Investigation of Surface Roughness of Single Point Diamond Turned Germanium Substrate by Coherence Correlation Interferometry and Image Processing

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Abstract. Germanium is a widely used material in the infrared range. Single crystal germanium is used as semiconductor and optical material due to its salient features like high refractive index and proper working in cryogenic conditions. Thus, germanium is an important substrate for infrared lenses having many applications in thermal imaging cameras, optical telescopes and miniaturization of infrared optical elements. These applications require optical elements of excellent surface quality and high dimensional accuracy. In addition to fulfill the demands, ultraprecision machine is used to fabricate the optical components. In this work, single crystal germanium (111) mirror is fabricated by using single point diamond tool with negative rake angle. A large number of experiments are performed to achieve the surface finish of nanometric range. The best and worst combinations of process parameters are found on the basis of surface roughness with the help of coherence correlation interferometry (CCI) measurement and image processing using Canny, Prewitt, Roberts and Sobel edge filters and histogram. These results can be used for fabrication of diffractive optical elements and aspheric lenses of germanium.

Keywords: Single Crystal Germanium, Coherence Correlation Interferometry (CCI), Image Processing, Single Point Diamond Turning (SPDT)

1. Introduction

In the present scenario, the whole world is moving towards quality products with high accuracies. The manufacturing industries of optical components are facing many challenges in producing excellent surface quality products with tight tolerances and accuracies. The finishing methods of excellent accuracy products are concerned in the terms of manufacturing time, labour accuracy, cost of production etc. This level of finish and accuracy cannot be achieved by conventional manufacturing methods.

The precise dimensional accuracy and good surface quality are the main objectives of many engineering applications. So, non-traditional machining processes are carried out to fulfil the demands. In optical devices and systems, high surface quality with nanometric range is necessary as the optical components with a smoother surface reduce the scattering of light and provide better optical efficiency and performance. The performance of the component in the system depends upon the surface texture.

In past few years, various unconventional processes are developed to fabricate high quality product
with low cost and excellent surface topology. The single point diamond turning (SPDT) is a machining process of high accuracy and provides nanometric finish of many materials like silicon [1], germanium [2-5], aluminium etc. Germanium is a vital material for IR optics, having numerous applications in military, security, thermal imaging cameras, medical instruments, surveillance, power line maintenance and so on [6-7]. Jiwang Yan et al. [4] fabricated Ge Fresnel lens having a surface finish of 20–50nm and error of 0.5μm measured by SEM and non-contact 3D profilometer. Prasad Pawase et al. [5] made spherical germanium lens through SPDT, and analysed the effect of parameters on the surface quality by using a white light interferometer. S. Kurada and C. Bradley [8] inspected the tool life and tool wear as well as surface texture by using image processing techniques on CCD images. M. A. Younis [9] proposed a new non-contact method based on computer vision system to measure the surface finish. Ali Akbar Akbari et al. [10] used image processing as well as artificial neural network techniques for examination of surface finish with the help of gray level images of machined surface. S. Dutta et al. [11] observed the surface quality and tool conditions by non-contact image processing method. Gray level co-occurrence matrix technique [12] applied to describe the surface texture with the help of CCD images. Neha Khatri et al. [13] improved the surface quality of single point diamond turned component by magnetic rheological finishing (MRF) method and the roughness value was analysed by using image processing of SEM images of the machined surface. Yakup Yildiz et al. [14] analysed the recast layer and surface roughness and correlation was carried out with the help of image processing of Leica DM optical microscope images in electrical discharge machining (EDM). Ravi Ranjan et al. [15] identified the surface defects on Friction Stir Welding (FSW) by using image processing technique.

A large number of researchers have used the image processing method to analyse and correlate the machine tool conditioning, tool wear and process parameters. But very few researchers have explored image processing technique in the domain of surface roughness and surface topology. Therefore, this discipline is still unexplored. In this work, image processing is used to analyse the best and worst combination of process variables for surface finish with the help of CCI images. The morphology and topology of germanium component are measured by CCI. The results of CCI images are validated using histograms and edge filters such as Canny, Roberts, Sobel and Prewitt.

2. Experimental Setup

Single crystal germanium having crystal orientation (111) has been machined using Nanoform250 (Taylor–Hobson make) SPDT in wet condition as shown in figure1. The specification of single point diamond tool and design of evaluation (DOE) are shown in Table 1 and Table 2. The sets of experiments are designed using spindle speed, tool feed rate, depth of cut and tool overhang as input variables. Central composite design (CCD) method is used for generating DOE and 31 sets of experiments are practiced for fabricating the germanium mirror using SPDT.
### Table 1. Tool Specifications for Germanium Substrate

| S. No. | Tool Material | Tool Specifications |
|--------|---------------|---------------------|
| 1      |               | Diamond             |
| 2      | Tool Nose Radius | 1.5mm               |
| 3      | Rake Angle     | -25°                |
| 4      | Relief Angle   | 10°                 |

### Table 2. Design of Experiments for Machining of Germanium Substrate

| S. No. | Spindle Speed (rpm) | Tool Feed Rate (µm/rev.) | Depth of Cut (µm) | Tool Overhang (mm) |
|--------|---------------------|--------------------------|-------------------|--------------------|
| 1      | 1000                | 1                        | 0.5               | 14                 |
| 2      | 2000                | 1                        | 0.5               | 14                 |
| 3      | 1000                | 6                        | 0.5               | 14                 |
| 4      | 2000                | 6                        | 0.5               | 14                 |
| 5      | 1000                | 1                        | 1.5               | 14                 |
| 6      | 2000                | 1                        | 1.5               | 14                 |
| 7      | 1000                | 6                        | 1.5               | 14                 |
| 8      | 2000                | 6                        | 1.5               | 14                 |
| 9      | 1000                | 1                        | 0.5               | 20                 |
| 10     | 2000                | 1                        | 0.5               | 20                 |
| 11     | 1000                | 6                        | 0.5               | 20                 |
| 12     | 2000                | 6                        | 0.5               | 20                 |
| 13     | 1000                | 1                        | 1.5               | 20                 |
| 14     | 2000                | 1                        | 1.5               | 20                 |
| 15     | 1000                | 6                        | 1.5               | 20                 |
| 16     | 2000                | 6                        | 1.5               | 20                 |
| 17     | 800                 | 3.5                      | 1                 | 17                 |
| 18     | 2200                | 3.5                      | 1                 | 17                 |
| 19     | 1500                | 0.5                      | 1                 | 17                 |
| 20     | 1500                | 6.5                      | 1                 | 17                 |
| 21     | 1500                | 3.5                      | 0.25              | 17                 |
| 22     | 1500                | 3.5                      | 1.75              | 17                 |
| 23     | 1500                | 3.5                      | 1                 | 12                 |
| 24     | 1500                | 3.5                      | 1                 | 22                 |
| 25     | 1500                | 3.5                      | 1                 | 17                 |
| 26     | 1500                | 3.5                      | 1                 | 17                 |
| 27     | 1500                | 3.5                      | 1                 | 17                 |
| 28     | 1500                | 3.5                      | 1                 | 17                 |
| 29     | 1500                | 3.5                      | 1                 | 17                 |
| 30     | 1500                | 3.5                      | 1                 | 17                 |
| 31     | 1500                | 3.5                      | 1                 | 17                 |
The surface smoothness is measured after practicing the experiments using CCI. Two sets of machining parameters (set 6 and set 9 shown in table 2) are performed which provides the maximum and minimum surface quality. Figure 2 shows the germanium component with maximum surface finish (5nm) achieved by performing set no 6 shown in table 2.

![Figure 2 Germanium Mirror with 5nm Surface Finish](image)

3. Results and Discussion

3.1 Evaluation of Surface Morphology using CCI

Roughness is a very crucial attribute which influences the functioning of the component and systems. It plays a vital role in examining how the object behaves in its actual conditions, the high rough surface becomes easy and more wear out. In this section, the surface morphology is measured with the help of the non-contact CCI (Taylor Hobson). Only two combinations of process parameters, which provided the maximum and minimum surface finish, are studied with the help of CCI images. These images depict the quantitative value of the surface roughness. The best surface finish of 5 nm is obtained when set number 6 (shown in table 2) is performed, similarly when set number 9 (shown in table 2) is practiced; surface finish of 31nm is achieved. The CCI images of these two sets are depicted in figure 3(a) and 3(b) respectively and the corresponding roughness versus distance diagram is also shown in figure 4(a) and 4(b). With the help of varying scale of CCI images, it can be proved that figure 3(a) and 4(a) show the best surface and figure 3(b) and 4(b) the worst surface.

![Figure 3(a) and (b) CCI 2D Image of Best and Worst combination](image)
3.2 Evaluation of Surface Morphology using Image Processing Technique

Image processing is a unique technique to enhance and modify an image in order to extract meaningful information by performing some enhancement operations. It is a type of signal processing in which input is an image and output may be image or characteristics/features associated with that image. An image is a two dimensional signal which is defined by the mathematical function $f(x,y)$ where $x$ and $y$ are the two co-ordinates horizontally and vertically. The value of $f(x,y)$ at any point gives the pixel value at that point of an image.

3.2.1 Edge Filters

Edge filters are used to identify points in a digital image at which the image brightness changes sharply or has discontinuities. This feature is used to determine the quality of the finished surface. Lesser the discontinuities, better is the surface finish and vice versa.

In this work, the CCI images are validated using image processing with different edge filters through MATLAB software. Canny, Roberts, Sobel and Prewitt edge filters are practised to analyse the surface roughness of the SPDT machined images. Figure 5 represents the images of machined surface after image processing. Row 1, Row 2, Row 3, Row 4 and Row 5 show the results of the Gray scale, Canny edge filter, Prewitt edge filter, Roberts filter and Sobel filter respectively. From the results, it is observed that the images of the column 1 are more homogeneous and having less irregularities than the
column 2. After visualising the images, it can be analysed that column 1 shows the images of the best surface finish and column 2 shows the worst surface finish.

![Image showing various filters used in image processing]

**Figure 5.** Various Filters Used in Image Processing

### 3.2.2 Histogram

Histogram is an analytical and statistical technique of image processing, in which image is analysed by variation of pixels values. Histogram of less width and small pixels variations depicts the smoother and better surface quality. On other hand, histogram having large width & broad pixel variations shows the worst quality of surface smoothness. In this section, histogram is plotted with the help of CCI images as shown in figure 6 (a) and 6 (b). The histograms are plotted by keeping frequency in Y-axis and pixels in X-axis. Figure 6(a) is less broad and pixel values are varying from 150 to 225 and frequency is 0 to 3000. In figure 6(b), the pixel distribution is wider (100-225) than previous one. Hence figure 6(a) shows the best surface quality and figure 6(b) the worst surface quality.
4. Conclusion

A germanium mirror is fabricated by performing sets of experiments on single point diamond turning machine and surface roughness is measured with the help of coherence correlation interferometry (CCI) to investigate the best and worst combination of process parameters. Results obtained from CCI are validated using image processing techniques with different edge filters and histogram. The analysis suggests that both results are in correlation with each other. The conclusion of this study is come out in terms of following points- The combination of machining parameters for achieving the best surface finish is obtained from CCI as well as image processing, which can be used in fabrication of germanium optical components. CCI images only give the value of surface parameters, while image processing can be provide the information of surface topology in terms of pixels and quality of images. Hence, it can be used as alternative method for analysing the surface.

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References

[1] Jasinevicius R G, Duduch J GandPizani P S 2007 Semiconductor Science and Technology 22 561
[2] Yan J, Maekawa K, Tamaki J I and Kubo A 2004 JSME International Journal SeriesC 47 29-36
[3] Ohta T, Yan J, Yajima S, Takahashi Y, Horikawa N and Kuriyagawa T 2007 International Journal of Surface Science and Engineering 1374-392
[4] Yan Jiwang, Maekawa Kouki, Tamaki Junichi and Kuriyagawa Tsunemoto 2005 Journal of Micromechanics and Micro engineering 15 1925-1931 (in Japan)
[5] Pawase P, Brahmanark P K, Pawade R S, and Balasubrmanium R 2014 International Conference on Advances in Manufacturing and Materials Engineering 5 2363-2368
[6] Teegarden B J 1999 Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 422 551-561
[7] Chang R S, Chern T C, Lin C S and Lay Y L 1994 Optics and lasers in engineering 21 257-272
[8] Kurada S and Bradley C 1997 Computers in Industry 34 55-72 (in Canada)
[9] Younis M A 1998 3rd International Conference on Computers and Industrial Engineering 35 49-52
[10] Akbari A A, Fard A M, and Chegini A. G 2006 World Automation Congress IEEE 1-6 (in Hungary)
[11] Dutta S, Dutta A, Chakladar N Das, Pal SK., Mukhopadhyay S, and Sen R 2012 Precision Engineering 36 458-466 (in India)
[12] Tuceryan M. and Jain A.K., 1998 The handbook of Pattern Recognition and Computer Vision, by CH Chen, L F Pau, PSP Wang (ed) Word Scientific Publishing Co
[13] Khatri N, Tewary S, Mishra V and Sarepaka RV 2014 Journal of Intelligent Material Systems and Structure 25 1631-1643
[14] Yildiz Y, Sundaram M M, Rajurkar K P, and Altintas A 2015 Proceedings of the Institution of Mechanical Engineer, Part E: Journal of Process Mechanical Engineering 0954408915600949 1-11
[15] Ranjan R, Khan A R, Parikh C, Jain R, Mahto R P Pal S, Pal S K and Chakravarty D 2016 Journal of Manufacturing Processes 22 237-253