Grinding of monocrystalline diamond

C. Brecher, A. Sobotka, C. Wenzel
Fraunhofer-Institute for Production Technology, Germany

Abstract

Within this paper, a machining system for the manufacturing of monocrystalline diamond tools is presented. The concept of this new machine tool, which was developed by Fraunhofer IPT, is to conduct the entire finish machining of grinding and lapping in one setup. Furthermore, the machine enables the manufacture of new tool geometries. In a second step, the machine is used as a test bench for contour grinding monocrystalline diamond. A systematic test approach has been set up to conduct a comprehensive investigation of the grinding process. The first results of these investigations are presented in this paper.

1 Introduction

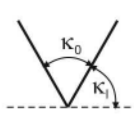
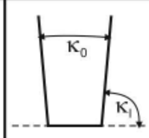
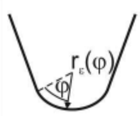
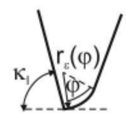
In various products that can be found in expanding markets such as medicinal devices, consumer products and measurement technology, smallest diffractive and aspherical structured optics are demanded. Due to the very high quality requirements regarding geometry and surface roughness only the diamond cutting process is feasible for manufacturing these optics and its mould inserts respectively. The applied diamond tools need to fit high accuracies regarding cutting edge and radius tolerances. Furthermore, the geometrical shape of state-of-the-art diamond tools is limited to spherical edges. For this reason, Fraunhofer IPT has developed a new diamond grinding and lapping machine for manufacturing ultra precision diamond tools with spherical as well as aspherical cutting edges in one setting [1, 2].
In a first step after the implementation of the machine, basic research was conducted regarding the grinding process of monocrystalline diamond on this new machine system [3]. A main quality feature of diamond tools is the accuracy and sharpness of the cutting edge. To achieve this, diamond tools are machined in a two step process. First, the geometry of the tool is machined in a grinding process. After that, the chip surface is polished to achieve a perfect cutting edge. Although the polishing process removes the chipping at the cutting

edge, which is caused by the grinding of the tool geometry, less chipping during the grinding process leads to less necessary removal and, hence, a shorter process time. Therefore, a comprehensive investigation of the grinding process is the first step to achieve better qualities of diamond tools.
The first results of the basic research regarding the grinding of monocrystalline diamond are presented in this paper. Based on a systematic method the main influences on the process result have been determined. The main goal of the process investigations is to correlate the crystallographic orientation and the direction of cutting to the quality of the rake surface and cutting edge.

2 Machining system for diamond tools

The Fraunhofer IPT has developed, designed and assembled a diamond grinding machine for finish machining monocrystalline diamond tools. Table 1 shows the tool geometries that should be manufactured on this new machine tool. First of all standard geometries like radius, V-forms and facettes were defined to compare the feasibilities of the new grinding machine with tools and machines that are already available. Beside this, the main focus is put on aspheric and freeform tools, which can be used for new applications like aspheric linear lens arrays. The second innovation of the diamond grinding machine is to allow the grinding of the contour and the lapping of the rake face in one setting. Furthermore, the machine system has a standard CNC-controller to put diamond machining systems on the same level as conventional machine tools, which will enable a better automation.

Table1: Requirements on diamond tools

Cutting geometry	V-form	Facette	Asphere	Freeform
Sketch				
Clearance angle α_0	5°	12°	5°	20°
Rake angle γ_0	0°	-20°	0°	0°
Opening angle φ_0	-	-	120°	80° / 90°
Point angle κ_0	60°	10°	-	-
Lateral angle κ_l	60°	85°	-	85° / 90°
Tolerance $\delta\gamma/\delta\kappa_l$	±2' /± 5''	±2' /± 5''	±2'	±2' /± 5''
Cutting edge radius r_β	50 nm	50 nm	50 nm	50 nm
Radius r_ε	4 µm	4 µm (2x)	max 500 µm	max 500 µm
Waviness	50 nm	50 nm	50 nm	50 nm

Based on the requirements for the geometry of diamond tool as given in table 1, a machining system with seven axes is necessary. The axes are four linear axes

(X, Y, Z and Z') and three rotary axes (A, B and C). To fulfil the requirements of grinding monocrystalline diamond the C-axis has to be a position controlled axis and a spindle to change the cutting direction according to the crystallographic orientation of the diamond. Furthermore, it has to be considered that grinding the contour of the diamond tool and lapping the rake face require different grinding and lapping wheel. Therefore, the machining system is equipped with two spindles; one for grinding and one lapping. Hence, this is the first machine to combine both processes for diamond tool machining in one machine tool in one setting of the tool. This simplifies the machining process and will lead to better accuracy of the machined diamond tool.
To achieve the dimensions of the diamond tools that are listed in table 1 the axes need the following ways of travel:

X-Axis: > 40 mm, depending on the width of the grinding wheel
Y-Axis: > 2 mm
Z-Axis: > 5 mm, to machine radius tools with R = 5 mm
Z'-Axis: 5 mm
A-Axis: 20°
B-Axis: ±90°
C-Axis: 360°, endless

To enhance the accuracy and to consequently achieve a machining operation in one setting, the machining system is equipped with an optical measuring system for the diamond tool. This enables correction machining without losing important reference points. The measuring system can be positioned by a triple axes positioning system. The size of the machine, which is shown in figure 1, can be explained by the number of axes that are mounted in a serial manner. Second, the machine was designed under consideration of high stiffness to achieve high accuracy during the process. This results in the machine having a bigger size.
For the following grinding test the system boundaries have been defined as depicted in figure 1. Inside the system boundaries the machine's grinding system can be divided into two subsystems, a material related subsystem and a kinematic related subsystem. The material related subsystem, which consists of the grinding wheel, the spindle, the C-axis and the X-axis, is used to realise the functionalities that are necessary to grind monocrystalline diamond that have strong anisotropic properties. In the first place, this is to adjust the cutting direction in accordance to the crystallographic orientation of the diamond. The kinematic related subsystem, which consists of the Z-axis, the A-axis, the B-axis, the Z'-axis and the tool, is used to realise the functionalities that are necessary to shape the tool according to the requirements listed in table 1.
Since the focus is on grinding the tool, the lapping spindle and the Y-axis are not considered, because they are used to machine the rake face of the tool. For this reason the measurement system is also not shown in the figure.

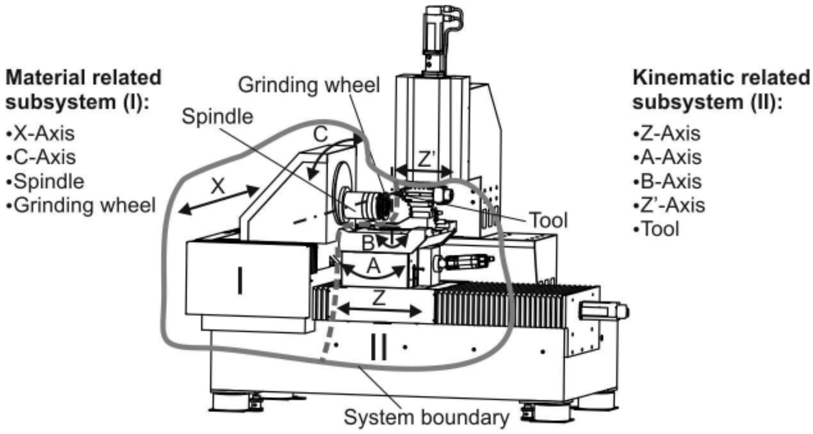


Figure 1: Diamond machining system

3 Deduction of a test strategy

The grinding of diamonds, in particular the grinding of high precision diamond tools, has not been investigated comprehensively in the past. These investigations have mostly been done empirically by the tool manufacturers, and have not been documented properly or are the only known to these manufacturers. On the contrary, the lapping of the rake surface has been investigated in more detail [4,5,6]. The presented machining system is an ideal test bench for the investigation of the grinding process of monocrystalline diamond. Since both the process and the performance of the machining system can be considered as relatively new, the major influences on grinding have to be determined in a first step. Therefore, a systematic test approach is a suitable procedure. A systematic test procedure is a systematic approach, which gains results covered by statistics [7]. With a suitable design of experiments, the influence of multiple input parameters on multiple outputs can be determined simultaneously in an efficient way.

Within the shown boundary conditions, the parameters listed in figure 2 can be deducted as input parameters for the considered system. They can be divided into defined changeable parameters and non-defined changeable parameters. The not defined changeable parameters have to be kept as constant as possible. Parameters, which can be used for the test, have to be independent from each other and must be constantly adjustable. Therefore, the seven parameters shown have been chosen as factors for the test procedure.

When considering a relatively new process a screening test procedure should be adapted to determine the major influences. In this case, a Placket-Burman test procedure was chosen. A Placket-Burman test procedure enables multiple factors to be tested with minimum tests. Although this limits the information that can be gained out of the test, it is a meaningful approach for an unknown process [8]. Each factor will be tested at two factor levels. To cover the entire range of the process field, the factor levels have to be set at the boundaries of their individual setting range.

List of parameters

Defined changeable parameters	Unit
Spindle Revolution of grinding wheel	1/min
C-Axis Position equals cutting direction*	Degree
X-Axis Oszilation speed	mm/min
Revolution of C-Axis*	1/min
B-Axis Position equals crystal plane	Degree
A-Axis Clearance angle and crystal plane	Degree
Z'-Axis Stiffness of controler	A
Infeed via Z-Axis or Z'-Axis+	-
Z-Axis Infeed rate+	m/s
Z'-Axis Infeed rate+	m/s
Dwell time per infeed	s
Total infeed	µm
B-Axis, oszilation speed	m/s
Number of oszilations	-
Non-defined changeable parameters	
Condition of grinding wheel	-
Quality of raw tools	-
Thermal elongation of spindle	µm
Humidity	%
Room temperature	°C
Vibrations from external sources	m/s²

*,+ not arbitrarily combinable

Test procedure

Factor	Factor levels	
A [1/min]: Revolution of spindle	1700	2700
B [-]: C-Axis	n_c	fest
C [°]: B-Axis	0	59
D [A]: Stiffness Z'-Axis	1,4/0,7	3/1,5
E [-]: Infeed axis	Z'	Z
F [s]: Dwell time per infeed	120	600
G [µm]: Total infeed	4	8

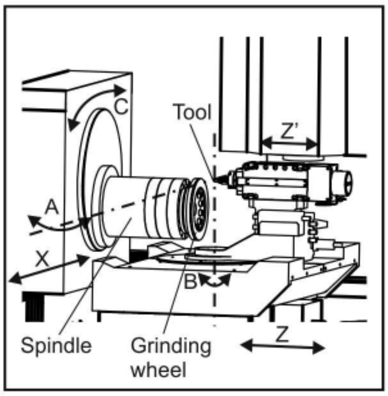


Figure 2: List of parameters and test procedure

The output parameters, whose dependency on the factors is investigated, are called quality characteristics. Ideally they can be measured. In terms of diamond tools there are two main quality measures that define their usability for ultra-precision machining techniques. First, the cutting edge has to be very sharp, which means it should have a cutting edge radius lower than 30 nm [9,10], and that it is free of chippings. Second, the clearance surface has to be smooth and of low waviness, since form and roughness errors continue into the cutting edge. Therefore, these measures were chosen as quality characteristics for the tests as shown in figure 3. A reduction of the roughness at the cutting edge is equal to less chippings, which is one goal when grinding the tool contour. It has to be noted that it is sufficient to have low chippings, since the following lapping of the rake face will remove the chippings. But less chippings will reduce work during the lapping process. Furthermore, a low waviness at the clearance surface is the aim. Both quality characteristics can be measured, and, hence, fulfil the requirements for the test procedure.

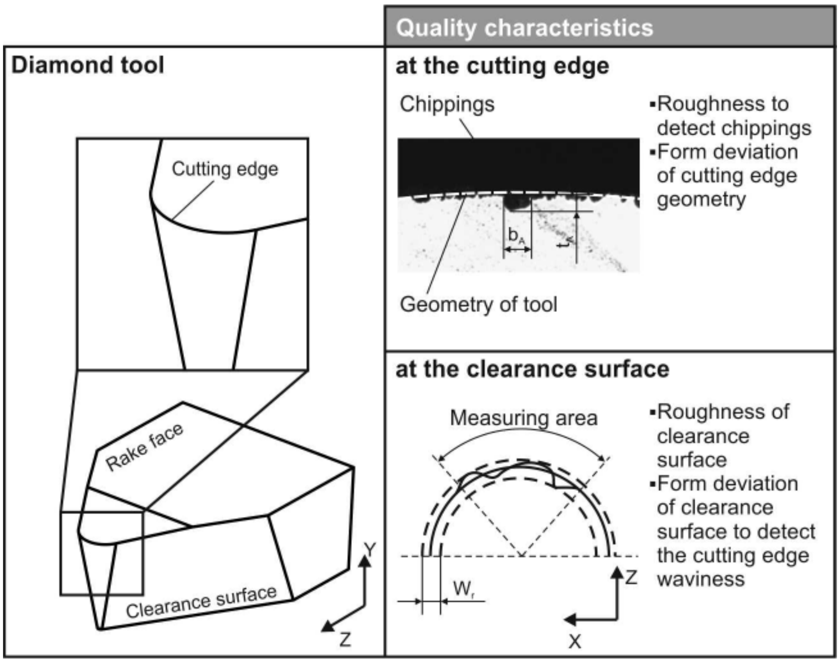


Figure 3: Quality characteristics for contour grinding

4 Results of grinding tests

The first tests were conducted on a linear tool geometry as it is used in V-form and facetted tools to limit the complexity of the considered factors.
First of all, the influence of the C-axis on the chipping of the cutting edge was investigated with the test. The results can be seen in figure 4, which shows only the tests with the B-axis at 0°. Since the C-axis is used to vary the cutting direction, these tests validate that a constant cutting direction leads to less chippings than a continuous change of cutting direction. All tests were conducted on the same tool to keep constant material properties during the test series. Therefore, figure 4 shows also that the chippings can be removed by using a total infeed bigger than the chippings for the next machining operation.

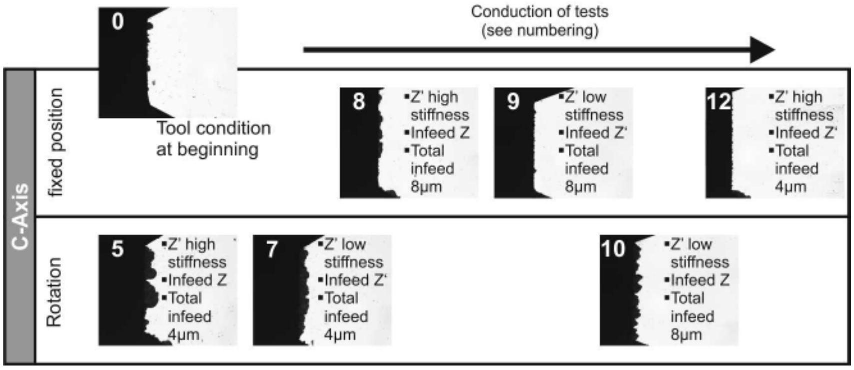


Figure 4: Influence of C-axis

The results of the tests were obtained by an analysis of variance according to Pfeifer [7]. With this analysis, the significance of the factors or the standardized effect on the quality characteristics can be determined by isolating statistical spreading. Figure 5 depicts the effects of the factors. The significance level describes the probability that an effect is not caused by statistical deviations but by changing of the factor. When the α-value is 0.1 (0.05), a 90% (95%) probability is given that the factor has an influence on the related quality characteristic.

In accordance with the results shown in figure 4, the analysis of variance underlines that the C-axis has a major effect on the chippings at the cutting edge (see figure 5). Therefore, this factor has to be adjusted to minimize the chippings in the first step. Second, the roughness of the clearance surface is significantly influenced by the position of the B-axis. This can be explained by the crystallographic properties of diamond. As already published in a number of research papers [11], the removal rate is not only dependent on the cutting direction, it is also dependent on the crystallographic plane of diamond. Since the B-axis changes the crystallographic plane, which is in contact with the grinding wheel, the cutting properties change as well and this results in a different roughness at the clearance surface. All the other factors do not have a significant effect on the quality characteristics.

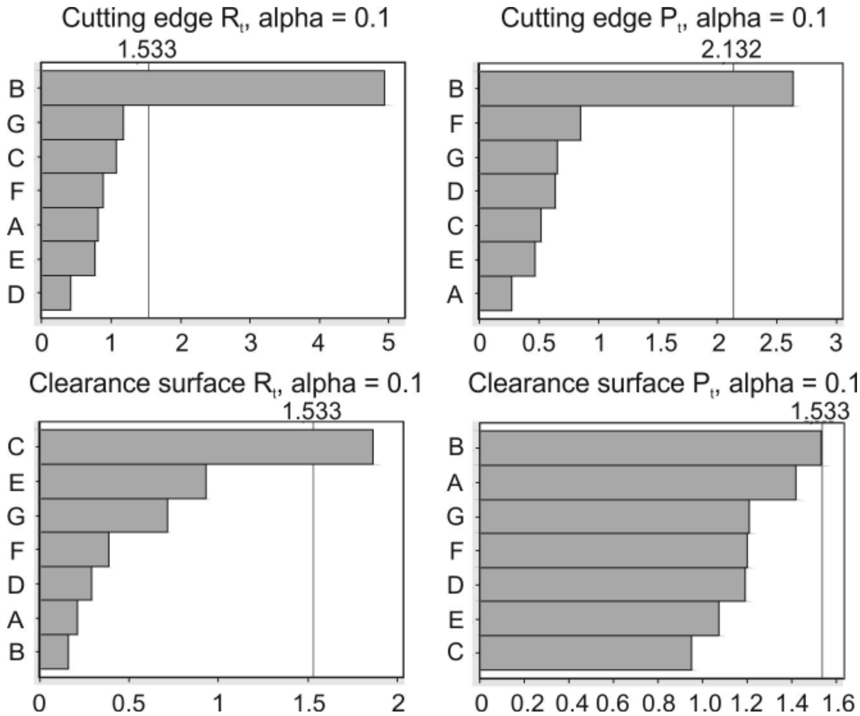


Figure 5: Main effects on grinding

Regarding the significant factors a main effects diagram shows the qualitative dependency of the quality characteristics and the factors. For the factors B (C-axis) and C (B-axis) the main effects on the roughness R_t of the cutting edge and the clearance surface are given in figure 6. It clearly depicts that the roughness is lower when the C-axis is fixed. Considering the cutting edge, this means that there are fewer chippings after the grinding process. The roughness on the clearance surface is better when the position of the B-axis is bigger. Since the position of the B-axis defines the crystallographic plane, which is in contact with the grinding wheel, the difference of the roughness is in relation to the different material removal rates on the respective crystallographic plane. The crystal plane at 0° is 100, while the plane at 59° is nearly 110. When considering the cutting direction, which was 100 in both cases, a higher removal rate on the 110 plane can be expected in accordance with Yuan [11]. Hence, this is an explanation for the better surface roughness.

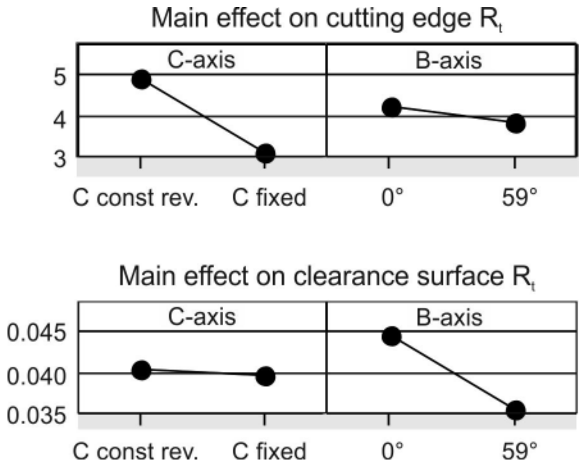


Figure 6: Tendency for main effects

5 Summary and Outlook

Within this paper a newly developed diamond grinding machine for monocrystalline diamond tools has been presented. Due to the fact that this machine is a prototype, the properties of the machine and the grinding process on this particular machine have to be investigated. Therefore, a systematic approach was chosen to conduct the grinding tests. Based on the first test series, which was used to determine the significant influence parameters on the grinding results, it was shown that a process with a fixed C-axis results in a better surface roughness. Furthermore, it has been determined that the different removal rates on the crystallographic planes have an influence on the surface roughness as well.
In the future, the grinding process will be investigated in more detail on this new machining system. This will include the measurement of process forces and acoustic emission signals. To transfer the results into an application, monocrystalline diamond tools will be machined and tested afterwards.

6 Acknowledgments

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