Micro abrasive pencils with CVD diamond coating

Jan Gäbler a, *, Lothar Schäfer a, Bernd Menze b, Hans-Werner Hoffmeister b

 a Fraunhofer-Institut für Schicht- und Oberflächentechnik IST, Bienroder Weg 54 E, 38108 Braunschweig, Germany
 b Institut für Werkzeugmaschinen und Fertigungstechnik, Technical University Braunschweig, Langer Kamp 19 B, 38106 Braunschweig, Germany

Abstract

Abrasive pencils (burs) for grinding can be made by coating cemented carbide bodies with a rough chemical vapour deposition (CVD) diamond layer. These tools have advantages compared to conventional abrasive pencils made by electroplating or sintering of diamond grains. Different CVD diamond abrasive pencils were manufactured with tip diameters ranging from 0.06 to 2.0 mm. A hot-filament CVD reactor was used in combination with a substrate holder system having a capacity of up to 240 tools. The grain size is the most important property of grinding tools. It must therefore be adjusted carefully in the coating process. The basic influence of tool geometry and coating parameters on the crystal size is presented. By prolonging the coating time to 90 h, crystal sizes of up to 50 μm can be achieved. Manufacturing of abrasive pencils even with such long coating times can be economical, because thousands of tools could be coated in one process by industrial coating in bigger reactors. The relation between the crystal size and the roughness of ground workpieces is presented.

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1. Introduction

For the increasing demand for micromechanical parts and microstructures in mechanical engineering components, the machining by abrasive pencils (burs) is an appropriate way for small dimensions, smooth surfaces, low form tolerances and flexible geometries. Using diamond as cutting material, workpieces made out of hard materials, like cemented carbide, glass, silicon, ceramics or hardened steel can be machined with abrasive pencils. Conventional diamond abrasive pencils are made of sintered diamond or coated with diamond by electroplating. With chemical vapour deposition (CVD), thin layers of diamond can be deposited onto substrate bodies with extremely small dimensions. The layers have a rough surface, formed by the sharp edges of the small diamond crystallite faces. If these diamond layers are deposited onto cylindrical pins, an abrasive pencil is generated, using the sharp crystallite edges as cutting edges [1,2]. It has been shown, that CVD diamond coated abrasive pencils have a lot of advantages compared to conventional diamond abrasive pencils. These advantages are first of all smaller diameters and smaller ‘grain sizes’. Abrasive pencils with diameters down to 50 μm and ‘grain sizes’ below 1 μm have thus been realized [3].

The grain size is of great importance for abrasive pencils. Therefore, investigations were carried out to develop the relations between substrate geometry, coating parameters and the crystal size. The tools were tested by grinding of cemented carbide workpieces.

2. Experimental

Abrasive pencils with cylindrical geometry, different diameters and different crystal sizes were manufactured. The substrate material was cemented carbide. It was a WC:Co-carbide with 4% Co, WC-grain size 1.1–1.5 μm, class K 10. The 3 mm-blanks were ground, so that cylindrical tips with diameters from 0.04 to 2.0 mm were formed. Tip length was 0.8–5 mm, depending on the tip diameter. The total length of the tools was 36 mm.

The substrates were pretreated by a roughening etching in Murakamis agent (K,[Fe(CN)₆]+ NaOH, both 23%, 1:1, 20 s, 20 °C). Some substrates were etched much more, until the shiny ground surface had changed
to a totally dull surface. This took 5 min and the etching depth was approximately 5 µm. Afterwards, all tools were cobalt-etched in HNO$_3$ (70%, 90 s, 20 °C). The seeding was done by dipping the tips into a diamond suspension (diamond particles <1 µm in water).

For the diamond coating, a SPS controlled, self designed hot-filament CVD reactor was used (chamber volume 85 l, coating area 0.05 m$^2$). The substrates were placed horizontally with a distance of 10 mm next to the vertical Ta-filaments (diameter 0.5 mm) on a substrate holder. The shafts were covered by ceramic pipes. The gas mixture was hydrogen with 1.2% methane with a total flow of 1 slm. The filament temperature $T_{fil}$ was approximately 1970 °C, measured with a glowing-filament pyrometer. The filaments were carburized before the coating process, so that they consisted mainly of TaC.

The adhesion of the diamond films was tested using a particle blasting device. Round glass perls with diameters from 70 to 110 µm were blasted against the abrasive pencils with a distance from blasting nozzle to substrate of 5 mm. Afterwards, another spot on the substrate was blasted with Al$_2$O$_3$ (corundum) particles with a grain size between 62 and 88 µm. The corundum particles have sharp edges and act more aggressive than the glass perls. Each test started with a pressure of $2 \times 10^5$ Pa, testing 60 s, repeating with 3, 4 and $5 \times 10^5$ Pa.

The machining tests were carried out on a NC-controlled precision machine tool. The workpiece material was WC:Co cemented carbide, K-type. The grinding parameters were:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>tool diameter (mm):</td>
<td>1</td>
</tr>
<tr>
<td>crystal widths (µm):</td>
<td>17, 50</td>
</tr>
<tr>
<td>depth of cut f (µm):</td>
<td>3, 5</td>
</tr>
<tr>
<td>width of cut $a_w$ (mm):</td>
<td>2.2</td>
</tr>
<tr>
<td>cutting speed $v_c$ (m/s):</td>
<td>2.3</td>
</tr>
<tr>
<td>feed rate $v_f$ (mm/min):</td>
<td>10</td>
</tr>
<tr>
<td>cooling liquid:</td>
<td>emulsion</td>
</tr>
</tbody>
</table>

The roughness of the ground surfaces was measured by a stylus profiler (measuring length 1.25 mm, stylus tip radius 2.5 µm, angle 90°).

3. Results and discussion

Fig. 1 shows the tip of the smallest abrasive pencil with a tip diameter of 60 µm and a length of the cylindrical tip of 0.87 mm.

3.1. Crystal sizes

The crystal height is the important value for the grinding tools. It can not be measured by stylus profiling, due to the small tool size and the high wear of the stylus tip. By taking SEM pictures, the crystal height can only be estimated. It is approximately a third of the visible lateral crystal width. The crystal width on the surface can be measured very precisely and was therefore taken as the parameter to characterize the size of the diamond crystals. Crystal widths from 2 to 50 µm were achieved in the experiments (Fig. 2). A certain variation of the crystal size on each surface was determined, so that both minimum and maximum width was recorded.

3.1.1. Influence of substrate diameter

Above 0.8 mm, the substrate diameter has no major influence on the crystal width (Fig. 3). With smaller diameters, the crystal size decreases. This could be caused by the small surface area of these thin diameters. It leads to a lower substrate heating by hydrogen recombination. Then, the lower substrate temperature causes a lower growth rate and therefore a smaller crystal size. Due to the very small substrate size, their temperature could not be measured.

The crystal size was not uniform over the whole tip area. In the direction to the shaft, the crystal width decreases to approximately 60% in a distance of 4 mm beneath the tip. This is caused by the temperature decrease from the tip to the shaft.

On the abrasive pencils with the smallest diameter 0.06 mm, the crystal widths were between 2 and 7 µm. Due to a shorter tip length, they are not comparable to the geometries in Fig. 3.

3.1.2. Influence of coating time

By changing the coating time, the crystal size can be achieved in a broad range. Fig. 4 shows the linear
relation between coating time and crystal size. Variation of the coating time is therefore the easiest way to get a certain crystal size.

3.1.3. Influence of coating temperature

In the experiments, the coating parameters were chosen in a way, that a high activation was achieved. This means, that the filament temperature was kept in a certain ratio to the methane content, so that on the filament surface the subcarbide phase Ta₃C was in equilibrium. If the filament temperature is too low for a given methane value, TaC is formed on the filament surface instead of the subcarbide Ta₃C. In that case, due to a change in emission, the activation would decrease strongly and a high secondary nucleation in the layer growth would be obtained. This would lead to small crystal sizes. The crystal width decreased to approximately 20%, when the process was run with such filaments having a TaC surface ($T_{fil} = 1930$ °C instead of 1970 °C, equal methane concentration of 1.2%).

3.2. Adhesion

The adhesion tests were carried out with tools of 1.5 mm diameter. Most of the tools reached the highest adhesion values with no flaking after the whole blasting series from 2 to $5 \times 10^5$ Pa with glass perls and repeated with Al₂O₃. This shows, that only a short roughening etching (20 s) seems to be enough to get an appropriate adhesion. However, machining lifetime tests must confirm this conclusion.
Table 1

<table>
<thead>
<tr>
<th>Crystal width</th>
<th>Rz</th>
<th>Rt</th>
<th>Ra</th>
<th>Rpk</th>
<th>Rk</th>
<th>Rvk</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>2.18</td>
<td>4.11</td>
<td>0.27</td>
<td>0.35</td>
<td>0.81</td>
<td>0.61</td>
</tr>
<tr>
<td>50</td>
<td>5.96</td>
<td>7.52</td>
<td>1.03</td>
<td>0.92</td>
<td>3.39</td>
<td>1.72</td>
</tr>
</tbody>
</table>

All values in micron (μm).

3.3. Machining

Tools with two different crystal sizes were tested in the machining experiments. The workpiece roughness was measured in Table 1.

These results show, that a ratio of crystal width to workpiece roughness Rz of 8 can be achieved with the CVD diamond abrasive pencils.

4. Conclusion and outlook

It has been shown, that the abrasive pencils can be manufactured with a broad range of crystal sizes. Below 0.8 mm, the substrate diameter must be taken into account. The coating time is an easy-adjustable parameter for getting a certain crystal size.

Thinking for the production of abrasive pencils as a product, the long process time, needed for big crystal sizes, could be seen as a factor for high production costs. But this is eliminated by the high amount of substrates, that can be coated in one process. With the existing holder set, 240 pieces can be put into the chamber; lot sizes of more than 1000 are possible using reactors with a size according to today's industrial standard. This leads to very small coating costs, even with long process times. However, for regarding the total tool costs, the production costs of the cemented carbide substrate body must be taken into account, which is more expensive as with conventional abrasive pencils having a steel shaft.

With different crystal sizes, a broad range of workpiece roughnesses can be achieved with the CVD diamond abrasive pencils. Rz-values of 2–6 μm have been measured in grinding of cemented carbide workpieces. The ratio of crystal size to roughness Rz was approximately 8.

Next steps will be the manufacturing of geometries other than cylindrical, e.g. round or cone-shaped. The machining experiments will go on with the testing of the adhesion of the diamond layer and of the tool lifetime. Other workpiece materials will be tested, including hardened steel.

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References