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Investigation of nanopolycrystalline diamond tools for ultra-precision machining of ppKTP-crystals for quantum communication applications

E. Uhlmann[1,2], M. Polte[1,2], T. Hocke[1], M. Wendt[1], C. Polte[1], J. Tschöpel[1]

[1]*Institute for Machine Tools and Factory Management IWF, Technische Universität Berlin, Germany*
[2]*Fraunhofer Institute for Production Systems and Design Technology IPK, Germany*

wendt@tu-berlin.de

Abstract
The security of digital communication is of utmost importance in a digital and highly interconnected world. Quantum communication methods represent a key technology in this context, as the use of quantum characteristics provides strong encryption methods that enable reliable and secure data transmission. To improve the performance of quantum communication, quantum light sources are in focus of research and development. Crystals with brittle-hard characteristics are typically used for high performance optical components. According to the state of the art, significant limitations in manufacturing of these components lead to reduced surface qualities with groove formations and a limited freedom of design. A novel approach for the machining of brittle-hard materials is the application of ultra-precision (UP)-turning using binderless nanopolycrystalline diamonds (NPD) as cutting material. In comparison to conventionally used single crystal diamonds (SCD), NPD shows a higher hardness and specific cutting-edge micro-geometries, indicating great potential for ductile and crack-free machining of hard-brittle crystals. Extensive investigations were carried out to gain a fundamental knowledge about the manufacturing of dedicated potassium titanyl phosphate (ppKTP)-crystals. The initial cutting-edge micro-geometries of the used tools made of NPD with a corner radius of r_ε = 400 µm were characterised and subjected to fundamental cutting experiments with variation of the depth of cut and the feed. Based on the investigations by means of dedicated scratching tests using the ppKTP-crystals, the brittle-ductile transition as well as the minimum chip thickness could be identified. First results show a ductile chip formation for the manufacturing of ppKTP-crystals using innovative NPD tools, which indicate a great potential for further investigations.

Keywords: hard-brittle materials, nanopolycrystalline diamond, crystals, cutting mechanisms

1. Introduction

The issue of data security while handling personal and sensitive data in digital communication is of central importance in today's society. To ensure self-determination and security in the digital connected society, research is increasingly focusing on novel quantum communication methods. Unique advantages are offered by quantum communication through the use of entangled photon pairs and the associated quantum encryption. This provides an encrypted communication that enables a reliable and secure data transmission.

According to the current state of the art, the components required for this application are conventionally manufactured by machining with geometrically undefined cutting edges, mainly by grinding and polishing. However, this approach shows limitations in terms of the achievable geometries such as the production of curvature radii of r_f < 10 mm. In addition, the process results in grooves on the workpiece surfaces, which reduce the surface quality of the optical components and lead to distortions in the light input and output [1]. In order to overcome the challenges of the state of the art, a novel approach for manufacturing brittle-hard crystals was investigated. In this work, ultra-precision machining using nanopolycrystalline diamond tools was applied for machining of the crystals. To obtain fundamental knowledge of the cutting characteristics of ppKTP-crystals and the identification of the ductile cutting regime, specific experimental tests were carried out to identify suitable sets of cutting parameters for achievieng a ductile cutting.

2. Experimental setup

The experimental tests were conducted using a 5-axis ultra-precision machine tool Moore Nanotech 350 FG manufactured by Moore Nanotechnology Systems, Swanzey, USA. Three different NPD tools with a corner radius of r_ε = 0.4 mm, sourced from two different tool manufacturers, were analysed and used in the experiments. These differ in their specific characteristics of the cutting edge microgeometries, with significant differences in cutting edge radius of 0.484 µm ≤ r_β ≤ 9.164 µm and maximum chipping of the cutting edge of 0.032 µm ≤ $R_{S,max}$ ≤ 0.361 µm. The first tool type used was supplied by the company A.L.M.T. Corp, Osaka, Japan, whereas the other two types of tools were manufactured by Sumitomo Electric Hartmetall GmbH, Willich, Germany.

Both Sumitomo tool types differ in the final production process. On one of the tool types the final brushing step has been omitted to achieve a smaller cutting edge radius. The cutting-edge micro-geometries of the tools were measured utilising a focus variation microscope InfiniteFocus by Alicona Imaging GmbH, Graz, Austria, as well as a scanning electron microscope (SEM) from Leica Electron Optics, Wetzlar, Germany. The ppKTP-crystals applied for the experiments were supplied by Eksma Optics, Vilnius, Lithuania, which are widely used in optical applications due to their non-linear properties. The samples are characterised with a length l = 4 mm and width w = 4 mm. The cutting results were measured and analysed using a white light interferometer (WLI) type Zygo NewView 5010 from Ametek Germany GmbH, Weiterstadt, Germany.

3. Cutting results

Before conducting the experimental tests, the NPD tools were analysed to determine their microgeometrical properties. This step is essential to ensure the validity and interpretability of the subsequent experimental results. For machining hard-brittle materials in the ductile regime, the ratio of the cutting edge radius to the chip thickness needs to be $r_\beta > h$, ensuring the generation of a hydrostatic pressure state during the cutting process [2, 3]. Table 1 presents the results of the microgeometry measurements of the cutting edges for the three tool types used. The macrogeometry of the tools is identical for all types and is characterized by a radius of $r_\varepsilon = 0.4$ mm, a rake angle of $\gamma = 0°$, and a clearance angle of $\alpha = 15°$. The state-of-the-art macrogeometry ensures efficient tool production and maximum stability when cutting hard-brittle materials.

Table 1 Results of the cutting edge microgeometries for the NPD tool types used

Cutting edge characteristics	in [µm]	Type 1 (A.L.M.T.)	Type 2 (SUMITOMO)	Type 3 (SUMITOMO)
cutting edge radius	r_β	0.484 ± 0.06	3.056 ± 0.483	9.164 ± 0.378
maximum chipping of the cutting edge	$R_{s,max}$	0.032 ± 0.013	0.198 ± 0.039	0.361 ± 0.051

Founding on this analysis, the experimental cutting tests aimed to evaluate the tools´ performance in achieving ductile machining of ppKTP-crystal. The cutting test were conducted with a depth of cut in the range of $0\ \mu m \leq a_p \leq 4\ \mu m$ to investigate the transition from ductile to brittle machining regimes. The SEM images in Figure 1 highlight the distinct differences in cutting edge quality between the tool types. Tools from A.L.M.T. CORP. exhibit superior cutting edge quality, characterized by a smaller cutting edge radius r_β and a maximum chipping of the cutting edge $R_{s,max}$ compared to the tools from SUMITOMO ELECTRIC HARTMETALL GMBH.

After conducting the scratch tests, the surface quality was analysed in detail. The images in Figure 2, obtained using tool type 2 (SUMITOMO without brushing), illustrate the differences in machined surface characteristics between ductile and brittle material behavior.

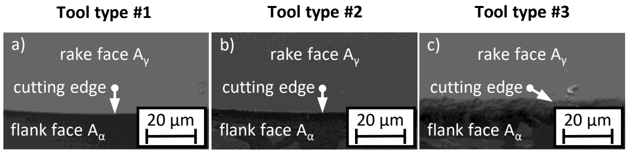

Figure 1. Different NPD turning tool types; a) A.L.M.T. CORP., b) SUMITOMO ELECTRIC HARTMETALL GMBH without brushing and c) SUMITOMO ELECTRIC HARTMETALL GMBH with brushing

The brittle behavior image shows visible cracks, while the ductile image demonstrates smooth, continuous chip formation. In the ductile regime, surface roughness values of Ra = 14 nm and Rz = 62 nm were achieved, whereas in the brittle regime, surface roughness measurements yielded Ra = 131 nm and Rz = 348 nm.

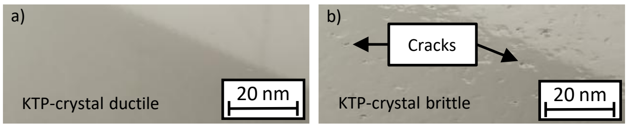

Figure 2. Machined surfaces: a) ductile surface and b) brittle surface obtained from WLI measurements

In Figure 3 exemplary machined grooves for each tool type, along with their respective cutting forces F_C are presented. The maximum cutting forces range between $0.5\ N \leq F_C \leq 3{,}8\ N$, with tool type 1 exhibiting the lowest forces F_C, as reflected in the resulting groove geometry. Within the investigated depth of cut a_p, tool type 1 maintains continuous ductile material behavior up to a depth of cut $a_p \leq 4\ \mu m$. In contrast, tool type 2 exhibits a ductile-brittle transition at a depth of cut $a_p = 91$ nm, corresponding to depth of cut to a cutting edge radius $r_\beta / a_p \leq 0.029$. For tool type 3, the ductile-brittle transition is identified at a depth of cut $a_p = 68$ nm, with a ratio of $r_\beta / a_p \leq 0.007$. The ductile-brittle transition regions are highlighted in red in Figure 3.

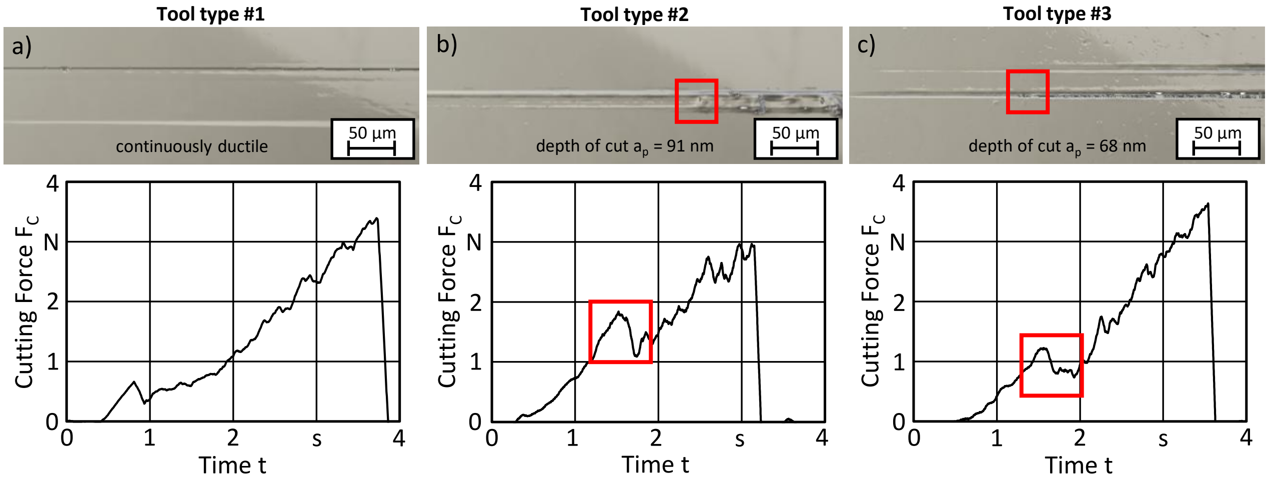

Figure 3. Exemplary grooves with corresponding force profiles a) A.L.M.T. CORP., b) SUMITOMO ELECTRIC HARTMETALL GMBH without brushing step and c) SUMITOMO ELECTRIC HARTMETALL GMBH with brushing step

4. Conclusion

The conclusion drawn in this study are based on fundamental cutting tests. The complete micro- and macrogeometry of the three NPD tool types allowed the identification of fundamental cutting mechanisms for machining ppKTP-crystals. Regarding the microgeometry of the cutting edge, an industrially relevant range of $a_p \leq 4\ \mu m$ for ductile cutting was observed for tool type 1 from A.L.M.T. CORP. No brittle material behavior was identified for this tool type, highlighting its potential for ductile machining. Further investigations examine the influence of feed f in more detail in order to fully understand the fundamental cutting mechanisms in the machining of ppKTP. This work was funded by the Federal Ministry of Education and Research (BMBF) under the funding number 16KIS1718.

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