Femtosecond Laser Structuring of Diamond Tool Tips for Microoptics Fabrication

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Abstract

Within this work we investigate ultra precision fs-laser processing of mono- and polycrystal diamond to modify diamond tool tips for ultra precision turning, grinding and milling. As long as these tools are generated by commonly used precision grinding techniques the shapes of the tool tips are limited to very simple geometries, e.g. planes, cylinders and spheres. Furthermore thermal stress and process induced forces limit the achievable structures to the size of some ten to hundred microns in diameter and small aspect ratios. Processing with the use of fs-laser pulses thermal induced stress and process forces are negligible so that the structure size is only limited by the laser focus diameter and the precision of the positioning system. It is possible to generate almost every geometrical tip shape by direct laser writing into the diamond, independent of its crystal orientation.

1 Introduction

Due to its excellent mechanical and thermal properties, like high thermal conductivity, hardness and high wear resistance, diamond is commonly used as material for tools for ultra precision turning, milling an grinding [1]. Because of its crystal orientation dependent hardness, polishing diamond, especially in the (100) direction, is very time and material consuming. By using common abrasive techniques, only a small variety of tool tips with (a)spherical, saw tooth like and straight shapes can be produced. Femtosecond laser structuring allows cutting almost every arbitrary shape into the diamond independent of its crystall orientation.

1 Experimental setup

The cutting experiments were carried out with amplified femtosecond Ti:Sa Lasers, Tsunami from Spectra-Physics and Mira from Coherent, respectively, with pulse durations of 150 to 250 fs within a pulse energy range of 40 nJ to 10 µJ at a center wavelength of about 800 nm. The repetition rate is 1 kHz for the Spectra-Physics system and 100 kHz for the Coherent system, respectively. Without any additional beam shaping element in the lasers pathway the beam is focussed directly onto the sample by a NA 0.25 microscope objectives. Using this technique, focus diameters of about 2 µm can be achieved. The sample is mounted on an Aerotech ABL1500/1000 positioning system composed of three perpendicular axes x,y and z. With an additional ABRS150 (Aerotech) rotary stage it is also possible to rotate the sample 360 degrees continuously. Sample materials are natural single crystal diamond (Contour) and artificial polycrystalline CVD diamond (Diamond Materials). Experimental results obtained by using SEM, AFM and white light interferometry.

2 Results and discussion

2.1 Cutting, beam entry and exit

Directing the focussed laser beam in straight and curved meander-like lines over the sample while varying the z-position line by line (see Figure 2) quasi arbitrary structures and cutting edge shapes can be generated. For simplicity in the first experiments the laser focus was moved in straight lines to produce plane cuts (Figure. 1).

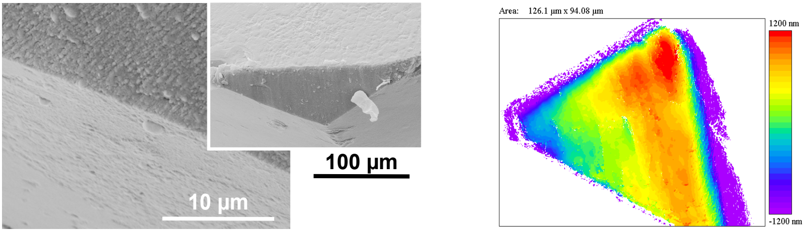

Figure 1: Left: beam exit (edge radius of about 400 nm). Inset: diamond tool – whole cut. Right: shape and roughness analysis of cutting area by white light interferometry (area is depicted upside down).

Using a fluence of 1.57 J/cm^2 (single pulse threshold fluence $F_{th}(1)$ for diamond is around 1.5 J/cm^2 [2]) within the laser focus and a writing speed of 80 µm/s roughness as low as 30 nm rms can be obtained. Both an increase in cutting speed and even more in laser fluence leads to an increase in surface roughness.

Usually the surfaces generated parallel to the laser beam show ripples in the nm-regime (Figure 1). They have a lateral period of 400 nm which is exactly half the laser wavelength. These ripples always appear with constant size and period perpendicular to the polarization of the laser light which implies that these ripples are formed due a correlated interaction between the material itself and the linear polarized photons by superposition of the incident and reflected beam. Reducing the pulse energy to the ablation threshold, no ripples are visible and a surface roughness of 30 nm can be achieved (Figure 2). Slight distortions in the flatness of the laser generated planes are due to imperfection in the tuning and therefore yawing of about 1 µm of the positioning stage (Figure. 1). Significant is the difference between the edges of the beam entry and exit. While the edge of the beam entry is radiused to 9 µm (not shown), the edge at the beam exit is very sharp with a radius of 400 nm (Figure 1).

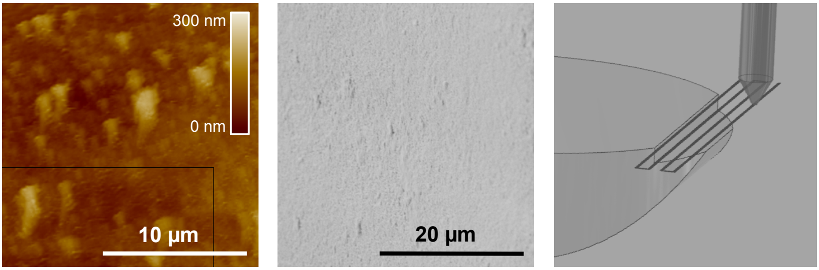

Figure 2: Roughness analysis. Left: AFM image of a laser-generated surface with 30 nm rms. Center: Large area SEM image of the 60° tilted diamond surface containing the area of the AFM-image. Right: schematic depiction of the laser pathway along the sample.

2.2 Tool tips

With femtosecond laser cutting generation of stress-free cutting edges in diamond independent of the crystal orientation is possible. Therefore high aspect ratio tool tips are achievable. Figure 3 depicts two prototype tool tips (left and right) and one modification of a tool tip surface (center). The lateral aspect ratio of the needle-like structure in the left image is greater than 1:10 and the needle has a depth of 100 µm. The picture in the center shows a chip guiding structure in the diamond surface. Size, depth and distance between the single structures can be adjusted arbitrarily for individual chip guiding. The right image depicts a prototype of the edge of a milling tool tip with 25 µm deep saw teeth arranged in a straight line. The saw tooth structure can also be produced on a circle for structuring a cylindrical milling tools.

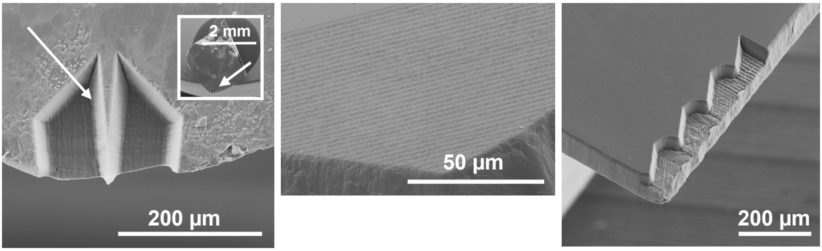

Figure 3: Left: prototype of 100 µm high needle-like tip (see arrow) in a discharged natural single crystal diamond, aspect ratio < 1:10, the inset shows the whole diamond tool. Center: chip guiding structure in with nano-ripples in polycrystalline cvd-diamond surface. Right: prototype of a saw tooth structure (25 µm deep) for diamond micro miller in polycrystalline cvd-diamond.

3 Summary and outlook

We have successfully generated and modified diamond tool tips for cutting, turning an milling applications by using femtosecond laser ablation. The quality of surface and form of the structures is quite good, but not sufficient for direct diamond turning and cutting for optical applications yet. Therefore further investigations have to address an increase of surface contour quality and writing speed as well as to decrease the cutting edge radii.

References:

[1] Workshop "Ultra Precision Manufacturing of Freeforms and Microstructures" Jena, 2008

[2] P. Bartholome, Diploma Thesis 2007, University of Applied Sciences, Jena