# Study of Machining Parameters of Focused Ion Beam in Fabrication of Texture on Single Crystal Diamond Tool

**Ganesan G[a], M V V S Aditya[a], Akhilesh Gupta[b], Sonal[c], Rakesh G Mote[a], R. Balasubramaniam[d] and A.S. Rao[b]**

[a] Department of Mechanical engineering, Indian Institute of Technology, Bombay, 400076.
[b]Department of Mechanical engineering, Veermata Jijabai Technological Institute, Matunga, Mumbai, Maharashtra, 400031.
[c]National Centre for Aerospace Innovation and Research, Indian Institute of Technology, Bombay, 400076.
[d]Bhabha Atomic Research Centre, Trombay, Mumbai, Maharashtra 400085

**Abstract**

Single crystal diamond (SCD) is the preferred tool material for ultra-precision machining for cutting operation at nanometric level. Due to the well-known and exceptional difficulty in shaping, the fabrication of diamond-cutting tool requires special processing methods. If there is any damage (wear, chipping) on the tool, it is directly reflected on workpiece surfaces. Patterning and sharpening have been done on diamond tools with a nano level, which can be used for some special applications like micro-lens arrays, sinusoidal grid, Fresnel lenses and pyramids array. The limitation of conventional techniques like polishing and lapping can produce up to the scale of tens of microns. Focused ion beam (FIB) technique is a well-established technique for machining materials at micro and nanoscale. Our point of focus is on the fabrication of texture on the diamond tool using focused ion beam (FIB) milling technology. Effect of parameters as beam current, milling time, surface conductivity is studied and optimized.

**Keywords:** Single crystal diamond tool (SCD), Scanning electron microscope (SEM), Focused Ion Beams (FIB), Nanofabrication.

## 1. INTRODUCTION

Single crystal diamond tools are widely used for ultra-precision mechanical machining because of their superior wear resistance, sharp cutting edge, low affinity and other desired properties. Single crystal diamond tool is used for fabrication of parts such as molds, optical lenses and biomedical implants in various industries [1, 2]. Diamond is one of the hardest known materials but it still experiences wears after working on hard materials like Silicon and Germanium, which reduces the machining quality like surface finish and dimensional accuracy. Therefore, improving the performance and efficiency of the diamond tool is still an industrial concern.

Adding textures on tool surface improves the tribological characteristics between surfaces [3]. Applying a microscale or nanoscale texture to a surface has been shown to reduce the surface friction by modifying the hydrodynamic pressure, increasing the effectiveness of a lubricant and the other factors. These techniques are effective in improving surface characteristics such as friction and are applied to the sliding surface[4-5].The texture fabrication method using the femtosecond laser was proposed in the past studies [6] but has less lateral resolution than the machining size for the diamond tool, which affects the shape of cutting edge. Therefore, a more effective method is required to fabricate texture on the surface of a diamond tool. Fabrication of nanotexture with the heat treatment process is studied but optimum machining parameters were not proposed for FIB [7].The focused ion beam (FIB) direct milling method is an effective method for fabricating various microscale and nanoscale shapes and optimization of the process parameter is required.

In this paper, the study of various parameters for micro and nanotexture formation by using FIB milling on single crystal diamond tool is carried out. This is followed by results, discussion and conclusions.

## 2. METHODOLOGY

### 2.1 Method and Steps to Fabricate Texture on Tool

1. A bitmap image is generated by assigning a suitable dimension to each pixel.
2. For instance, in an image 50nm was considered as one pixel. If the width of a channel to be made in 2 µm, then 40 pixels should be allotted in the bitmap image to attain a channel of width 2 µm.
3. The bitmap image is overlapped virtually on the surface of the specimen that directs the gallium ion beam to mill the darkened region of the image.

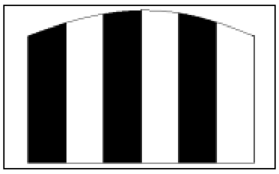


Fig 1: Bitmap image of pattern

### 2.2 Experimental Setup Details

*2.2.1 Workpiece material*

A diamond-cutting tool of type IIb with a rounded corner radius of 1.5 mm was used for the texture fabrication. The rake and clearance angles were 0º and 10º respectively.

*2.2.2 Machine specification*

For FIB irradiation, a Zeiss FIB facility with a gallium liquid metal ion source was used (Carl Zeiss Auriga 45-58 dual beam FIB-SEM).The shape of the texture was measured by the same SEM.



ISBN: 978-93-80689-28-9

*2.2.3 Carbon Coating*

Since SCD is non-conducting material, majority of FIB milling (except some initial trials) were performed after coating the SCD with a conductive material. The conductive coating used in this work was carbon sputter coating. Carbon coating of 8 nm thickness was done on SCD tool using sputter coating machine Polaron E5150.

*2.2.4 Parameter Selection*

FIB texturing was performed for two parameters i.e. mill for time and mill for depth at different current and time.

## 3. EXPERIMENT

### 3.1 FIB Patterns on Mono-crystalline Diamond tool

Total 12 square patterns were made on SCD rake face without conductive coating (ref fig.2) and the details of texture are given in table 1. Patterns 1-5 were milled at different currents maintaining 2 minutes as milling time. Patterns 6 to 12 were milled by fixing the different time of milling; 5 minutes for $6^{th}$, $8^{th}$ & $9^{th}$ pattern and 10 minutes for the $7^{th}$ pattern. Patterns 10 to 12 were milled by fixing depth of 4um.

**Table 1: Applied current with milling time**

| Sr. No. | Current | Time |
|---|---|---|
| 1 | 1nA | 2 min |
| 2 | 1nA | 2min |
| 3 | 2nA | 2min |
| 4 | 5nA | 2min |
| 5 | 500pA | 2min |
| 6 | 500pA | 5min |
| 7 | 500pA | 10min |
| 8 | 1nA | 5min |
| 9 | 200pA | 5min |
| 10 | 200pA | 483sec |
| 11 | 500pA | 194sec |
| 12 | 1nA | 97sec |

### 3.2 Patterning on rake face of SCD tool with coating

Square patterns were made on rake face of SCD tool with conductive carbon coating of 8 nm thickness. Details of the probe currents applied for making square-shaped patterns are given in table 2. Squares 1 to 6 were milled for depth by fixing depth at 5µm and squares 7-12 were milled for time i.e. fixing the time of milling at 2 minutes.

**Table 2: Current intensity for square patterns**

| Sr. No. | Current | Sr. No. | Current | Sr. No. | Current |
|---|---|---|---|---|---|
| 1 | 5nA | 5 | 50pA | 9 | 500pA |
| 2 | 500pA | 6 | 2nA | 10 | 200pA |
| 3 | 200pA | 7 | 5nA | 11 | 100pA |
| 4 | 100pA | 8 | 1nA | 12 | 50pA |

### 2.3. Pattern with varying ion beam current

Rectangular shaped bars enclosed under a curvature were milled on the SCD tool with a carbon coating of 8 nm thickness considering the parameters given below,

1. 200pA current.
2. 500pA current.
3. 1nA current.

These three patterns thus obtained can be seen from the figures 4, 5 and 6. At each current, depths and time of milling was varied. The parameters of time and depth of milling at 200pA, 500 pA and 1 nA currents are listed in the tables 3, 4 & 5 respectively.

**Table 3: Milling at 200 pA**

| Sr. No. | Depth | Time |
|---|---|---|
| 1 | 40 nm | 13.5 sec |
| 2 | 0.35 µm | 120 sec |
| 3 | 0.89 µm | 300 sec |

**Table 4: Milling at 500 pA**

| Sr. No. | Depth | Time |
|---|---|---|
| 1 | 40 nm | 6 sec |
| 2 | 70nm | 120 sec |
| 3 | 1.7 µm | 300 sec |
| 4 | 3.5 µm | 600 sec |

**Table 5: Milling at 1 nA**

| Sr. No. | Depth | Time |
|---|---|---|
| 1 | 40 nm | 6 sec |
| 2 | 0.929µm | 120 sec |
| 3 | 2.3µm | 300 sec |
| 4 | 4.6 µm | 600 sec |

### 3.4 Pattern with varying time*:*

Milling was done on SCD tool at 500-pA current for 2, 5, 10 and 15 minutes as shown in figure 8.

## 4. RESULTS AND DISCUSSION

### 4.1 Effect of carbon coating

*4.1.1 SCD Tool without Carbon Coating:*

Ion beam parameters for different patterns obtained on the mono-crystalline diamond tool with the conductive coating are given in table 1 and the patterned surface is shown in figure 2. For the uncoated tools, the ion beam was found to be drifting on the single crystal diamond tool.

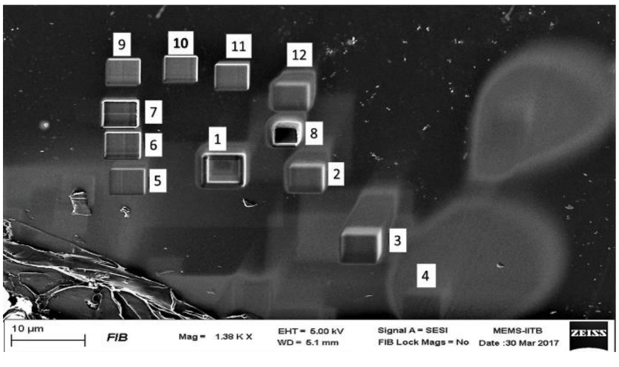



Fig 2: Square patterns milled on uncoated SCD tool.



ISBN: 978-93-80689-28-9

Since the diamond is a dielectric material, an additional electric field will be generated when it is bombarded by the charged particle such as Ga+. Consequently, the incident ion beam will be deflected before it reaches the diamond surface, which greatly deteriorates the milled surface. From the patterns 2, 3 and 4 of figure 2, we found that the deflection is more when there is an increase in the ion beam current and the patterns do not occur at the desired location and at desired dimensions.

*4.1.2 SCD tool with carbon coating:*

Due to coating, deviation of ion beam was minimized as the coated surface was conductive which attained negative charge and attracted positive gallium ions. However, further optimization in current and time to obtain desired depth of texture is required. The square patterns that were milled on the coated diamond tool surface are shown in figure 3. At higher currents, increase in the beam width has caused an increase in milled area.

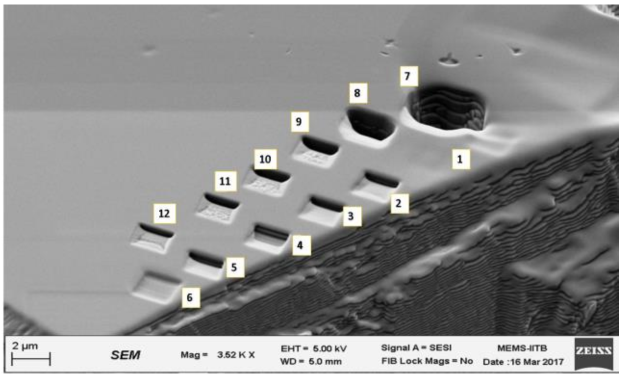



Fig 3: Square patterns milled on SCD tool with coating with varied parameters

**4.2 Effect of ion beam current with milling time:**

Milling was performed at currents of 200 pA, 500 pA and 1 nA. At each current, the time of milling was varied and its effects were studied as given in figure 4, 5 and 6. In each of these figures, the leftmost pattern is for the lowest milling time and the right extreme is for the maximum milling time. It is seen that as the milling current increases for a given milling time, the amount of material removed increases; however, it also leads to a reduction in spatial resolution of the pattern (ref fig 5 and 6)

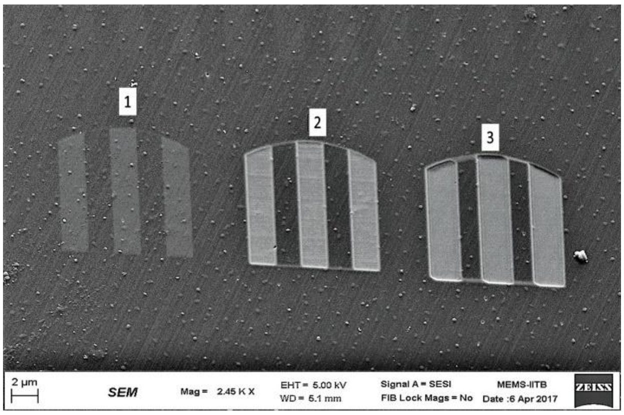



Fig 4: Patterns made with varying depth and time at 200pA current

The most desired pattern was obtained for 200pA and 120 sec (ref fig 4).

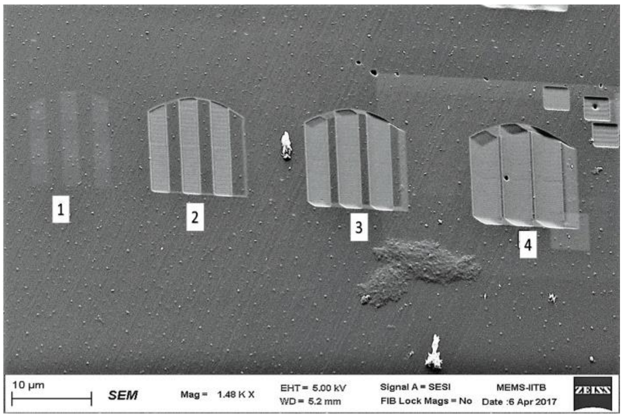



Fig 5: Patterns made with varying depth and time at 500 pA Current

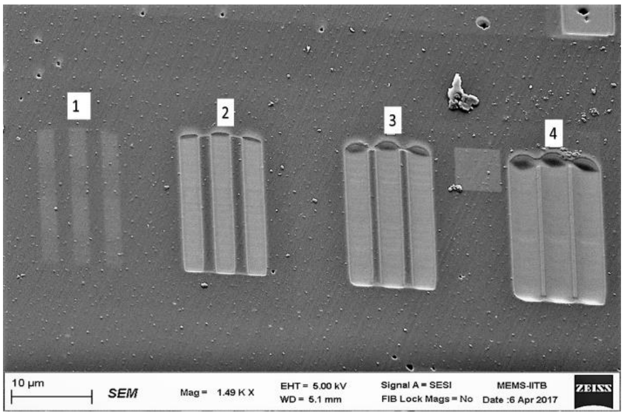



Fig 6: Patterns made with varying depth and time at 1nA current

In figure 5, four patterns milled at 6 seconds, 120 seconds, 300 seconds and 600 seconds (indexed as 1, 2, 3 & 4 respectively) are shown. At 600 seconds of milling time, a huge area is milled which lead to overlapping of consecutive milled channels. Extra milling is also observed at 300 seconds of milling time. Desired pattern is obtained at 120 seconds of milling time and the almost negligible pattern is observed at milling time of 6 seconds.

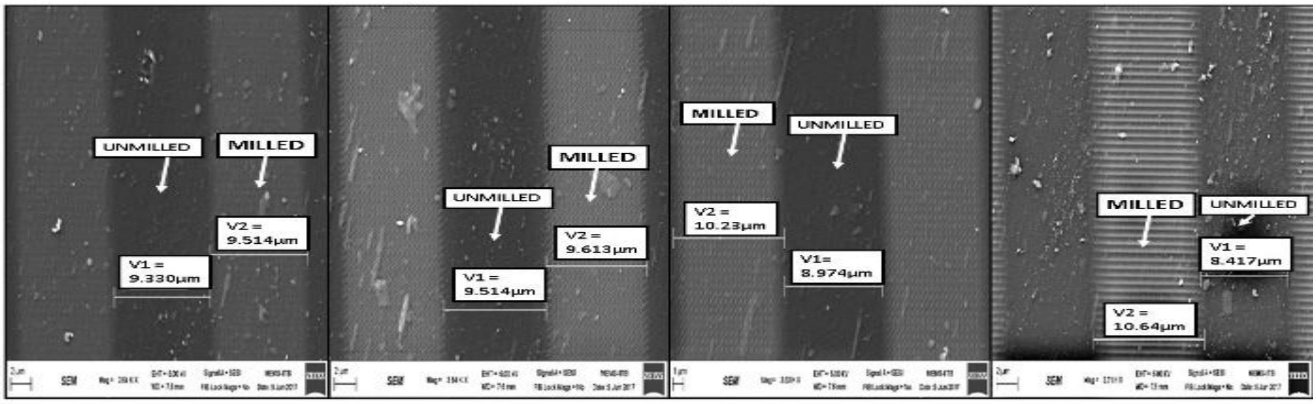
**4.3 Effect of milling time**

FIB milling was done on a SCD tool by using the bitmap image shown in figure 7. Milling was done at 500 pA currents with variations in milling time for 2, 5, 10 and 15 minutes. The width of each channel is designed to be 10 µm. The patterns obtained are shown in figure 8.

Fig 7: Bitmap image used for milling



ISBN: 978-93-80689-28-9




(a) 2 min (b) 5 min (c) 10 min (d) 15 min

Fig. 8 Milling at constant current for different time.

As seen from the fig.8, the original dimensions of the milled channel width are varying with current and time of milling. The width of the channels of milling obtained at 500-pA current and varying time is listed in table 6. From data in table 6, it can be said that milled width increases with time. At 10 min optimum pattern was observed.

**Table 6: Milling at constant current for different time**

| Sr. No. | Time | Milled width | Unmilled width |
|---|---|---|---|
| 1 | 2 min | 9.514µm | 9.330 µm |
| 2 | 5 min | 9.613µm | 9.514µm |
| 3 | 10 min | 10.23µm | 8.974µm |
| 4 | 15 min | 10.64µm | 8.417µm |

## 4. CONCLUSION

The fabrication of nano and microtexture on single crystal diamond tool were studied and found that,

1. FIB milling without coating is not effective due to drifting of ions at high current. At higher currents, drifting is large when compared to low current values.

2. For bitmap image of certain dimensions, a pattern with original dimensions and considerable depth were obtained at 200 pA current milled for 120 seconds (ref fig.4) which is an optimum texture obtained compared to the ones obtained at 500pA and 1000pA currents.

3 .For textures consisting larger surface area, optimum patterns were obtained at milling parameters of 500-pA current, 10 minutes of milling time as compared to 2, 5 and 15 min.

4. For a given beam current, the width of the milled channel initially increases rapidly with increase in milling time; however later asymptotically saturates with increasing milling time.

## 5. ACKNOWLEDGMENT

The authors gratefully acknowledge the support provided for this work by National Centre for Aerospace Innovation and Research, a Department of Science and Technology – Government of India, The Boeing Company and IIT Bombay collaboration and BRNS, Department of Atomic Energy (DAE), India via project no.34/14/06/2015/BRNS.

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ISBN: 978-93-80689-28-9