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Increasing the cutting performance of CVD-coated diamond abrasive tools in micromachining by creating additional chip space

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Abstract

Today's technical products consist of components that are becoming smaller and smaller. Finest structures must be produced very precisely in hard and brittle materials that are difficult to cut. These micro parts are often processed by grinding with small tool diameters. Electroplated diamond abrasive tools as well as abrasive tools with bonded grains are usually used. Abrasive tools with bonded grains require a complex tool-preparation and are only used if electroplated tools cannot meet the requirements for the workpiece surface. Both tool types have diamond grains that cut the material. CVD-coated diamond abrasive tools represent a completely different tool concept. These tools can be used without any tool preparation. Due to the even growth of cutting diamond crystals, better workpiece surface roughness is achieved compared to electroplated tools. But, at the same time the material removal rate is lower, due to clogging which also results in increased cutting forces.

In this work, the process behaviour of a novel design of CVD-coated diamond abrasive tools is investigated. In experimental tests, workpieces made of quartz glass and zirconia are machined. The evaluation criteria are the surface roughness of the workpieces and the cutting forces during machining. For this new design, a manufacturing process has been developed that allows grooves to be precisely and repeatable cut into the tool body before coating. These grooves creates additional chip space and ensures a better supply of cooling lubricant in the cutting zone. The risk of clogging as well as the cutting forces are reduced. As a result, the material removal rate is increased while the workpiece surface roughness remains the same. For comparison, all experimental tests were also performed with standard non-grooved CVD-coated diamond abrasive tools as well as with electroplated tools.

Micro Machining, Grinding, Micro Abrasive Tools, Structured Tools

1. Introduction

One typical application for micro diamond abrasive tools are glass lenses which are produced in mass production. But it is not the lens itself that is made with abrasive tools, but the mould that produces many lenses in large-scale production by hot embossing. The moulds are made of tungsten carbide and need to be machined with diamond abrasive tools. Another application is the production of solenoid valves that are installed in fuel injectors for diesel engines. These valves open and close to control the fuel flow. This movable component must reliably seal against pressures up to 2,000 bar. The sealing surface is manufactured by internal cylindrical grinding with diamond abrasive tools.

In this field electroplated diamond abrasive tools are commonly used. These tools have diamond grains which are fixed to the tool body by a thin nickel layer. Thus, there is large chip space between the grains that results in a fast cutting tool and high productivity. But, with the cost of high surface roughness compared to bonded abrasives [1]. An alternative tool concept are CVD coated diamond abrasive tools. During CVD coating process diamond crystals are growing and form a closed layer with many sharp cutting edges on the tool body. The even growth of the crystals is the main advantage compared to electroplated tools and results in low surface roughness. But, the high density of active cutting edges leads to lower productivity, because the chip space is relatively small compared to electroplated tools. This leads to increasing grinding forces and causes deflection of the tool. The risk of clogging increases and, in combination with high grinding forces, this might end in tool breakage [2].

The aim of this work is to increase productivity to get a CVD coated diamaond abrasive tool that achieves low surface roughness and high productivity at the same time. Therefore an enlargement of the chip space is necessary for better chip removal and also to improve the supply of coolant in the cutting area. As a result, it will be possible to increase the material removal rates.

To increase the chip space, several researchers use a laser source to structure a relatively large grinding wheel after its manufacture [3-5]. In this work, chip space is increased by machining grooves into a relatively small tool body before it becomes a grinding tool.

2. Structured CVD coated diamond abrasive tools

In order to machine grooves into the tool body, v-shaped grinding wheels are used. The process of machining grooves is described in detail in previous work [6]. With the used machine setup, it is possible to vary some parameters of the groove's geometry to produce a tool specifically for individual requirements. The diameter of structured tools ranges from 1.5 mm down to 0.2 mm.

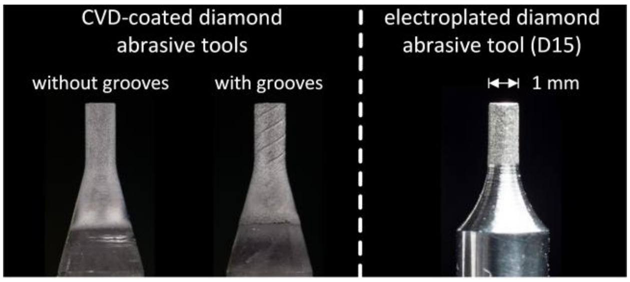

Figure 1. CVD-coated tools as well as an electroplated diamond tool were used for the machining tests.

The next step after structuring the tool body is the CVD coating process. For the initial machining tests tools were used with diameters of 1.0 mm. In addition to structured CVD coated tools, unstructured CVD coated tools were also used to derive the influence of the grooves from the results. Electroplated tools were also used as a comparison to the state of the art (Fig. 1).

3. Machining setup and results

Fig. 2 shows the machine setup used for machining tests. It is a 3-axes precision machine tool (Primacon PFM 24) equipped with a high frequency spindle (Precise SC1060-OA). The machine manufacturer specifies a positioning accuracy of 2 µm. An Kistler AE-sensor (Type 8152) is installed to the workpiece clamping system to detect reliably the contact between workpiece and tool. During machining, the grinding forces are measured with a multicomponent dynamometer from Kistler (Type 9256). Afterwards the surface roughness of the machined workpiece is measured as well as the effective lateral infeed into the workpiece (Mahr MarSurf LD 130).

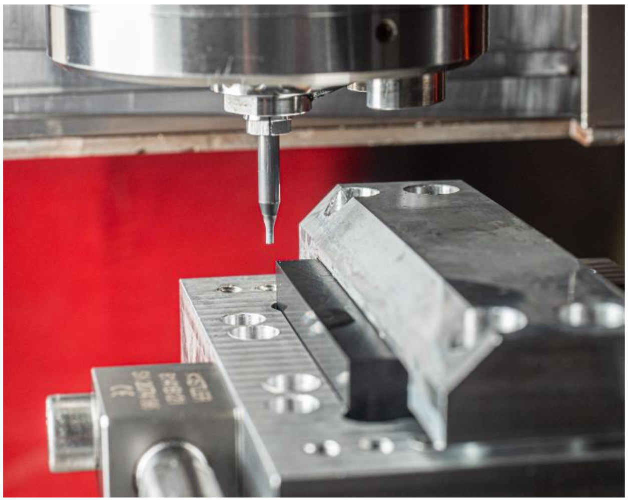

Figure 2. Sensors were used in this Test set-up for detecting workpiece contact and for measuring grinding forces.

The machining process is set up to grind along the edge of workpieces made of zirconia. The length of this edge is 50 mm. In a first step, the edge of the workpiece is pre-ground at a width of cut of 1.8 mm. This step ensures a well defined starting surface and eliminates alignment errors that could occur when clamping a new workpiece. Then, starting from the base surface, the next step is grinding for examination. For this cut, the desired feed speed v_f is set as well as the desired lateral infeed a_e. The width of cut is reduced to 1.5 mm to create a step to the pre-ground surface. In Fig. 3, the described step is shown from the red to the green surface. This step allows to measure the effective lateral infeed after machining.

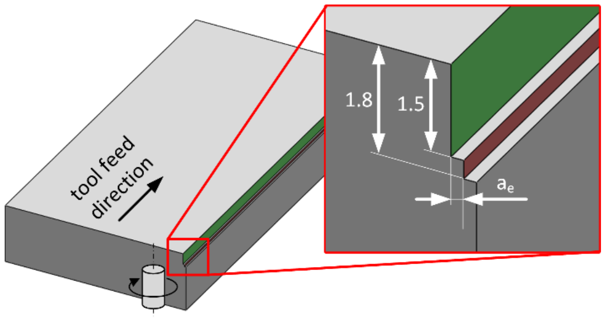

Figure 3. A preliminary pre-grinding step enables the measurement of the effective lateral infeed.

In the machining tests an oil-in-water emulsion (5 % oil) is used as coolant. The lateral infeed is set to 20 µm and the feed speed varies from 32 mm·min^{-1} to 512 mm·min^{-1} at an overall constant cutting speed of 7.89 m·s^{-1}. The tool paths starts 2 mm in front of the workpiece and ends 2 mm behind the workpiece. Each test was repeated 6 times in order to statistically confirm the tests.

The results of the machined surface roughness are shown in Figure 4. The electroplated tool consistently produces higher surface roughness compared to cvd coated diamond tools. In addition, new electroplated tools initially produce rougher surfaces. After a certain time, a constant surface roughness establishes. Looking at both types of the CVD-coated tools, the surface roughness, produced by the grooved CVD-coated diamond tool, is slightly higher. During machining, the grooves interrupt chip formation for a short time while the tool continuous to move at a constant feed rate. As a result, directly behind the groove, the first rows of diamond crystallites produce thicker chips and thus a rougher workpiece surface. Right after that, the topography of the abrasive layer is equal to that of the non-grooved tool. On average, the grooved tool produces slightly thicker chips than the non-grooved tool. Nevertheless, the difference in surface roughness between both of the CVD coated tools is rather small.

In summary the surface roughness when machining with CVD coated diamond tools is lower by a factor of about two compared to electroplated diamond tools. In addition, the surface roughness is almost constant right from the beginning.

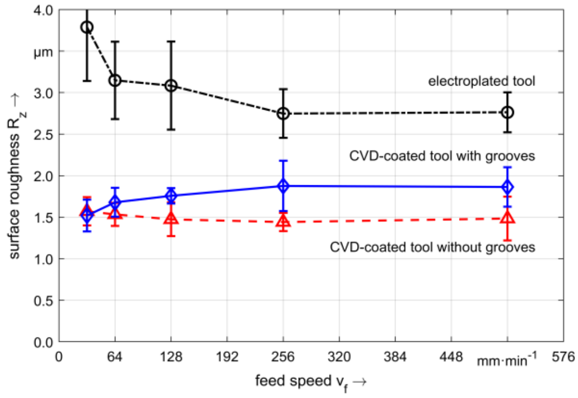

Figure 4. A comparison of the produced surface roughness with variation of the feed speed.

The measurement of the grinding forces, in particular the grinding normal force, are shown in Figure 5. When comparing the cvd coated tools, the forces when machining with the grooved tool are slightly lower. This behavior could be observed in other machining tests as well. The grooves reduces the number of active cutting edges, as discussed before. This leads to a decrease of friction between diamond crystallites and workpiece in the active cutting zone and therefore to a decrease of grinding forces. In addition, the grooves contribute to lubrication by better transporting the coolant into the active grinding contact zone.

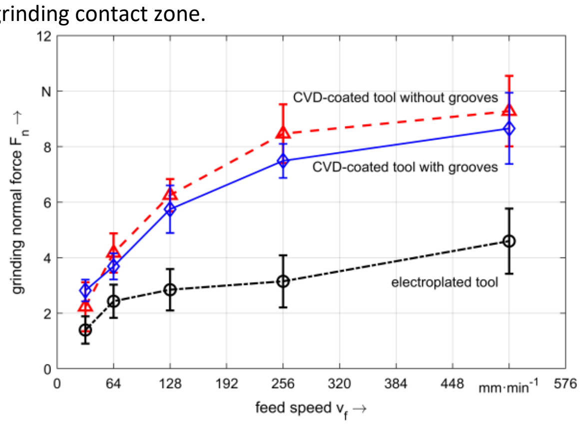

Figure 5. A comparison of the grinding normal forces with variation of the feed speed.

In comparison, these results also show the advantage of the large chip spaces of an electroplated diamond tool. This tool design has even less active diamond grains and therefore less friction which results in less grinding forces.

In summary it can be said, that the grinding forces when machining with an electroplated tool are lower by a factor of about two compared to CVD-coated diamond tools. When comparing CVD-coated tools, grooved tools lead to a decrease of grinding forces.

As mentioned before, the effective lateral infeed $a_{e,eff}$ of each workpiece is also measured. In the machining tests the desired lateral infeed a_e was programmed into the CNC control with a value of 20 µm. This set point is shown as a green dotted line in Figure 6 comparing all three diamond tools.

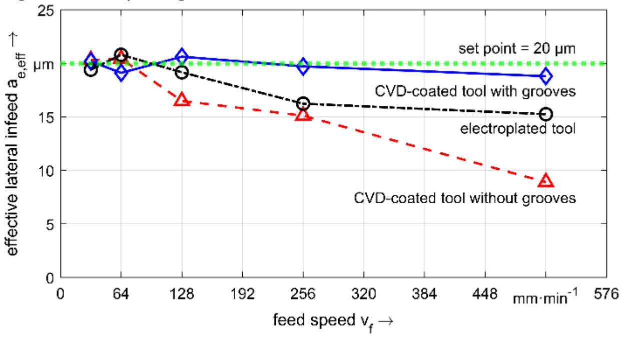

Figure 6. A comparison of the effective lateral infeed with variation of the feed speed. The standard deviation is on average 3.6 µm.

A clear difference can be seen when comparing both of the CVD-coated tools. When looking at these tools, the highest deviation of lateral infeed from the nominal value can be determined for the non-grooved CVD tool. As seen before in Fig. 5, with increasing feed speeds the grinding force increases as well. The CVD-coated tool without grooves has the highest grinding forces, which leads to the largest deflection compared to all three tools. Small chip spaces between the diamond crystallites also support a relatively high hydrodynamic pressure caused by a thin film of coolant that builds up between the tool and the workpiece. This hydrodynamic pressure additionally enhance the deflection of the tool that results in a reduction of effective lateral infeed.

On the other hand, the CVD-coated diamond tool with grooves performs best. It shows a reliable and reproducible machining process even at high material removal rates. The grooves allow a better chip removal and a better supply of coolant at the same time. Dimensions of the grooves are sufficient to suppress the deflection of the tool caused by the hydrodynamic pressure.

In comparison, the electroplated diamond tool is in between of both CVD-coated tools. One would assume that the electroplated tool behaves similarly to the non-grooved CVD-coated tool due to the large chip spaces. The base material is identical and the load bearing cross section of the tool body is even larger because there are no grooves that weaken the tool. To get further insights, a scanning electron microscope (SEM) was used to take a closer look at the electroplated tool (Fig. 7).

The SEM images reveal wear on the leading edge of the electroplated tool. There are no more cutting grains on the surface of the cylinder over a length of approx. 30 µm. The lack of cutting grains can be attributed to the manufacturing process of electroplated tools.

When manufacturing these tools, the electrostatic attraction ensures that the tool is coated with diamond grains. The larger the surface on the base body, the greater the electrostatic attraction. The effective surface for electrostatic attraction is very small at edges, which is why the density of diamond grains is lower at these edges than on flat or slightly curved areas, e.g. the outer surface of the cylindrical tool.

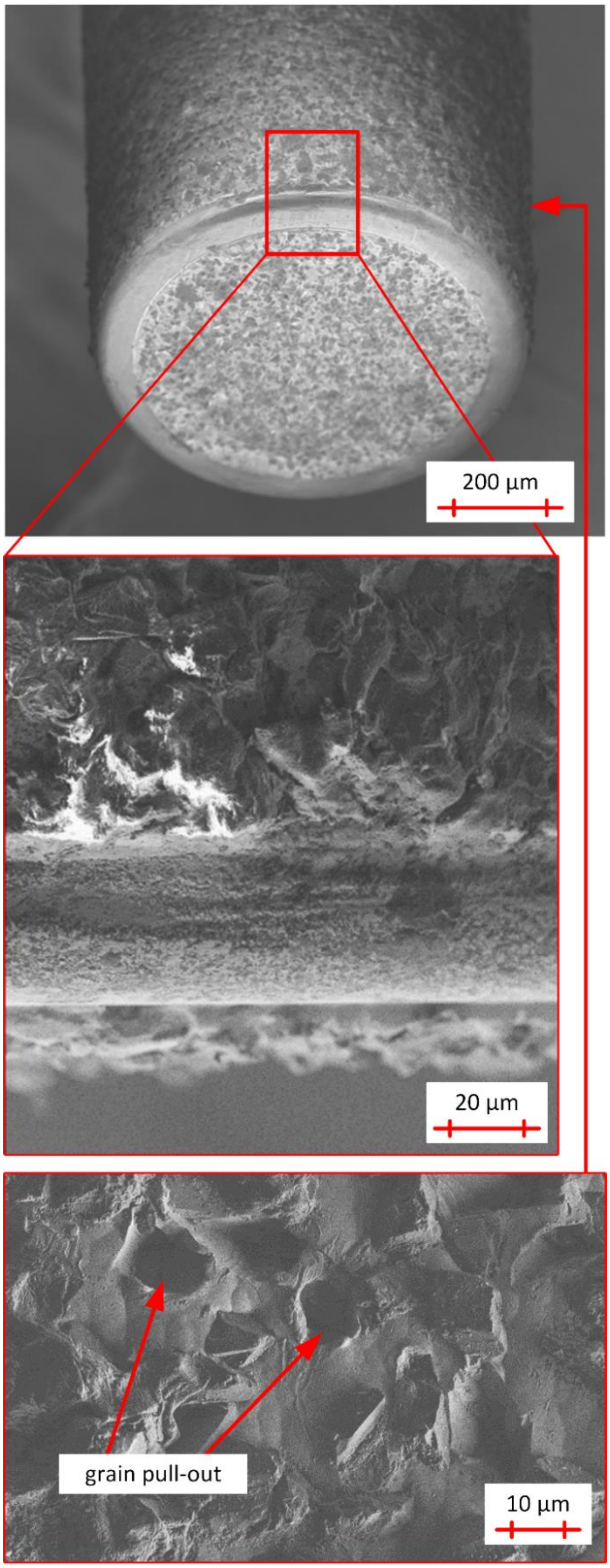

Figure 7. Detailed SEM pictures of the electroplated tool. Overview picture (top), tool tip (middle) and lateral surface (bottom)

This means that the few cutting grains on the tool edge are exposed to higher loads and therefore wear out faster. After a certain time, there are no longer active cutting grains on a narrow strip at the tool tip and cutting can no longer take place. An energy dispersive X-ray spectroscopy (EDX) has shown that mainly tungsten can be detected on this narrow strip, which corresponds to the base material. There are still small traces of nickel to be discovered that come from the nickel bond.

As a result of the wear, the tool deflects slightly out of cut. This wear behavior contributes to the fact that the effective lateral infeed decreases due to tool deflection. This leads to a decrease of dimensional accuracy.

In addition, there are some areas on cylindrical surface of the tool in which cutting grains have broken out. This means that wear was not only found on the tip of the tool, but also on the cylindrical surface of the tool.

Additional SEM images were taken to see the wear behavior of the grooved CVD-coated tool (Fig. 8). These pictures show a major advantage of CVD-coated tools over electroplated tools. The density of diamond crystallites does not decrease towards the tool edge. The pictures also show the very high number of active cutting edges. No wear on the cutting edges has so far been detected on this tool. The diamond crystallites are still very sharp, both on the tool tip and on the lateral surface of the tool.

Slight adhesions of zirconium oxide can be seen between the crystallite tips. In the investigations carried out, these chip accumulations had no negative effects on the tool or the workpiece and were not measurable in the process. Compared to the non-grooved tool, significantly less chip accumulations are visible on the grooved tool. However, a major advantage of electroplated tools can also be derived from these images. The large chip spaces of electroplated tools ensure that no chips remain on the tool topography.

As a result, it can be stated that the wear of CVD-coated tools during the performed edge grinding tests is significantly less compared to electroplated tools. When comparing the CVD-coated tools, the grooves lead to a reduction of the deflection, which leads to an effective lateral infeed that best fits the setting parameter.

4. Summary and outlook

This work presents a novel diamond abrasive tool concept based on CVD coated diamond abrasive tools. The objective was to enlarge the chip space in order to increase space for chip removal and to improve the supply of coolant at the same time. To increase the chip space, grooves are ground into tool bodies made of tungsten carbide before they are coated with diamond. With the used setup it is possible to grind grooves into tool bodies with a diameter down to 0.2 mm.

Experimental tests have shown, that CVD-coated tools with grooves have highest process stability. In these experiments they achieve highest dimensional accuracy and low workpiece surface roughness at the same time. These experiments also reveal that electroplated tools wear out faster than CVD-coated tools. The tool tip of electroplated tools in particular is subject to heavy wear, which lead to poor dimensional accuracy.

In the future it will be examined how the wear differs when comparing both types of CVD-coated tools. It is checked whether the grooves increase the tool life.

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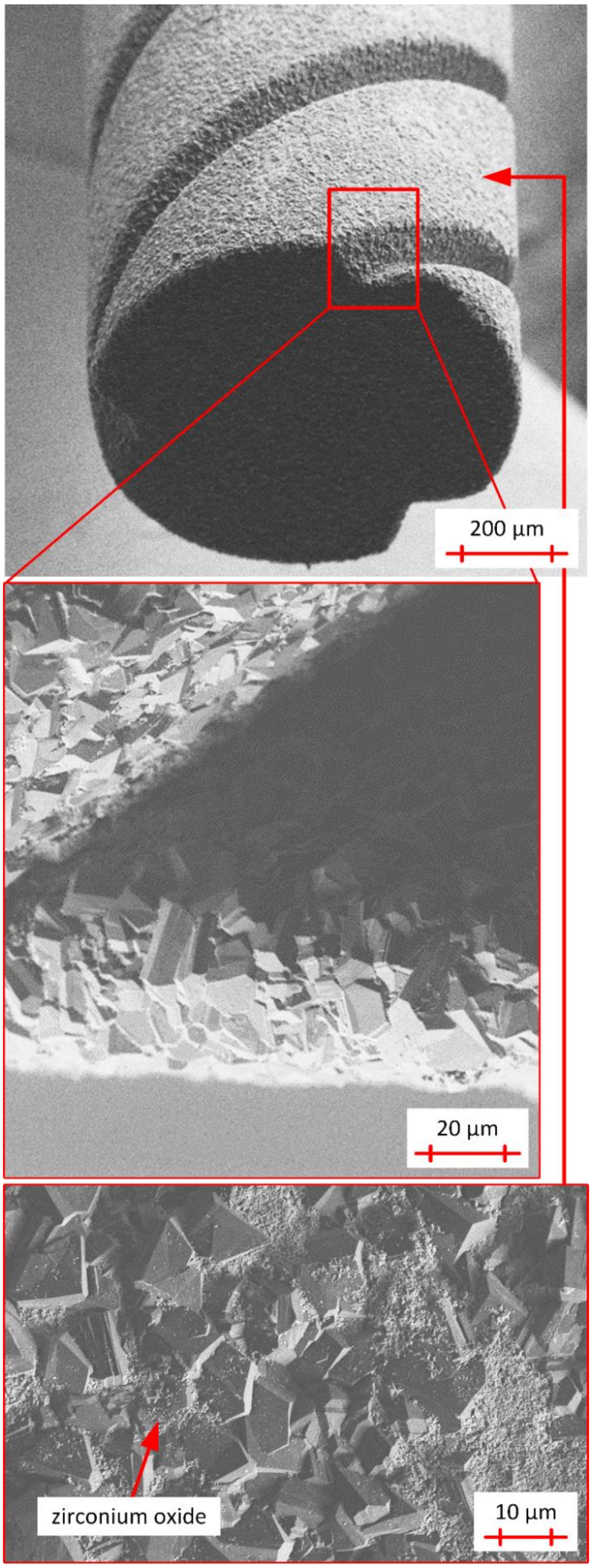

Figure 8. Detailed SEM pictures of the CVD-coated tool with grooves. Overview picture (top), tool tip (middle) and lateral surface (bottom)

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