Laser preparation of PcBN cutting tools is a new approach to improve the performance of different machining applications. Laser machining is robust and wear-free which offers benefits compared to conventional methods, such as grinding and brushing. Moreover, the conventional preparation methods are limited for the preparation of super hard cutting tool materials and the generation of complicated geometrical features because of high tool wear. A highly demanding application of PcBN cutting tools is the machining of Ni-based super alloys such as Inconel 718. For various high and low temperature applications in aerospace systems this material is popular because of its temperature, oxidation and corrosion resistant characteristics. However, these characteristics and an intense work hardening behavior make Inconel 718 a hard-to-cut material. A possibility to increase the performance in cutting hard-to-cut materials is the application of a process specific cutting edge rounding prepared by laser machining. However, there is no available knowledge neither on the influence of laser machining on the material properties of PcBN nor on the influence on the cutting performance. This research deals with the effect of laser preparation on the cutting performance of PcBN tools in machining Inconel 718. Different laser preparation strategies are applied to provide necessary knowledge regarding the laser preparation process. The formation of hexagonal boron nitride (hBN) on the surface is found for all of the applied laser preparation strategies, however the degree of the cBN to hBN transformation differs between the applied strategies. Within the cutting experiments the wear behavior is closely linked to the formation of hBN, which decreases the hardness of the PcBN material. Furthermore, process forces for the laser prepared tools are reduced compared to the conventional tools, which might be an influence of the hBN acting as a solid lubricant. Finally, it could be shown that the achieved tool life of laser prepared tools is at least on a par with conventionally machined tools.

Introduction
Cutting edge microgeometry has a strong impact on cutting performance and tool life [1–3]. The underlying physical mechanism is the reduction of the stress concentration in the cutting wedge [2]. Several conventional methods such as grinding, brushing and abrasive jet machining have already been established in industry to provide adequately rounded cutting edges. Still, difficulties arise from the cutting edge preparation of superhard cutting materials such as polycrystalline diamond (PCD) or PcBN due to high tool wear of the applied preparation tools and low resulting process reliability. In this case laser based preparation of cutting edges and tool geometries is gaining importance in research and industry [4–8]. Pulsed laser ablation (PLA) technology is used to transfer high specific energy to the sample in a targeted area, which allows for a direct sublimation of the material. Pacella and Pacella et al. investigate laser machining of different PcBN and PCD grades and their thermal response to laser ablation. Regarding PcBN, the formation of hBN and other lattice modifications of the cubic boron nitride form is detected on
the laser machined surface using transmission electron microscopy (TEM) [5,6]. Suzuki et al. found that the hardness of PcBN tools is increased up to 20% due to the formation of hard TiB₂ within the binder matrix [7]. The hardness increase of the PcBN tool could be linked to a decreasing roughness in the turning experiment. Similar results were obtained by Breidenstein et al. [8]. In contrast to the formation of TiB₂, the presence of hBN at the surface is expected to have a negative influence on the cutting tool properties (such as a reduced hardness). However, this lattice transformation is difficult to measure using XRD methods, especially if the transition area is small. Therefore, it is the aim of this research to quantify the influence of possible hBN formation in laser machining of PcBN and link the presence of hBN to the cutting performance in cutting Inconel 718.

### Experimental setup

In this investigation PcBN tools (SECO CBN170 CNGA120408) with a specified cBN-content of c_{cBN} = 65 wt%, TiCN as binder material and a mean grain size of d_{grain} = 3 μm were used. The exact chemical composition as measured by EDX on the tool surface is given in Table 1. The material texture before laser preparation is shown in Figure 1.

A DMG Sauer Lasertec 40 machine tool is used for the laser preparation. This machine tool is equipped with a 13 W Q-switch Nd:YVO₄-Nanosecond laser with a wavelength of λ = 1,064 nm, a pulse distance of τ_P = 70 ns and a focus diameter of 40 μm. The experiments were conducted with a constant repetition rate of f_r = 100 kHz. The mean power P_m and the laser feed speed v_f were varied according to Table 2. The applied laser parameters enable a constant areal fluence F_A for all parameter combinations (P1–P3), whereas differences regarding the single pulse fluence F_p are applied by changing the laser mean power P_m [5]. In so far the introduced laser beam energy per layer is equal for all laser experiments, whereas the configuration regarding energy impact time and impact intensity is different. The track distance TD was chosen according to the pulse distance PD to ensure an evenly structured surface. The pulse distance PD can be calculated as quotient of laser feed velocity v_f and repetition rate f_r. Unidirectional hatch style was chosen.

The roughness was characterized by a roughness tester Hommel-Etamic-W5. Each measurement was repeated three times. The cutting edge geometry was examined on an Alicona InfiniteFocus G5 focus variation microscope. The cutting experiments were performed on a CNC lathe Gildemeister CTX 520 linear. The machine was equipped with a high pressure coolant supply (70 bar), focussed on the cutting tool rake face. Cutting speed, depth of cut and feed were set at v_c = 200 m/min, a_p = 0.2 mm and f = 0.1 mm, respectively. The cutting experiments were conducted up to 5 minutes for all specimens. Tool wear was analyzed on a digital microscope Keyence VHX600.

Cutting forces were measured with a Kistler dynamometer type 5015. Surface topography, texture and adhesion on the surface of laser prepared and worn tools were analyzed using a scanning electron microscope (SEM) Zeiss EVO 60 VP. For the analysis of the crystallographic structure of the laser processed PcBN, Raman measurements were conducted. Raman spectra were analyzed using a Bruker Senterra Raman spectrometer with an excitation wavelength of λ = 532 nm, a beam intensity of P = 20 mW and a focal spot size of d_{focus} = 5 μm. Vickers hardness measurements were conducted on a Struers Duramin 5 hardness tester. Each hardness measurement was repeated four times.

### Results and discussion

For the preparation of cutting tools the test plan as depicted in Table 3 was established.

All cutting tools were ground previously to the cutting edge preparation with a resulting cutting edge radius of approximately 4 μm. To generate the cutting edge geometry on the cutting tool, an stl-file was designed in Siemens NX® and applied in the control software of the laser machine tool to derive the required laser beam paths. P1, P2 and P3 parameter combinations are used for producing a small radius micro geometry tool which is around S_x = S_y = 25 μm. A bigger radius micro geometry (S_x = S_y = 40 μm) is produced by P1 and P3 parameter combinations. The cutting edge preparation was performed in two different strategies. First, the preparation of the cutting edge is finished by a preparation perpendicular to the rake face. Second, a combined preparation of flank face and rake face is used. The corresponding preparation strategies are named “P1 comb.” and “P3 comb.”

### Table 1

<table>
<thead>
<tr>
<th>Element</th>
<th>B</th>
<th>N</th>
<th>Al</th>
<th>Si</th>
<th>Ti</th>
<th>W</th>
<th>C</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>36.9</td>
<td>25.8</td>
<td>7.0</td>
<td>1.9</td>
<td>19.3</td>
<td>2.2</td>
<td>3.3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Figure 2 presents the laser prepared PcBN tools after PLA, examined by the optical measurement instrument Alicona Infinite Focus G5. Moreover, the achieved cutting edge roughness for each of the displayed parameter combinations is given. The lowest cutting edge roughness is achieved for the reference tool which was conventionally brushed using a diamond containing brushing tool. The other preparation methods result in an increased cutting edge roughness. Especially the combined preparation from flank and rake face leads to a reduced cutting edge quality.

Figure 3 presents the resultant cutting edge size of $S_x$ and $S_y$ after PLA. It is shown that the desired values for the cutting edge are achieved with a maximum deviation of approximately 10 μm for the combination strategy P1. For the case of the combined preparation from flank and rake face leads to a reduced cutting edge quality.

### Table 3

<table>
<thead>
<tr>
<th>Geometry 1: $S_x = S_y = 25 \mu m$</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P1 comb.</th>
<th>P3 comb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry 2: $S_x = S_y = 40 \mu m$</td>
<td>G1-P1</td>
<td>G1-P2</td>
<td>G1-P3</td>
<td>Not conducted</td>
<td>not conducted</td>
</tr>
</tbody>
</table>

**Laser source**
- ns-Laser
- $\tau = 70$ ns
- $\lambda = 1,064$ nm

**Laser parameters**
- $P_m = 3.5 - 5.5$ W
- $f = 100$ kHz
- $v_f = 0.7 - 1$ m/s
- Binder: TiCN

**Tool**
- CNGA120408
- cBN-content: 65%

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**FIGURE 2**
Alicona Infinite Focus G5 image of PcBN tools after laser preparation.

**FIGURE 3**
Resultant cutting edge size of $S_x$ and $S_y$. 
processing the cutting edge geometry is harder to control due to the fact, that both ablation steps interact with each other. The last preparation step was always executed perpendicular to the rake face. Because the flank face preparation also resulted in a small rounding of the cutting edge, the applied geometrical model to generate the final geometry in the combined preparation was changed to a smaller radius by 10 \( \mu \text{m} \).

Figure 4 represents Raman analyses of both unprepared and laser prepared tools. In the different Raman spectra the peaks of cBN \((X_{\text{TG}} = 1,054 \text{ cm}^{-1}, X_{\text{LO}} = 1,304 \text{ cm}^{-1})\) and hBN \((X = 1,364 \text{ cm}^{-1})\) are visible [9]. Furthermore, flat signal peaks resulting from the presence of non-stoichiometric \( \text{TiC}_{1-x} \) are visible as a resultant transformation of the titanium based binder [10]. Moreover, in one Raman spectrum for P1, the presence of boron oxide \( \text{B}_{2}\text{O}_{3} \) is detected.

The unprepared specimen is characterized by the presence of solely cBN peaks. Applying laser preparation to the cutting tool results in the presence of hBN independently of the applied laser parameter combination. However, for P1 and P3 Raman spectra with a dominant hBN peak compared to the cBN peaks are obtained, which proofs a high amount of transformed boron nitride in the specific area of measurement. For the P3 parameter combination, the cBN-peaks remain dominant, even though hBN presence is visible. In so far it is likely to assume that the transformation from cBN to hBN is only partly for that parameter combination. To quantify the impact of the surface transformation the hardness of the surface after PLA was measured for all parameter combinations and the results are shown in Table 4. Each measurement was repeated five times. All specimens show a significant decrease in hardness compared to the unprepared reference tool. The highest hardness of laser prepared specimens is achieved for P3, which validates the interpretation of the Raman results. Investigating the microstructure of the laser prepared tools using SEM in Figure 5 shows that for P1 the surface is characterized by a dense, probably hBN, structure. In contrast to that the surface of the P3 specimen is more porous and reveals protruding sharp edges from “untransformed” cBN-grains.

Figure 6 shows the progression of the flank wear land for the laser prepared cutting tools with small radius geometry (G1) in comparison to conventionally prepared tools. Moreover, the flank wear land progression for laser prepared cutting tools with big radius geometry (G2) is shown in Figure 7. The presented graph values represent mean values of two experiments, the corresponding minimum and maximum value is also displayed.

<table>
<thead>
<tr>
<th>Laser source</th>
<th>Laser parameters</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>ns-Laser</td>
<td>( P_m = 3.5 \sim 5.5 \text{ W} )</td>
<td>CNCA120408</td>
</tr>
<tr>
<td>( \tau = 70 \text{ ns} )</td>
<td>( f = 100 \text{ kHz} )</td>
<td>cBN-content: 65 %</td>
</tr>
<tr>
<td>( \lambda = 1,064 \text{ nm} )</td>
<td>( v_f = 0.7 \sim 1 \text{ m/s} )</td>
<td>Binder: TiCN</td>
</tr>
</tbody>
</table>

![Figure 4](image)

**Figure 4**
Raman analysis of unprepared and laser prepared P-cBN tools.

**Table 4**

<table>
<thead>
<tr>
<th>Hardness of the laser prepared specimens.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
</tr>
<tr>
<td>Hardness ( HV_1 ) and standard deviation ( \sigma )</td>
</tr>
</tbody>
</table>

Moreover, SEM images of the tools after a cutting time of five minutes are displayed in Figure 8. In Figure 6 it can be seen that lowest flank wear is achieved for parameter combination P3. It is to mention that one P3 tool showed a severe cutting edge...
breakout between three and five minutes of cutting time, which made the evaluation of the flank wear after five minutes impossible. The other applied parameters exhibit a tool wear behavior very close to the reference tool. Based on the above shown analytical results it is likely to assume that the P3 parameter combination is beneficial compared to the other laser parameter combinations due to a higher tool hardness induced by less hBN formation. As it can be seen in Figure 8 the cutting tool prepared with parameter combination 1 (G1-P1) exhibits higher notch wear and chipping compared to G1-P3. However, the reduced tool wear compared to the reference tool cannot be explained based on this finding, because the hardness of the laser prepared tool is still lower compared to the conventional one.

In Figure 7 it can be seen that the lowest flank wear is also achieved by P3 parameter combination using the ablation strategy perpendicular to the rake face. Both tools with parameter combinations P1 and P3 show a more stable cutting edge compared to the applied tools with geometry G1, due to the higher edge stability (Figure 8). However, flank wear for P1 is still slightly increased compared to P3. A combined preparation of flank and rake face leads to an increase of the obtained flank wear due to the lower surface quality of the flank face and the presence of hBN on the flank face. In particular this applies for the high single pulse preparation setup P1, which results in severe chipping of the cutting edge (Figure 8). However, to investigate the reason for the superior behavior of the parameter combination P3 compared to the other specimens and the reference tool, force measurements were conducted. The results are displayed in Figure 9.

For the displayed force measurements the mean values for the two applied tools per parameter combination were considered. Force measurements were conducted after 1, 3 and 5 min of cutting time. All applied tools exhibit a decrease in the process forces compared to the reference tool. Maximum forces decrease portion is about 20% depending on the force direction. For P1 parameter combination a distinct rise of the cutting force for the increased cutting edge radius is found which is not visible for the P3 parameter combination. A possible reason for the decrease of the cutting forces is the presence of hBN material in the cutting zone, which can act as a solid lubricant [7].
However, an exceeding of a critical cBN to hBN transformation grade can result in an increased wear due to a stability lack of the cutting wedge.

**Conclusion**

Based on the obtained results the following conclusions can be drawn:

- PLA using ns-laser leads to a transformation of cBN to hBN in all considered laser parameter combinations.
- The cutting tool hardness is significantly decreased by the hBN formation down to 1,700 HV\(_1\) (from over 3,400 HV\(_1\)). However, not all laser parameters reduce hardness by the same amount.
- Tools with laser prepared cutting edges achieve comparable tool wear to reference tool when applying appropriate laser parameters.
- There is an indication that the transformed hBN acts as a solid lubricant, which leads to a decrease of the cutting forces.
- High tool life can be achieved by a laser preparation which forms enough hBN to act as a lubricant without reducing cutting edge stability to a critical value.

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**References**