INTRODUCTION
Ultra precision machining of metals has an increasing importance for especially mould and die making. Depending on the machined materials, roughness values of $Ra < 1$ nm and form accuracies of less than one micron can be realised with ultra precision technologies by use of monocrystalline diamond as cutting material. With different replication technologies, it is possible to transfer these values to the final product. Injection molding, hot embossing and glass-pressing are of high potential for molding optical components. Until recently, manufacturing of metallic moulds and dies by cutting with geometrically defined cutting edges was limited to work piece materials that are traditionally machinable with monocrystalline diamond. These materials are non-ferrous metals and especially platings of electroless nickel-phosphorus (ElNiP). Ultraprecision machining of steel with geometrically defined diamond cutting edge is not yet a stable industrial process. Therefore the optical surface quality corresponding to the optical function on the final product is achieved by polishing, classically. Unfortunately, the form accuracy of the work piece is affected by polishing processes.

At the present time there are four different approaches to overcome the disadvantages of polishing by direct machining with ultraprecision technologies:

**Approach I: Shortening the contact time between work piece and tool**

Beside lattice faults, diamond wear is mainly caused by the transformation of diamond into graphite, which is the more stable phase of carbon at room temperature. This transformation results from high pressure and/or high temperature. The pressure and temperature values for the diamond-to-graphite conversion depend on the properties of the diamond used. Particularly with regard to natural diamond there is to observe a broad range of dispersion. Adequate accurate data are not available, especially for the necessary pressure. The temperature of graphitization can be specified as $T > 550^\circ\text{C}$. With shortening the contact time between work piece and tool, the temperature of the cutting part can be reduced significantly. Thereby, in steel it is possible to achieve an arithmetical mean deviation of $Ra = 5$ nm [1].

**Approach II: Tool cooling**

With the same goal, the reduction of the cutting part temperature, tools are cooled in process. E.g. liquid nitrogen is used as coolant to reduce the temperature of the diamond cutting part. Up to now, no relevant advantage was obtained for steel machining by research activities [2].

**Approach III: Work piece material modification**

Initial point of this approach is a special characteristic of nickel. Nickel alloyed with phosphorus is diamond machinable while nickel itself is not. Free electrons that could react with carbon are bound by the alloying addition. Regarding this, efforts are made to use a similar effect for steel machining. With surface layer nitration of steel materials, first promising results were obtained [3].

**Approach IV: Use of alternative cutting materials**

Comprehensive investigations were made to substitute monocrystalline diamond as cutting material for ultra precision machining with geometrically defined cutting edge. Cutting materials used are e.g. aluminium oxide, cBN or diamond coated hard metal. Especially the application of cBN seems to be successful. 25CrMoS4 (60 to 65 HRC) was machined with PcBN BNX10 at a minimum roughness of $Ra = 10$ nm [4]. A roughness value of $Ra = 65$ nm has been achieved with monocrystalline cBN [5].
Objective
Starting from existing results mentioned above, objective of a research project at the Center for Production Technology (PTZ) in Berlin is to scrutinize the potential of Binderless cBN as cutting material for ultraprecision machining of steel with geometrically defined cutting edge. Goal is the complete machining by cutting of mould and die surfaces for the replication of optical components. At least, the process chain for the production of steel replication tools shall be shortened considerably by substituting process steps. Thus, a higher form accuracy of the final product will be achieved.

Experiments
Facing experiments with steel 40CrMnMoS8.6 were conducted. The material was used fully heat-treated by the manufacturer with a measured hardness of 54 HRC. The experiments were done at a 5-axis ultraprecision machining system Nanotech® 350 FG (Moore Nanotechnology Systems, Keene/USA). For measurements a confocal Laser-Scanning-Microscope LSM 5 Pascal (Carl Zeiss, Jena/Germany), a White-Light-Interferometer NewView 5010 (Zygo Corporation, Middlefield/USA), a Scanning-Electron-Microscope DSM 950 (Carl Zeiss SMT, Oberkochen/Germany), and a machine integrated optical tool setter were used.

Experimental Results with PcBN
First, experiments with PcBN were conducted. Within these tests, input parameters for the following experiments with Binderless cBN were identified.

<table>
<thead>
<tr>
<th>Cutting material</th>
<th>Tool corner radius $r_{c}/mm$</th>
<th>Cutting edge roundness $r_{b}/µm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTC 2000</td>
<td>1.5</td>
<td>8</td>
</tr>
<tr>
<td>HTC 2000</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>BZN 9100</td>
<td>3</td>
<td>25</td>
</tr>
</tbody>
</table>

The cutting edge roundness is measured by ZEISS LSM 5 PASCAL (Objective Epiplan Neofluar 50/0.8), respectively. The particular roundness was determined as average value of 10 measurements on different tool corner positions. Thereby 3-point circle determination was used. The tool corner radii are measured by the optical tool setter.

During these experiments were varied cutting speed $v$, feed per revolution $s$, and depth of cut $a$. Regarding roughness as criteria for the surface quality, the best result was achieved with an arithmetical mean deviation of $Ra = 27$ nm. Best Peak-Valley value was $P-V = 285$ nm. The roughness was measured with a Zygo NewView 5010 (Objective 20/0.4) at a measuring length of 670 µm. The tool had a cutting part made of HTC 2000 and a corner radius of $r_{c} = 3$ mm. Total tool path was $W(Ra) = 40$ m. As criterion of tool wear an increase of roughness value of 50% was defined. Used machining parameters were:

- Cutting speed: $v = 145$ m/min,
- Depth of cut: $a = 5$ µm,
- Feed per revolution: $s = 10$ µm/r.

These were the starting values of the facing experiment with Binderless cBN as cutting material.

Experimental Results with Binderless cBN
According to specifications provided by the manufacturer, Binderless cBN has the following properties:

- Hardness: 45 GPa
- Elasticity (Young’s modulus): 710 GPa
- Thermal stability on air: 1300°C
- Grain size: < 0.5 µm
- cBN proportion: 99.7 %
- Other constituents: hbN.

It was not possible, due to the disposability of the cutting material, to use the same tool corner radii as for the PcBN experiments. The tests were made with the specifications mentioned in Table 2. The tool geometry measurements are done similarly to the PcBN tools.

<table>
<thead>
<tr>
<th>Tool No.</th>
<th>SEM image</th>
<th>SEM image</th>
<th>SEM image</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1.png" alt="SEM image 1" /></td>
<td><img src="image2.png" alt="SEM image 2" /></td>
<td><img src="image3.png" alt="SEM image 3" /></td>
</tr>
<tr>
<td>2</td>
<td><img src="image4.png" alt="SEM image 4" /></td>
<td><img src="image5.png" alt="SEM image 5" /></td>
<td><img src="image6.png" alt="SEM image 6" /></td>
</tr>
<tr>
<td>3</td>
<td><img src="image7.png" alt="SEM image 7" /></td>
<td><img src="image8.png" alt="SEM image 8" /></td>
<td><img src="image9.png" alt="SEM image 9" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tool corner radius</th>
<th>Cutting edge roundness</th>
<th>Rake face</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 mm</td>
<td>3 µm</td>
<td>raw</td>
</tr>
<tr>
<td>0.8 mm</td>
<td>2.1 µm</td>
<td>ground</td>
</tr>
<tr>
<td>0.8 mm</td>
<td>1.4 µm</td>
<td>finished</td>
</tr>
</tbody>
</table>
The scrutinized tools have a chip angle of $\gamma = 0^\circ$ and a clearance angle of $\alpha = 8^\circ$.

Starting with the previously mentioned and in the PcBN tests established cutting parameters, experiments were made under variation of $v$, $s$, and $a$. Regarding the roughness, it was found that best results were obtained at a cutting speed of $v = 135$ m/min and a feed per revolution of $s = 5$ $\mu$m. The results are listed in Table 3.

**TABLE 3: Arithmetical mean deviation $Ra$ as result of facing experiments with Binderless cBN (measured with a Zygo NewView 5010; objective 20/0.4; measuring length 900 $\mu$m)**

<table>
<thead>
<tr>
<th>Tool No.</th>
<th>Cutting distance m/m</th>
<th>Arithmetical mean deviation $Ra$ $/nm$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cutting distance m/m</td>
<td>Depth of cut $a = 10$ $\mu$m</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>495</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>395</td>
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<td>45</td>
<td>182</td>
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<tr>
<td>2</td>
<td>5</td>
<td>77</td>
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<td></td>
<td>25</td>
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<td>5</td>
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<td>36</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>27</td>
</tr>
</tbody>
</table>

The SEM image of a surface topography made with tool No. 3 is shown in Fig. 1. Fig. 2 is a white light interferometric image of the same surface.

![Figure 1. SEM image of a faced surface, machined with Binderless cBN; $v = 135$ m/min, $s = 10$ $\mu$m, $a = 5$ $\mu$m](image1)

![Figure 2. WLI image of a faced surface, machined with Binderless cBN; $v = 135$ m/min, $s = 10$ $\mu$m, $a = 5$ $\mu$m](image2)

Both images demonstrate a surface of high quality. Fig. 1 illustrates the formation of a homogeneous turned surface. Fig. 2 is to display the evenness of the surface. At the same time the image indicates the crossover between the different areas caused by different tool states.

During the experiments, there were different wear indications noticeable at the tool edges. E.g.: wear by cratering, flank wear, and cutting edge chipping. Fig. 3 shows the topology of the cutting edge of tool No. 2 during the machining. It also illustrates the potential of creation cutting edges with smaller cutting edge roundness.

![Figure 3. Topology of a Binderless cBN cutting edge during a facing experiment; unprocessed (top left), condition at the beginning of the machining (top right), condition during machining (bottom left), worn (bottom right); $v = 135$ m/min-$1$, $sf = 10$ $\mu$m, $a = 5$ $\mu$m](image3)
Four conditions can be distinguished:

**Condition I: Unprocessed condition**
The tool is unused. The cutting edge roundness is determined by the cutting edge preparation.

**Condition II: Starting condition**
There is to observe starting flank wear and thus leveling of the cutting edge roundness. This leads to machining condition.

**Condition III: Machining condition**
A quasi-stationary condition of the cutting edge is reached. At this condition, the best roughness values can be achieved.

**Condition IV: Wear condition**
Dominant wear indication is flank wear followed by adhesion of workpiece material onto the flank. It is assumed, that these adhesions lead to a stronger deflection of the tool. This causes tool vibration and chattering. The resulting impact load onto the cutting part leads to cracks and chipping of single grains out of the cutting edge. Thus it is reached the starting point for catastrophic tool wear.

**Conclusion and Outlook**
Successful ultraprecision facing experiments of fully heat-treated steel 40CrMnMoS8.6 has been made with Binderless cBN as cutting material. Results of roughness values Ra < 35 nm and peak to valley of P-V < 200 nm were achieved. Removal rate is Q > 0.1 mm³/s and the tool total path is about W(Ra) = 80 m. The generated surfaces show a homogeneous structure. Tools can be evaluated regarding geometrical characteristics and abrasion. Experiments show, that the cutting material Binderless cBN is of high potential regarding the machining of steel for moulds and dies. Despite the achieved roughness, the obtained surfaces are not of optical quality. This is documented by a Ra/P-V ratio of about 1/7. And despite the homogeneity, the surface is refractive and therefore appears rough.

In further research activities, particularly the preparation of the cutting edge has to be scrutinized. This is necessary to guarantee a stationary condition of the cutting edge from the beginning of the machining. With an adapted geometry of the cutting edge, this condition can be sustained considerably longer as currently possible. Further investigations must be carried out in the area of adapted cutting part geometry.

This is essential for broadening the machinable material spectrum to stainless steel, too. Goal is the direct ultraprecision machining of different tool steels. That requires comprehensive analytic investigations in order to anticipate surely the in-process behaviour of the cutting edge and thus to increase process reliability.

**REFERENCES**