

Effect of Nose Radius on Surface Roughness of Diamond Turned Germanium Lenses

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Effect of nose radius on surface roughness of diamond turned Germanium lenses

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Abstract. The desire for quality infrared lens with better surface finish has brought about the usage of brittle materials like germanium to be machined via a single point diamond turning machining process. However, achieving the required surface finish is complex if special machining techniques and approaches are not employed. In this paper, the effect of two different tool nose radius parameters on surface roughness of single point diamond turned germanium workpiece were studied and analyzed. The machining parameters selected for this experiment were feed, speed and depth of cut. Box-Behnken design was adopted to optimally create a combination of cutting parameters. Measurement of surface roughness after each run in both experiments was achieved using a Taylor Hobson PGI Dimension XL surface Profilometer. The resulting outcomes show that at most experimental runs, the surface roughness value decreased with an increase in nose radius. Mean absolute error was also used to compare the accuracy validation of the two models.

Keywords: Nose radius, Germanium, Single point diamond turning, Ductile regime machining, Surface roughness, Response surface method.

Introduction

Infrared optical lenses have gained more recognition recently in various industrial field applications such as thermal imaging, military usage, dark field optical instruments, and medical instruments [1]. The generation of infrared optics with the desired surface finish within nanometric range is a real challenge in manufacturing industries thus continuous studies are conducted to reduce the manufacturing cost, production time, and labour accuracy [2].

Brittle materials like germanium and silicon are highly suitable in the production of infrared optical lenses due to their salient properties which include high refractive index, high corrosion resistance, and high homogenous transmissivity in the electromagnetic spectrum (2 to 12 μm wavelength) [3]. The machining of germanium has traditionally been carried out through the grinding, lapping, and polishing process. However, this process is expensive and time-consuming. Also, this process instability due to the unavoidable defects has contributed to its unsuccessful outcome in the manufacture of optical lenses with complex geometries. Single point diamond turning (SPDT) is currently the thriving ultra-precision process in the machining of brittle materials to produce excellent optical components. This has

been actualized by exploiting the process of ductile regime machining where brittle materials are machined to excellent surface integrity utilizing plastic deformation rather than a brittle fracture [4, 5].

In Blake and Scattergood's [6] study, germanium was diamond turned to achieve nanometric surface roughness. They observed that low feed rates, negative rake angle, and smaller depth of cut than the tool edge radius provided the required hydrostatic pressure necessary for plastic deformation. Jasinevicius *et al.* [7] also conducted the diamond turning experiment on single-crystal silicon. At a feed rate, depth of cut, tool nose radius, and negative rake angle of 2.5 $\mu\text{m}/\text{rev}$, 5 μm , 0.65 mm, -25° respectively, a ductile cut with the best surface roughness of 1.6 nm R_a , was achieved. At an increased feed rate of 8 $\mu\text{m}/\text{rev}$, micro-cracks were noted, with the average roughness value increasing up to 91.25 nm. Furthermore, germanium substrates having crystal orientation (111) were diamond turned with tools with different values of nose radii (1.15 mm – 11.22 mm). They concluded that surface quality was much better when a small nosed radius tool was employed. Pawase *et al.* [2] also found out that low feed rate, low depth of cut, and sharp edge tool with a 0.75 mm nose radius and negative rake angle of -25° enabled machining in the ductile mode to generate a good optical surface. Furthermore, in Dogra *et al.* [8] study, an increasing nose radius at reduced feed rates and higher cutting speed leads to an increase in surface finish. It is quite evident that the cutting tool nose

radius contributes significantly to the cutting dynamics and stability of a machining process. To achieve optical components with high accuracy and better surface roughness within a few tens of nanometer, careful selection of suitable machining parameters and cutting tool geometry is very crucial. This paper focuses on the effect of nose radius on surface roughness during the SPDT of monocrystalline germanium using two tools with nose radius of 1.0 mm and 1.5 mm respectively.

Methodology

The experimental work was executed on a Precitech Nanoform 250 ultra-grind precision lathe. The machine employs the use of its sophisticated technological improvements to achieve a nanometric level of surface roughness submicron level dimensional accuracy. This precision machine possesses quality features like five-axis capability, ultra-high precision air bearing spindle for low heat generation and friction, vacuum chuck, granite base to withstand shock and vibration, and oil hydrostatic slides to improve the achievable accuracy. Single-crystal germanium with (111) orientation was used as the workpiece. Water is used as a cutting fluid. Both diamond tool used for this experiment is made up of single-crystal diamond with a rake angle of -25° , included angle of 60° and a clearance angle of 5° . Before machining, the germanium lens is placed in the adapter firmly and attached to the vacuum chuck as shown in Figure 1 and is centered using a dial indicator.

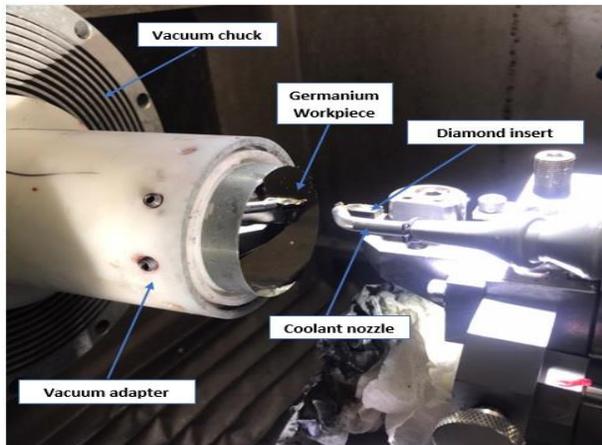


Figure 1: Diamond turning process setup

Tool centering and spindle balancing experiments shown in Figure 2 and Figure 3 were also carried out so that the axis of the workpiece must be aligned with the spindle axis on which the vacuum chuck is situated. The variable input machining factors used are

feed, cutting speed, and depth of cut. Also, Box-Behnken design (BBD) based on response surface methodology (RSM) design was used to study the process with a combination of input machining factors shown in Table 1. Tool nose radius of 1.0 mm and 1.5 mm were utilized respectively for each run to act as a measure of comparison. After the turning experiment at each run, the average surface roughness of diamond-turned germanium was measured and noted using Taylor Hobson PGI Dimension XL surface profilometer shown in Figure 4.

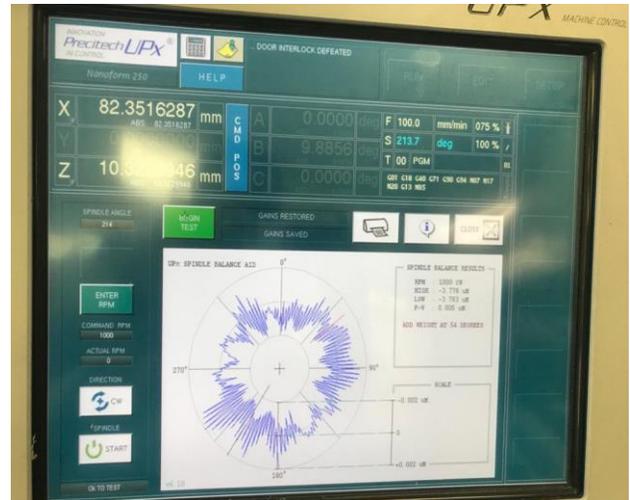


Figure 2: Spindle balancing Interface DIFFSYS

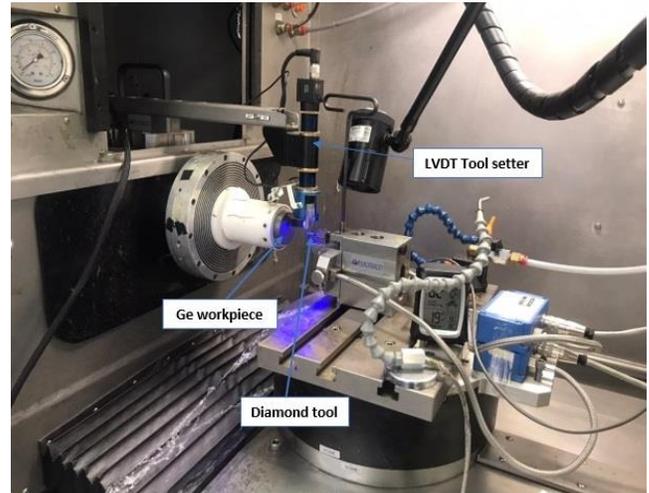


Figure 3: Tool centering process

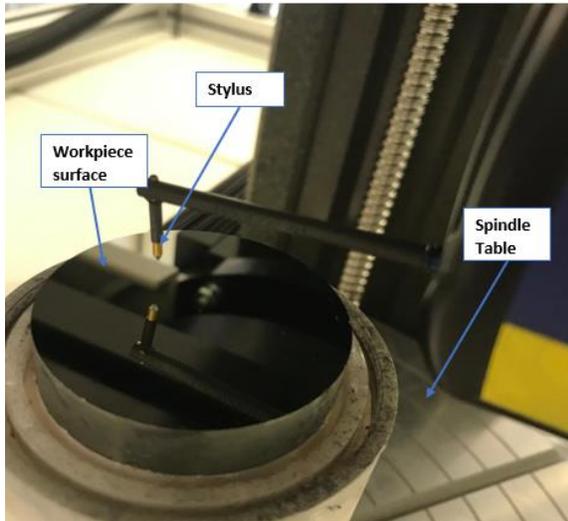


Figure 4: Taylor Hobson PGI surface profilometer

Results and Discussion

Table 2 highlights the surface roughness of diamond-turned germanium using a nose radius of 1.0 mm and 1.5 mm respectively for the 15 cutting combinations generated by RSM. Minitab software was used to create the series plot graph highlighting the variation of surface roughness as shown in Figure 5(a-b). From the plot, the best surface roughness of 1.7 nm and worst surface roughness of 280 nm for a 1.0 mm tool nose radius was obtained at run order 8 and run order 10 respectively. Meanwhile, for a tool with a 1.5 mm nose radius, the best surface finish of 2 nm was obtained at run order 5 and the worst surface finish of 230 nm at run order 10. Comparing the nose radius

Table 1: Process parameters with their corresponding values at three level

Parameter		Level I	Level II	Level III
A	Feed rate (mm/min)	2	11	20
B	Speed (rpm)	400	1200	2000
C	Depth of Cut (μm)	2	11	20

in terms of experimental runs, an increase in nose radius was observed to exert more positive influence on the surface quality of the germanium workpiece with the exception of run 6,8, and 14 where the increased nose radius was noticed to produce higher surface roughness, with a closeness in value when a lower nose radius is employed. This favorable feature of a higher nose radius can be attributed to the elevated edge roundness outcomes from negative rake angle thereby suppressing the workpiece in front of the cutting edge to enable a dominating compressive stress state in the cutting region [9]. This clearly shows that at a combination of low feed, high speed, and effective nose radius, it is possible to machine germanium lens in the ductile mode to obtain nanometric surface finish.

Table 2: Experimental run combination and resulting surface roughness using two nose radii

Experiment Run	Feed, f (mm/min)	Speed, v (rpm)	Depth of Cut, d (μm)	Ra (nm) (1.0 mm nose radius)	Ra (nm) (1.5 mm nose radius)
1	20	1200	2	44	36
2	11	1200	11	10	7
3	11	400	2	108	60
4	11	1200	11	10	7
5	2	2000	11	2	2
6	20	1200	20	28	32
7	11	2000	20	6	4
8	2	1200	20	1.7	2.5
9	11	2000	2	6	3
10	20	400	11	280	230

11	20	2000	11	20	11
12	2	400	11	4.6	3
13	11	1200	11	10	7
14	2	1200	2	2.3	5
15	11	400	20	100	40

A final regression model based on response surface methodology was developed for each turning experiment using the two tool nose radii. This was achieved using Design expert Software based on the experimentation input data and output responses available. Equation 1 is the final model to determine the surface roughness for monocrystalline germanium

using a tool nose radius of 1.0 mm, while equation 2 is the final model to determine the

surface roughness of monocrystalline germanium using a tool of 1.5 mm nose radius.

$$R_a = e^{(3.08481+0.244203(f)-0.003619(v)-0.011545(d)+0.0000012(v)^2-0.000063(f*v))} \quad (1)$$

$$R_a = (0.385032 - 0.022962(f) + 0.000181(v) + 0.002042(d))^{-2} \quad (2)$$

Where R_a = Surface roughness, f = feed rate, v = cutting speed and d = depth of cut.

Figures 5 and 6 represent series plots for surface roughness of nose radius 1.0 mm and 1.5mm.

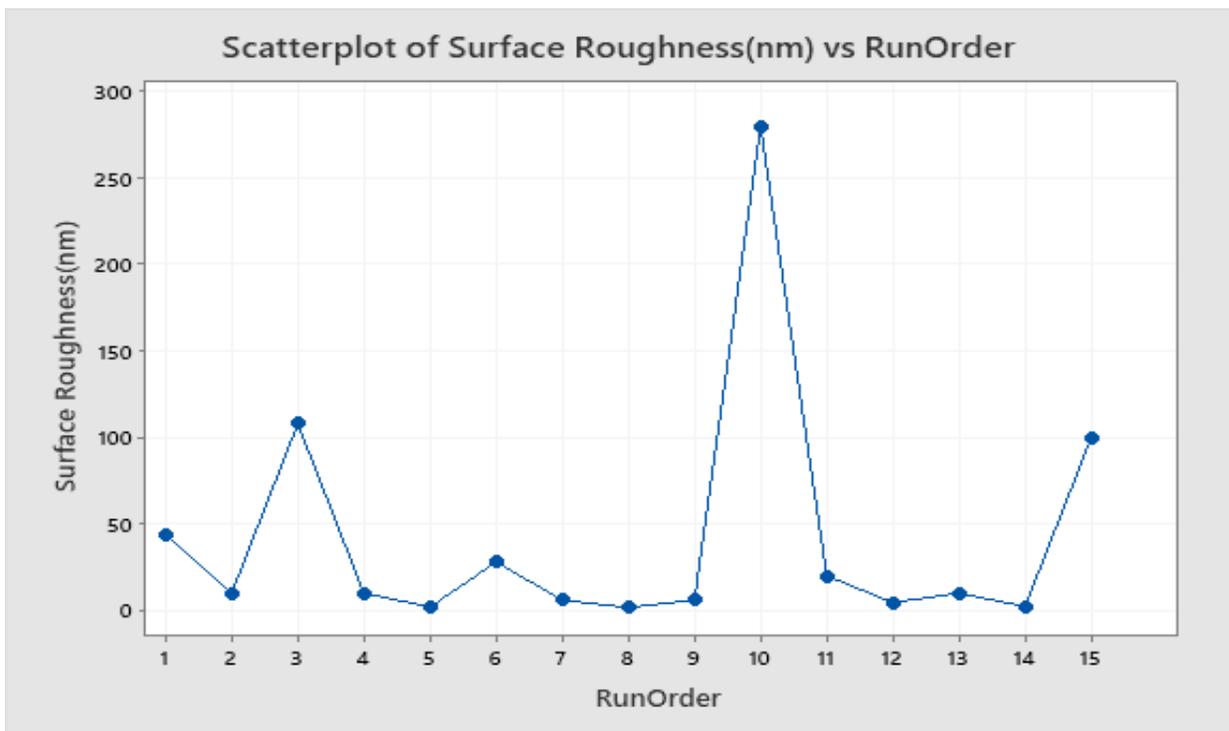


Figure 5: Series plot of surface roughness for nose radius 1.0 mm

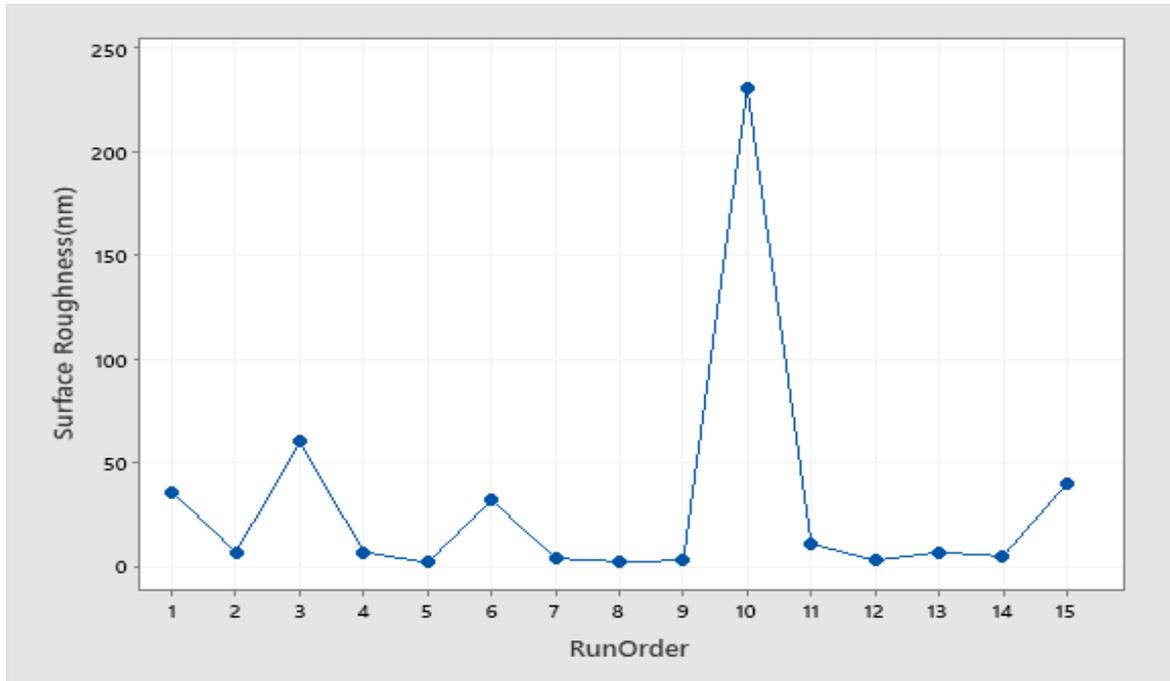


Figure 6: Series plot of surface roughness for nose radius 1.5 mm

Also, the summary of regression coefficient using both tools is displayed in Table 3 to demonstrate the significance of the models using a desirable high R-squared (R^2) value that is close to 1. This simply confides that 96.08% and 89.65% of the total variations using a nose radius of 1 mm and 1.5 mm respectively support the claim that the data fit well at a confidence level of 95%. Further investigation is conducted using the mean absolute error (MAE) to validate the accuracy of both models for the provided dataset.

$$MAE = \frac{1}{n} \sum_{i=1}^n |R_{a,i} - R_{a,i}^P| \quad (3)$$

Where n = total number of measurements, i = estimated measurement for a specific run, $R_{a,i}$ = the measured surface roughness for a specific run, $R_{a,i}^P$ = the predicted surface roughness for a specific run.

Table 4 displays the comparison of some data sets of the experimentally measured surface roughness with the corresponding predicted values of the regression models. MAE value was measured as 10.4 and 5.66 for experiment 1 and experiment 2 respectively.

Table 3: Summary of regression coefficient (R^2)

	Experiment 1 Values	Experiment 2 Values
R^2	0.9608	0.8965
Adjusted R^2	0.9391	0.8682
Predicted R^2	0.8197	0.7785
Adeq Precision	22.8451	18.5598

Table 4: Comparison of experiment and RSM predicted surface roughness

Experimental Run Order	Experiment 1 (Nose radius of 1.5 mm)		Experiment 2 (Nose radius of 1 mm)	
	Experimental Ra (nm)	RSM Predicted Ra (nm)	Experimental Ra (nm)	RSM Predicted Ra (nm)
11	20	17.94	11	10.4

12	4.6	8.5	3	5.3
13	10	9.01	7	7.2
14	23	2.19	5	3.2
15	100	55.4	40	16.6
MAE		10.4		5.66

Conclusion

The influence of nose radius on the surface roughness of diamond turned germanium was studied in this paper. Two different nose radii of 1.0 mm and 1.5 mm were considered in the tool geometry parameters. Box-Behnken design was selected as the response surface method for this study. Feed, speed, and depth of cut were selected as the cutting variables. It was noticed that the feed rates exert dominant influence in the experimental analysis. From the surface roughness results, it can be concluded that using a nose radius of 1.5 mm leads to better surface finish than a 1.0 mm nose radius in diamond turning of germanium. Also, from the accuracy validation, the surface roughness with a 1.5 mm nose radius has better accuracy when compared with a 1.0 mm nose radius.

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Conflict: No conflict

Authors contributions: Adeleke Adeniyi and Abou-El-Hosseini conceived of the presented idea. Adeleke Adeniyi developed the theory and performed the

experiment. Odedeyi Peter and Adeleke Adeniyi carried out the data analysis and verified the analytical methods. Odedeyi Peter, and Abou-El-Hosseini investigated optimization modelling and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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