Experimental Investigation on the Influence of Cutting Parameters on Surface Quality obtained in SPDT of PMMA

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Abstract: Manufacturing of an optical lenses demand a specialized technology and thus needs sophisticated precision manufacturing process. PMMA is one of the most used optical polymer for manufacturing of optical lenses, the shaping of which into the required precision and accuracy is a challenging task. The focus of the present paper is to understand the effect of machining parameters on the surface characteristics especially flatness obtained in single point diamond turning (SPDT). The experiments were conducted according to Taguchi L9 design. The machining parameters chosen are feed rate, spindle speed, depth of cut and cutting environment. Analysis of results reveals that the spindle speed is more influential on the surface flatness generated by the SPDT. All the flatness measurements were done by the non contact type of measurement. It is observed that the minimum *PV* value produced is 0.837 µm.

Keywords: ANOVA, Flatness, Non-Contact Measurement, Optics, SPDT, Taguchi DOE

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1 INTRODUCTION

In the present era, polymers have growing applications in the manufacturing of optical products. Manufacturing of such optical products especially in high quality lenses is a specialized technology and need sophisticated technique. At present, very few researchers succeeded to develop manufacturing technology for the production of highly precise optical products. Commercially available polymers which fulfill the requirements of optics field are Polymethylmethacrylate (PMMA), Polystyrene (PS), Polycarbonate (PC), Cyclic olefin copolymer (COC), Allyl diglycol carbonate (ADC), Polyetherimides (PEI), and Polyethersulfone (PES). So shaping of these optical polymers into desired optical products to required precision and accuracy is a challenging task.

It has been observed from the available literature that very few researchers have conducted research in precision machining of polymers. The information required for successful and rapid development of optical product is not adequate. In this context, few researchers have begun their work at their research laboratories and academic institutions. The research in machining of polymers is classified in the areas such as tool wear pattern and tool life, surface finish and quality of the machined polymer, chip formation process, temperature distribution on work piece and tool during machining, etc. The precision cutting on a precision turning lathe enables a high flexibility in the production process and an increased production rate of asymmetric products. Especially the non-rotational symmetric lenses can be produced with high flexibility by using fast tool servo mechanism.

The precision machining using a precision turning lathe enables a high flexibility in the production of asymmetric products. Higher form and shape accuracies may be achieved by the precision turning process than with conventional grinding and polishing techniques [1], [2]. This ultra precision process is known as 'Single Point Diamond Turning' process.

The present investigation aims at quantitative as well as qualitative analysis of surface topography of the machined surface produced using diamond turning and CNC turning operations. The analysed results could help prescribe suitable machining techniques that produce most favourable and acceptable surfaces for optical applications.

The ultra precision machining methods such as diamond turning and precision CNC turning have been used by very few researchers to analyse the machinability of optical polymers in the past. The ultra precision machining methods such as diamond turning and precision CNC turning have been used by very few researchers to analyse the machinability of optical polymers in the past. The following paragraph throws light on some of the earlier studies related to machining of optical polymers.

Grabchenko investigated the mechanism of surface formation using photo emission technique during machining of polymers [3]. Mamalis investigated the wear of diamond tool in ultra precision and diamond turning operations [4]. He observed that the latent defects of diamond crystals or misalignment by the operations are the reasons for macro wear on diamond tool wedge. A diamond turning of CD/DVD pick up lens on PMMA has been carried out by Liu [5]. Gubbels performed diamond turning on polycarbonate and PMMA using different cutting environments [6], [7]. It is observed that the type of cutting environment during machining influences the tool wear pattern in diamond turning. He further explained the tribo-chemical wear as a predominant phenomenon as compared to other wear.

Carr performed single point diamond turning of various polymers [8]. It has been reported that the rake angle has a major role on the surface roughness, which further influences the direction of crack propagation into the surface. It was found that the rake angle of -2° produces better surface finish. He achieved the form accuracy of less than 1 µm within a tolerance of 1 µm. Guido P. H. G. investigated the tool wear and temperature deformation in diamond turning of glassy polymers [9]. Cheung C. F studied the theoretical and experimental investigation of surface roughness formation in ultra-precision diamond turning [10]. Kobayashi did a thoroughly investigation on machining of plastics [11]. Jagtap K. investigated the roughness and flatness on diamond turning of PMMA [12]. It has been reported that the minimum roughness and flatness values are up to 9 µm and 0.83 µm respectively.

2 EXPERIMENTAL

Diamond turning has prospective application in micro manufacturing and is extended to nano manufacturing. By diamond turning a surface finish up to nanometer levels can be achieved successfully. It's an emerging area in the field of machining of biotechnology, biomedical, household, automotive, prosthetic and strategic applications requiring very high degree of surface quality or the products and features with a size in micrometers. In diamond turning process a diamond tool is used with a controlled or uncontrolled waviness. The diamond turning machine has special features with respect to the conventional machines.

It is nothing but the very accurate and precise lathe having high degree of spindle and bed accuracies, low tool feed and high thermal stability. Diamond turning machine uses an air bearing spindle, precision tool movement with a sensitive feedback.

In this study, diamond turning machine has an oil hydrostatic slide ways and liquid cooled air bearing spindle. Hydrostatic oil bearing slide ways have 350 mm travel on X axis and 300 mm on Z axis. It has < 0.3 µm straightness accuracy over full travel. Liquid cooled air bearing spindle provides rotational speed of 50 to 6000 RPM.

Brushless DC motor is used with Sony laser scale having 8.6 nanometers resolution. Monolithic invar scales are used in that machine. Scales are isolated from the thermal expansion of the carriage and mounted away from the cutting area. Machine has a monolithic, cast epoxy granite base, because epoxy granite is having an excellent damping property. Fig. 1 shows the diamond turning machine.

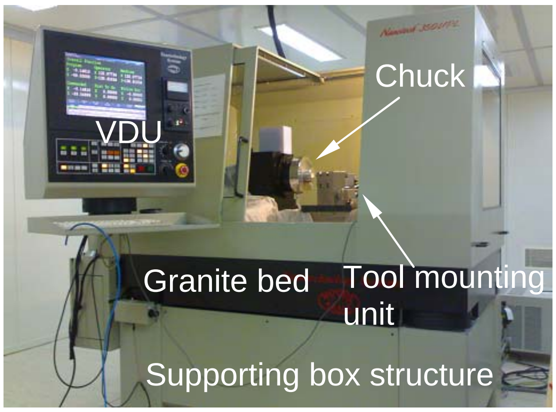

Fig. 1 Diamond Turning Machine

Table 1 Standard Experimental Design of L9 (3^4) Array

Sr. No.	Column			
	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

A Taguchi experimental design L9 orthogonal array was used for designing the parameter combinations for experimental trial (See Table 1). In this orthogonal array, number of factors are 4 and number of levels are 3. Hence total numbers of runs are 9. The response variable chosen is the arithmetic average of surface flatness for the experiments carried out on SPDT. The input control factors selected for diamond turning experiments are: depth of cut (5-20-40 µm), feed rate (2-5-8 mm/min), spindle speed (1000-2000-3000 rpm) and cutting environment (Dry - Dry with air - Air with mist). Table 2 presents the experimental runs with the assigned factors to each of the columns of OA for SPDT process.

Table 2 Experimental Factors with Actual Values

Sr. No.	Cutting Parameters			
	DOC (µm)	Feed (mm/min)	Spindle Speed (rpm)	Cutting Environ ment
1	05	02	1000	DWA
2	05	05	2000	AWM
3	05	08	3000	D
4	20	02	2000	D
5	20	05	3000	DWA
6	20	08	1000	AWM
7	40	02	3000	AWM
8	40	05	1000	D
9	40	08	2000	DWA

Initially nine workpieces were cut as substrates to the required length from a long rod of PMMA. These substrates are exactly made to the size of Ø25 × 8 mm thickness. An aluminium turning fixture to hold these substrates was fabricated to the size of Ø75 × 35 mm thickness, to facilitate holding of substrates during diamond turning operation. Three screws are used to hold the substrate tightly against the fixture. The fixture along with PMMA substrate, were mounted on the vacuum chuck of the machine.

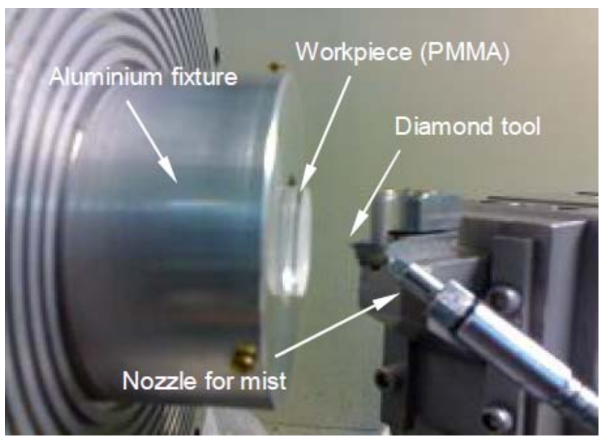

Fig. 2 Close set up view of Diamond Turning Operation

After machining trials, the PMMA polymeric diamond machine turned surfaces were measured by non contact type of measurement in a temperature controlled environment. The instrument used for measuring the flatness of machined surfaces is Fisba Optik interferometer, where Fisba Optik provides the measurement and analysis software µ shape^{TM} (see Fig. 3).

After setting the vacuum pressure, fixture is trued properly for perfect rotation as shown in Fig. 2. Initially a rough cut of 80 µm on each substrate's face is taken and finish cut is taken on surface of 25 mm diameter. Finally each substrate is machined as per the experimental trials given in Table 2. After each experiment the machined substrate of PMMA was wrapped by a food rapped paper to protect it from dust and swarf.

The interferometer machine has a laser source, µ shape™ software, live video facility and adjustable stand with fine movements. Due to the fact that the instrument is having laser source diameter limitation of 10 mm measurement, hence 10 mm diameter machined surface was measured on each substrate.

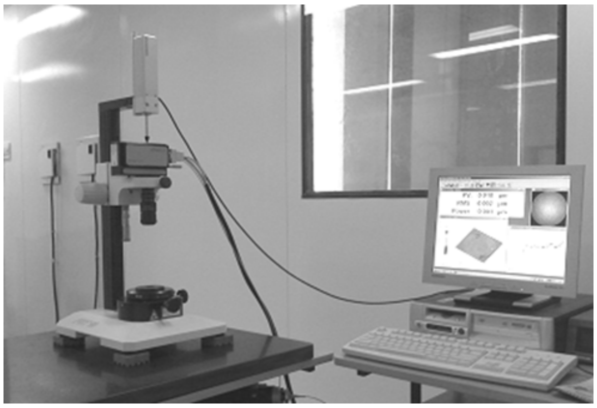

Fig. 3 Optical Interferometer for Diamond Turned Surface Measurement

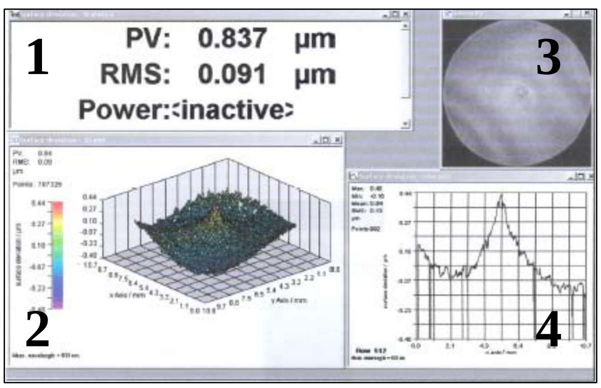

Fig. 4 Flatness Measurement of Diamond Turned Surfaces

3 RESULTS AND ANALYSIS

The surface characteristics, especially the surface flatness of machined PMMA substrates using diamond turning, is presented in this section. Table 3 shows the values of flatness of each substrate. The output screen of the flatness measurement has four windows (See Fig. 4). First window shows the PV value i.e. flatness on 10 mm diameter surface. Second window represents 3-D surface deviation profile of 10 mm diameter surface. Third window shows the fringe pattern on diamond turned surface. Fourth window shows the surface deviation plot on 10 mm diametral surface.

Table 3 Flatness Values of Diamond Turned Substrates

Substrate No.	Flatness Values (µm)
1	0.896
2	1.322
3	1.189
4	1.699
5	1.975
6	0.840
7	0.837
8	1.132
9	1.110

The main effects plots for flatness (ANOM) and the table of analysis of variance (ANOVA) are shown in Figure 5 and Table 4 respectivly. It is observed from the ANOVA table, that there is no statistically significant factor in this experiment. Since the P-value in the ANOVA table for any input parameter is not less than 0.05, there is a not statistically significant relationship between any input parameter and the response variables at the 95.0% confidence level. It is noticed that the highest P-value is 0.3532 in the ANOVA table. Since the P-value is not less than 0.05, hence that term is not statistically significant at the 95.0% confidence level. The percentage contribution of the input variables influencing the flatness are feed rate: 32.99%, depth of cut: 25.64%, environment: 22.30% and spindle speed: 19.06%. The effect of each input variables on the surface flatness are considered in detail using ANOM plots.

Table 4 ANOVA Table

Source	DF	Seq SS	Adj SS	Adj MS	F	P
d	2	0.31360	0.313598	0.156799	0.06	0.8063
f	2	0.40356	0.403564	0.201782	0.08	0.7818
s	2	0.23311	0.233111	0.116555	0.99	0.3532
e	2	0.27274	0.272743	0.136371	0.05	0.8362
re	0	-	-	-	-	-
Total	8	1.22302	-	-	-	-

The effect plot shows that there is drastically an increase in flatness from 1.15 µm to 1.54 µm when feed rate increases from 2 mm/min to 5 mm/min. But for further increment in feed rate up to 8 mm/min, there is a decrease in flatness rapidly to one half in magnitudes.

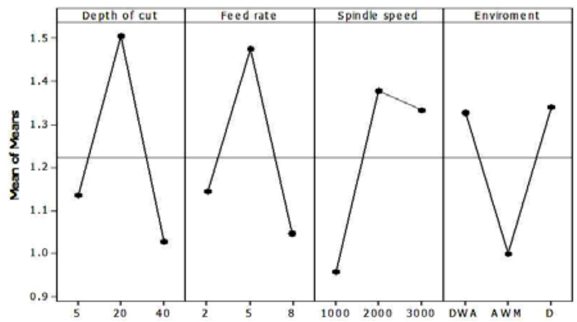

Fig. 5 Main effects plots for flatness in diamond turning of PMMA

It is observed from the main effects plot that feed rate shows linear effect on machined polymer. At 2 mm/min feed rate, the surface roughness is less. However, further increasing of feed rate to 5 mm/min increases the surface roughness by a smaller magnitude. But the trend is different at higher level of feed rates, i.e., 8 mm/min. At the highest level of feed rate, the mechanism of material removal and surface roughness might be complex due to involvement of some other factors during machining. Therefore, the surface roughness at this condition was less than other cases.

The effects plot shows that there is drastically an increase in flatness from 1.14 µm to 1.5 µm when depth of cut increases from 5 µm to 20 µm. But also for further increment in depth of cut from 20 µm to 40 µm, there is a rapid decrease in flatness.

PMMA is a ductile polymer, where in the diamond turning of ductile materials, the chip removal process may be classified into two types. One is the process due to plastic deformation on the characteristic slip plane and the other is due to cleavage fracture on the characteristic cleavage plane. Plastic deformation takes place in the work-material in front of the cutting edge when the resolved shear stress in the easy-slip direction exceeds a certain critical value inherent to the work-material before cleavage takes place. On the other hand, cleavage takes place when the resolved tensile stress normal to the cleavage plane exceeds a certain critical value before slip.

In other words, the ductile mode of deformation may occur in the same material and transition between them can be obtained by changing the scale or the rate of operation. The type of chip removal process is determined by the predominant depth of cut used in the process. At higher depth of cuts, plastic deformation is more in the machining zone. When a plastic deformation process is prior to a cleavage, a very smooth and fine surface may be obtained. Here this is happened when the depth of cut is changed from 20 to 40 µm. At the lowest level of the depth of cut, mechanism of material removal and flatness might be complex due to the involvement of some other factors during machining. Therefore, the flatness at this condition was lower than other cases.

When the environment is air dried then the flatness is 1.35 µm. But when the environment is changed to air with mist at that time, flatness is drastically reduced up to 1 µm. When the environment is changed from air with mist to dry, then flatness is rapidly increased to 1.4 µm.

In diamond turning process on polymers, submicron powdery chips are produced. These chips are very small, and may easily stick to the diamond turned surface because of temperature generation during process. So for getting better quality of flatness, removal of these micro-chips during machining is important. Therefore, air with mist is the good environment to remove these powdery micro-chips using mist flow.

In air-mist environment, air plays an effective role to cool the machining zone temperature. But on the other hand mist act as a lubricant during machining process hence, there is a possibility of getting good surface quality. While, in dry environment there is no chance of removing these chips or to cool the machining zone temperature, hence due to this, final minimum surface flatness is not maintained. In case of dry with air environment, the quality of machined surface is increased up to certain extent, but due to the absence of mist no lubrication takes place.

Spindle speed demonstrates a linear effect on flatness of diamond turned surface. When the spindle speed changed from 1000 rpm to 2000 rpm, flatness increased from 1 µm to 1.35 µm. But while the spindle speed increased to 3000 rpm, flatness is reduced by very small amount of 1.33 µm. The surface roughness profile of a machined surface provides a more faithful signature of the cutting process and the variation of material properties than that provided by the chip, since the distortion of the machined surface is minimal at lower spindle speeds.

In addition, an imprint of all the static as well as dynamic forces, stresses, strains, and material swelling during cutting is left in the surface roughness profile. So it can be contributed that when the spindle speed is minimum then flatness achievement is better. But as it is seen from Fig. 5, when the spindle speed is increased to 3000 rpm then flatness is reduced in very small amount.

4 CONCLUSION

Diamond turning is one of the important processes to achieve the optical quality on polymeric surfaces. Diamond turning produces surface finish up to few nanometers with good contour surface accuracy.

Hence, this technique is now preferred in many optical industries for producing optical products. The present work includes extensive experimental analysis of the single point diamond turning process to understand the ability of the process to generate high level of surface flatness on polymeric surface. The experiments were carried out to explore the effect of process parameters on machinability of optical polymer through ultra-precision turning operation. From the experimental results and subsequent Taguchi's analysis, the following conclusions can be deduced.

- The features such as surface deviation profile and surface deviation plot, may help in distinguishing the type of machining process carried out on the surface by non contact type of measurement system.
- As far as the effect of input factors is concerned, the spindle speed demonstrates dominating effect on surface flatness for the diamond turning operation.
- It is found that the single point diamond turning produced minimum *PV* value of 0.83 µm and machined surface also gives good optical surface quality.

5 NOMENCLATURES

d = depth of cut

f = feed rate

s = spindle speed

e = cutting environment

re = residual error

D = dry

AWM = air with mist

DWM = dry with air

SPDT = single point diamond turning

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