fixed factors	Value
Aperture of nozzle (material: Copper)	3 mm
Abrasive particle type	CeO_2, Al_2O_3
Experimental specimen	N-BK7 optical glass
Addition	Water
Mixing speed	120 rpm

Table 4. *The control factors and their levels in AJP experiments*

Control factors	Level		
	3	2	1
Polishing time (F)	45 min	30 min	15 min
Pump pressure (E)	5 (kgf/cm^2)	4 (kgf/cm^2)	3 (kgf/cm^2)
Standoff distance (D)	12 mm	9 mm	6 mm
Impact angle (C)	60°	50°	40°
Abrasive concentration (B)	20 (wt%)	15 (wt%)	10 (wt%)
Abrasive material (A)	-	Al_2O_3	CeO_2

Taguchi designs for experiments include three basic types: "larger is better", "nominal is best" and "smaller is better" type [12]. The surface roughness of polished sample must be less than the surface roughness of the ground sample. So, polishing technology is a case of "smaller is better". Value of η (S/N ratio) can be calculated as follows [12]:

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right]$$

where y_i is the observed data of quality characteristics at the ith trial and n is the number of repetitions at the same trial. The desired target of "smaller is better" type is always to maximize value of the S/N ratio (η).

3. Results and Discussion

3.1. The Optimal Level Combination for each Parameter

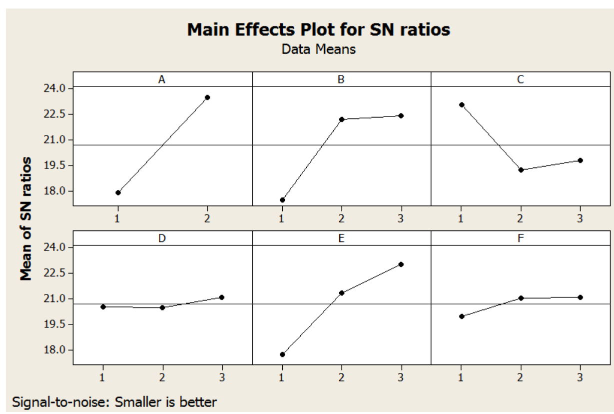

Figure 4. *The control factors effect in the AJP process*

The S/N ratio (η) of eighteen samples and the surface roughness (R_a) of polished samples are shown in Table 5. Mean S/N ratio for each level of control factors is illustrated in Table 6 and Figure 4. The optimal level for each parameter can be determined according to highest value of the S/N ratio and combination of the optimal parameters is $A_2B_3C_1D_3E_3F_3$ (Figure 4). So, the optimal polishing parameters include: the polishing time of 45 min, the pump pressure of 5 kg/cm^2, the standoff distance of 12 mm, the abrasive material of Al_2O_3 particles, the impact angle of 40° and the abrasive concentration of 20 wt%.

3.2. Confirmation Experiments

The last step in Taguchi's method is to conduct verification experiments based on the optimal polishing parameters. Mean surface roughness (R_a) of the polished sample is 0.018 µm (Table 7). Thus, improvement of the surface roughness for N-BK7 material is about 94.8%. Figure 5 and Figure 6 presents an N-BK7 3-D profile before and after AJP within an area 70.7×80 µm.

3.3. ANOVA Analysis

Based on the Taguchi experimental results, ANOVA is performed to identify control parameters that most affect the surface roughness of N-BK7 sample. Table 8 can conclude that the abrasive concentration is a greatest influence factor and the standoff distance and polishing time are smaller than 10% the abrasive concentration, so the standoff distance and the polishing time are good targets for pooling.

Degree of freedom for the pooled error is 10 and degree of freedom for control factors is 2. Based on *F*-distribution Table, value of $F_{0.05,\ 2,\ 10}$ is 4.1 (or 90% confidence level) [12]. Any parameters that has the *F* value bigger than 4.1 has an important influence on the surface finish of N-BK7. According to ANOVA results illustrated in Table 8, the dominant factors that affect the surface finish of sample include: the impact angle, the abrasive material, the abrasive concentration and the pump pressure.

Table 5. *Results of Taguchi's experiments for polished samples*

Expt. no.	Control factors						R_a (µm)			η (dB)	Average (µm)
	A	B	C	D	E	F	01	02	03		
18	2	3	3	2	1	2	0.089	0.084	0.085	21.3073	0.086
17	2	3	2	1	3	1	0.057	0.050	0.053	25.4475	0.053
16	2	3	1	3	2	3	0.020	0.028	0.025	32.1968	0.024
15	2	2	3	1	2	3	0.054	0.058	0.056	25.0325	0.056
14	2	2	2	3	1	2	0.061	0.074	0.072	23.1933	0.069
13	2	2	1	2	3	1	0.035	0.028	0.030	30.1338	0.031
12	2	1	3	2	2	1	0.131	0.129	0.134	17.6314	0.131
11	2	1	2	1	1	3	0.191	0.208	0.196	14.0465	0.198
10	2	1	1	3	3	2	0.071	0.079	0.080	22.2959	0.077
09	1	3	3	1	3	2	0.079	0.075	0.081	22.1167	0.078
08	1	3	2	3	2	1	0.145	0.172	0.153	16.0778	0.157
07	1	3	1	2	1	3	0.137	0.131	0.145	17.2159	0.138
06	1	2	3	3	1	1	0.185	0.190	0.194	14.4385	0.190
05	1	2	2	2	3	3	0.102	0.105	0.099	19.8255	0.102
04	1	2	1	1	2	2	0.095	0.098	0.091	20.4721	0.095
03	1	1	3	3	3	3	0.125	0.126	0.120	18.1530	0.124
02	1	1	2	2	2	2	0.152	0.148	0.139	16.6871	0.146
01	1	1	1	1	1	1	0.177	0.148	0.145	16.0638	0.157

Table 6. *Mean S/N ratios for each level of factors*

Factors	A	B	C	D	E	F
Level 1	17.89	17.48	23.06	20.53	17.71	19.96
Level 2	23.47	22.18	19.21	20.46	21.35	21.01
Level 3	-	22.39	19.78	21.05	22.99	21.07
Mean	20.685					

Table 7. *Results of confirmation experiments*

Trials	R_a (µm)			η	Average
	01	02	03	(dB)	(µm)
1	0.017	0.019	0.019	34.724	0.018
2	0.018	0.020	0.019	34.417	0.019
3	0.018	0.017	0.019	34.886	0.018
Mean				34.675	0.018

Table 8. *ANOVA analysis for the S/N ratio*

Control factors	d.f.	S.S.	M.S.	F- values	$F_{0.05,2,10}$
A	1	51.85	51.85	7.15	4.10
B	2	140.20	70.10	9.67	4.10
C	2	92.62	46.31	6.39	4.10
D	2	1.27	-	-	4.10
E	2	87.75	43.88	6.05	4.10
F	2	4.68	-	-	4.10
Error	6	66.54			
Total	17	444.91			
Pooled to error	10	72.49	7.25		

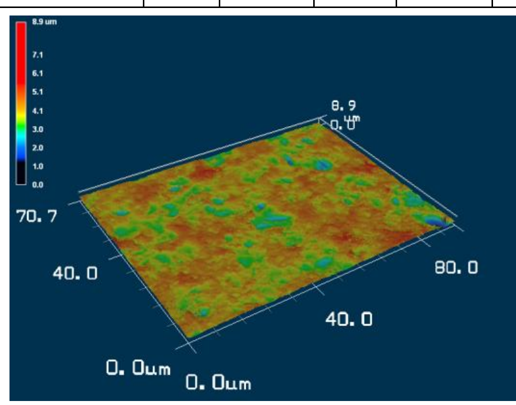

Figure 5. *A 3-D surface roughness profile of an NBK-7 ground surface*

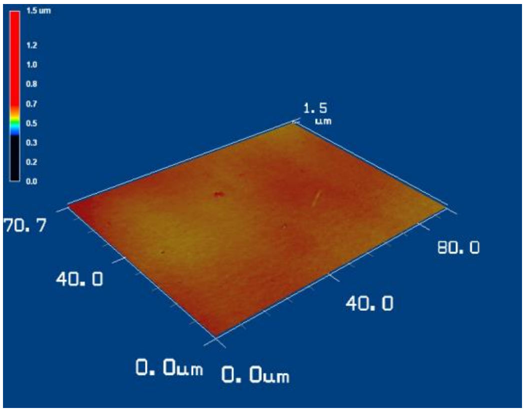

Figure 6. *3-D surface roughness profile of an N-BK7 polished surface*

3.4. Effect of the abrasive concentration

The abrasive concentration greatly affects material removal rate. If the concentration of abrasive is higher, more particles will strike the same surface area per second [10]. In order to investigate the effect of the abrasive concentration on the surface roughness, some NBK-7 samples are conducted using the optimal AJP parameters. The initial surface roughness of specimens is 0.350 µm. Figure 7 indicates that the surface roughness is the best (0.018 µm) for the abrasive concentration of 20 wt%. The abrasive concentration is less than 20 wt%, material removal is almost small, and surface roughness is higher. But as abrasive concentration is bigger than 25 wt%, particle-particle interaction will appear. The particles will lose their kinetic energy because of these collisions, and the lost energy will not be used to remove material. Therefore, the surface roughness is still higher (0.026 µm).

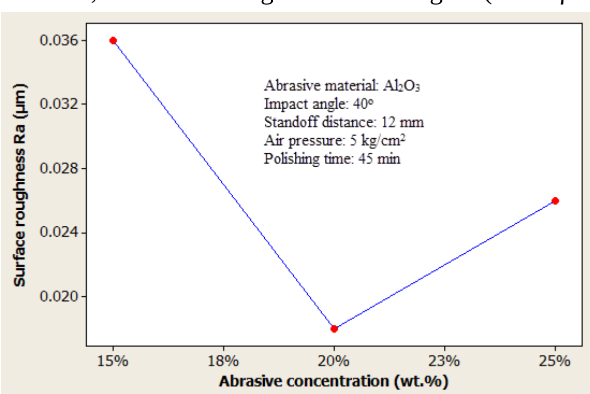

Figure 7. *Effect of abrasive concentration on the surface roughness*

3.5. Effect of impact angle

Li's study has concluded that the impact angle has a great effect on the groove geometry [13]. The depth of groove depends on the impact angle. As for small impact angles, material removal rate is small, and for larger impact angles, material removal rate is high [2].

Using the optimal AJP parameters, to determine effect of impact angle on surface roughness of sample, some ground NBK-7 samples are performed with the ground surface roughness of 0.350 µm. Figure 8 indicates that the surface roughness is the best (0.018 µm) for the impact angle of 40°. As the impact angle is smaller than 40°, the material is removed by sliding grinding mechanism. Hence, material removal rate is smaller, and the surface roughness is higher (0.032 µm). As impact angle is greater than 40°, the polishing force will impact strongly on the surface and the surface roughness is higher (0.029 µm).

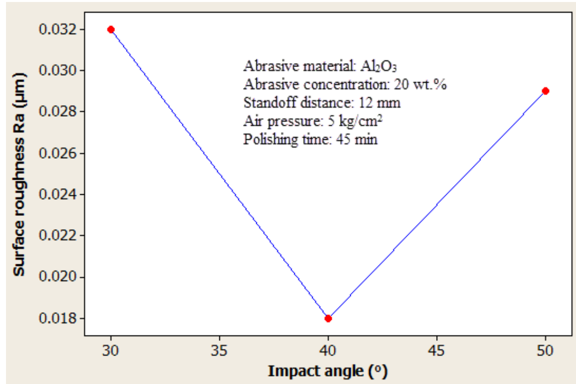

Figure 8. *Effect of impact angle*

3.6. Effect of pump pressure

Pump pressure greatly affects material removal rate, and it causes the abrasive particles to contact sample surface. Material removal rate is proportional to the impact. Because the kinetic energy per impacting particle is higher, the surface roughness is higher for higher pressure, [10]. To determine effect of the pump pressure on the surface roughness, some ground NBK-7 samples are performed with the original surface roughness of 0.350 µm. When pump pressure is 5 kg/cm^2, the polishing force is enough to destroy peaks but not enough to create grooves and the surface roughness achieves the smallest value (Figure 9). As the pump pressure is 4 kg/cm^2, polishing force is less sufficient to destroy peaks. Therefore, material removes less and as a result the surface roughness is still larger (Ra = 0.024 µm). If the pump pressure is 6 kg/cm^2, the polishing force increases strongly. Therefore, it can destroy existing peaks and create new grooves. As a result, the material removal rate increases sharply and the surface finish (Ra = 0.030 µm) decreases.

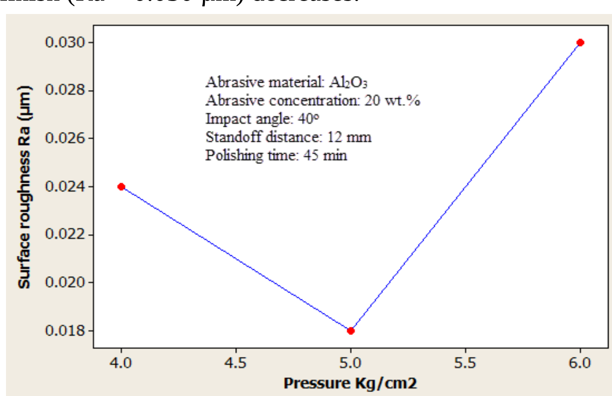

Figure 9. *Effect of pump pressure on the surface roughness*

4. Conclusions

The AJP has been introduced to amend the N-BK7 surface roughness. Based on results of experiments using Taguchi's method, the optimal AJP parameters are investigated. The optimal combination of parameters is as follows: the impact angle of 40°, the pump pressure of 5 kgf/cm^2, the standoff distance of 12 mm, the abrasive material of Al_2O_3, the polishing time of 45 min and abrasive concentration of 20 wt%. The results show that by using the optimal AJP parameters, the N-BK7 surface roughness is improved from initial value of 0.350 µm to final value of 0.018 µm, corresponding to an improvement of about 94.8 %. The dominant parameters that greatly influence the N-BK7 surface roughness include: abrasive material, abrasive concentration, the pump pressure, and the impact angle.

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