LASER GENERATED AND STRUCTURED PROTOTYPES OF DIAMOND TOOL TIPS FOR MICROOPTICS FABRICATION

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INTRODUCTION
Excellent mechanical and thermal properties, such as high thermal conductivity and extreme hardness and therefore high wear resistance, make diamond the number one material for tools for ultra precision turning, milling and grinding applications. However, in the same way these properties also make it hard to generate diamond tools, especially those for turning and milling applications where only single crystal tools can be used. Due to thermal and mechanical stress while machining tool tips with common techniques like grinding or lapping, only tools with dimensions of tens to hundreds of microns and with small aspect ratios can be produced,[1-3]. Furthermore, due to its hardness being dependent on crystal orientation, diamond can only be machined in certain crystal directions, which limits the variety of possible tip shapes to simple geometries, e.g. spheres, planes and cylinders.

Using the fs-laser pulse technique for structuring diamonds can overcome the above mentioned limitations. First, laser processing of diamond is independent of the crystal orientation. Second, within the very short interaction time (fs to ps) between laser and diamond, no significant amount of heat can dissipate from the laser ablation area into the diamond. Therefore thermal as well as mechanical stress within the unaffected areas of the diamond material is almost negligible. As a result, the achievable feature size is only limited by the spot size of the laser focus, which can be in the range of several hundred nanometers up to several microns. Furthermore, the laser focus as a machining tool, in comparison to the commonly used grinding tools, stays in shape at all process times because it depends only on the energy constancy and stability of the beam profile of the laser itself, neither of which are altered due to material tool interaction.

EXPERIMENTAL SETUP
The cutting experiments were carried out with amplified femtosecond Ti:Sa lasers, a Tsunami-Spitfire combination from Spectra-Physics or a Mira-RegA system 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 pulse repetition rate is 1 kHz for the Tsunami-Spitfire and 100 kHz for the Mira-RegA system. Without any additional beam shaping element the femtosecond laser beam is focused directly onto the diamond surface with a NA 0.25 microscope objective. Using this technique, focus diameters of about 4 µm can be achieved.

The samples are mounted onto a high precision 4-axes air bearing positioning system (Aerotech) with a total positioning error below 200 nm for x,y,z-movement at a resolution of 2 nm. The system consists of two perpendicularly stacked axes (ABL1500 and ABL1000) for sample movement in the xy-plane and an additional ABRS150-axis mounted on top for 360 degrees of continuous sample rotation. A mechanically decoupled z-axis (ABL1000) moves the microscope objective perpendicular to the xy-plane for focusing.

Sample materials are artificial polycrystalline CVD diamonds (Diamond Materials) and natural single crystal diamonds (Contour).

Experimental results were obtained by using SEM, AFM and white light interferometry.

RESULTS AND DISCUSSION

Cutting
Quasi arbitrary structures and cutting edges can be generated by directing the focused laser beam with synchronized xyz-movement over the diamond surface. The material is ablated within a volume predetermined by the size of the laser focus size and the ablation depth.
However, deep cuts (accumulated ablation depth of several µm) shade the incident laser beam in the boundary areas at the height of the primary surface, so that a) a significant amount of energy is lost and b) the energy density in the boundary areas may be sufficiently high to ablate material as well, which leads to a decrease of cutting edge sharpness. To minimize shading of the laser beam due to sample surface geometries, like steps or grooves, the laser focus is directed meander-like in an appropriate way, e.g. in straight or curved lines, over the diamond surface ablatting the material line by line with a depth of only about 2 to 100 nm, depending on the laser pulse energy. Afterwards, the laser focus is again positioned at the starting xy-position and the new z-position. The whole process is reiterated to ablate the diamond plane by plane until a desired depth is reached and the designed tool shape is complete.

For simplicity in the first experiments the laser focus is moved in straight lines meander-like over the diamond surface layer by layer to produce plane cuts, shown in FIGURE 1.

![FIGURE 1. Left: Depiction of the meander-like laser focus pathway over the sample surface. The working direction is indicated by the arrow. Right: Resulting simple plane cut in a discharged single crystal diamond tool.](image)

**Surface quality**

Usually the surfaces that are generated parallel to the laser beam show ripples in the nm-regime, shown in FIGURE 4. They have a height of about 120 nm and 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 direction of the laser light, which implies that these ripples are formed due to a correlated interaction between the material itself and the linearly polarized photons by superposition of the incident and reflected beam, [4,5].

Using a fluence of 1.57 J/cm² (single pulse threshold fluence \(F_{th}(1)\) for diamond is around 1.5 J/cm², [6]) within the laser focus and a writing speed of 80 µm/s, a roughness as low as 30 nm rms can be obtained and almost no nano-ripples are visible, FIGURE 2. Both an increase in cutting speed and, even more so, an increase in the laser fluence (energy per area) lead to an increase in surface roughness. Slight distortions in the flatness of the laser generated planes, which can be seen in FIGURE 3, are due to imperfections in the tuning and therefore yawing of the positioning stage.

![FIGURE 2. Left: AFM roughness measurement of a plane cut, roughness of about 30 nm rms can be obtained with appropriate laser and cutting parameters. Right: Large area SEM-image of the cut, containing the area of the AFM-image on the left, the sample tilt is 60°.](image)

**Beam entry and exit**

The difference between the edge radii at the beam entry and exit is distinctive. While the edge of the beam entry is radius to 9 µm, the edge at the beam exit is very sharp with a radius of 400 nm, FIGURE 4. This can be explained by the above mentioned shading, which occurs at cutting depths greater than the rayleigh length of the laser focus. At these depths up to half of the laser energy is absorbed at the sample surface, resulting in a significant decrease in edge quality.

![FIGURE 3. White light measurement of the surface geometry of a laser cut plane. Slight distortions in flatness of the surface are due to yawing of the positioning system.](image)
If the laser focus is moved towards the future edge while cutting, almost no shading effect is visible and the edge radius at the beam entry can be minimized to far below 1 µm as can be seen in FIGURE 6.

**Tool tips**
Using the femtosecond laser technique, generation of stress-free cutting edges in diamond independent of its crystal orientation is possible. Therefore high aspect ratio tool tips in almost any arbitrary shape are achievable.

**Laser generated tool tips**
In FIGURE 5 a top view of the first prototype of a needle-like tool tip machined into a discharged single crystal diamond tool is shown. The needle has a width at the backside of 20 µm and a total length of 200 µm, which leads to a lateral aspect ratio of 1:10 at a structure depth of about 100 µm. No cracks or disruptions are visible in the walls of the laser generated structure, which indicates that very little thermal or mechanical stress is applied due to the laser ablation process.

In addition, in some turning experiments where similar produced “tools” with plane cuts are used to turn aluminum, the tips showed no wear or raptures afterwards which also indicates that the femtosecond laser cutting of diamond is stress-free as far as possible.

FIGURE 6 shows a saw-tooth-like structure in polycrystalline CVD-diamond plate. The dimensions of a single tooth are about 130 µm in length and 30 µm in width. The cutting depth is about 25 µm.

Compared to the best cuts in single crystal diamond (roughness of 30 nm rms on a plane) the walls of this structure are slightly imperfect due to imperfections of the polycrystalline diamond itself and a non optimized cutting process at high process speed. At this time tools with this surface quality could already be used for milling (which is a highly statistical process), where the surface quality of the tool isn’t as important for obtaining a (very) good quality within the workpiece as in diamond turning.

The saw-tooth-like geometry can be easily projected onto an axially symmetric shape like a circle for generating a cylindrical milling tool, for example.

**Laser modified tips**
Femtosecond laser structuring can not only be used for cutting arbitrary shapes into diamond but to modify tool tips as well. FIGURE 7 shows the modified surface of a polycrystalline CVD-diamond platelet. The larger linear structures are directly carved into the diamond by moving the laser focus over the surface line by line with a lateral period of 5 µm. Within these structures even smaller, highly periodically and seamlessly
connected ripples with a period of 400 nm can be observed. The orientation of the nano-ripples only depends on the polarization direction of the laser beam and is absolutely independent of the laser pathway. Hence, the direction of the nano-ripples and the laser pathway along the surface can be adjusted arbitrarily and separately by changing the orientation of polarization of the laser light or the laser pathway, respectively. Furthermore, with a change in the laser wavelength even the period of the nano-ripples is adjustable. Such surface structures can be used to a) guide chips in a desired way or direction to minimize cutting forces while turning and/or b) adhere cooling lubricant while providing an enlarged interaction interface between cooling lubricant and the diamond tool for maximum heat transport away from the tool tip into the coolant.

**FIGURE 7.** Chip guiding structures with nano-ripples in the surface of a polycrystalline CVD diamond, tilt 60°. The period of the structure is 5 µm, the period of the nano-ripples is 400 nm. The inset shows a magnification of a representable part of the whole structured area.

It should be mentioned that femtosecond laser machining of diamond is at this point in time a relatively time consuming process. With an optimized cutting speed of about 80 µm s⁻¹ (NA 0.25) at 1 kHz pulse repetition rate it takes about two to three hours to generate tool tips, like those shown above, with dimensions of about 200x100 µm² and a structure depth of about 25 to 100 µm. The pulse energy at the highest available repetition rates of the research lasers systems which were used is the limiting factor. However, newly developed (fiber based) high power femtosecond and picosecond laser sources, with repetition rates in the MHz range and sufficient pulse energies are commercially available meaning that the technique of laser machining of diamond can easily be upscaled in process speed by a factor greater than 100 without decreasing the structure quality.

**SUMMARY AND OUTLOOK**

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

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**REFERENCES**