Technological investigation of binderless nanocrystalline cubic boron nitride (BNNC) as cutting material for groove turning of hardened steels

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Abstract. By using a high-pressure/high-temperature process (HP/HT), it is possible to synthesise new ultra-hard cutting materials called binderless nanocrystalline cubic boron nitride (BNNC). The starting material is a pyrolytically deposited hexagonal boron nitride (pBN), which is converted at temperatures of 1400 °C – 2200 °C and pressures of 10 - 20 GPa in a direct synthesis without any binding material. The average crystallite size of this material is 50 - 100 nm and is thus significantly smaller than conventional polycrystalline cubic boron nitride (PCBN) cutting materials. Compared to conventional PCBN cutting materials, this material has an increased hardness, hot hardness and better temperature resistance. This provides an excellent alternative to extend the process limits for the machining of hardened steels and superalloys. In this conference paper, the first technological results for groove turning in hardened steels with this new promising cutting material will be presented.

1. Introduction
The increasing demands on manufacturing quality in conjunction with lower costs and the ever-increasing competitive pressure are forcing metalworking companies to optimize their manufacturing processes as part of a continuous improvement process, for example by reducing manufacturing steps or applying more productive machining processes. The substitution of machining processes, especially abrasive processes, is an obvious solution. These processes are comparatively cost-intensive and can be replaced by processes with geometrically defined cutting edges in the form of hard machining. In addition, paths to the productive and economical processing of large quantities must be consistently followed.

The desire to replace grinding with hard turning is based on the advantages that hard turning offers against grinding:

- Shorter production times per component due to increased chip cross sections,
- Higher process flexibility,
- No cooling lubricant in classic form (oil, emulsion) required.

Cutting tools with polycrystalline cubic boron nitride (PCBN) as cutting material are used in machining of hardened steels (55 – 68 HRC), high-speed steels, grey cast iron and sintered metals with...
a geometrically defined cutting edge. With regard to the surface quality that can be produced, these PCBN cutting materials are limited (approximately \( R_z = 1 \mu m \)) [1]. This can be explained by the polycrystalline structure and crystallite sizes in the size range from \( 1 \mu m \) – \( 10 \mu m \). Furthermore, PCBN cutting materials have a binder phase which is attached between the crystallites and connects the individual crystallites with each other. Under heavy loads and high temperatures, the binder at the cutting edge will become softened and abraded, resulting in an increased grain breakage, which will reduce its stability. In addition, the mostly monocrystalline cBN grains in these conventional cBN sintered materials have a comparatively low intrinsic toughness of approximately \( 3 \text{ MPam}^{1/2} \) and break along preferred cleavage planes [2]. The consequence of all this is that the topology of the cutting edge deteriorates due to grain breakage, chipping and abrasion, which will reduce the surface quality of the machined workpieces.

A great potential is currently attributed to the binderless nanocrystalline boron nitride (BNNC - "boron nitride nanocomposite") [3], which can only be produced by high-pressure high-temperature synthesis (HP/HT). The decisive difference to the currently used PCBN cutting materials is that there is no metallic or ceramic binder phase between the cBN single crystals and that the single crystallites of the BNNC have a size between \( 50 – 100 \text{ nm} \) [4]. This can increase the tool life and improve the surface quality of the workpiece to be machined [5].

This research work describes the results of the manufacturing process, the material properties of the BNNC and the results of the technological investigation of groove turning with BNNC as cutting material for hardened steels.

2. Production and material properties of BNNC

BNNC consist of nanoscale domains of cubic (cBN), wurzitic (wBN) and hexagonal (h-BN) boron nitride and are synthesized under high pressure/high temperature conditions (HP/HT) by direct synthesis. A direct conversion into a diamond-like modification takes place without the use of a metallic melt as solvent and catalyst. Hot-pressed boron nitride (HDBN) or pyrolytically deposited boron nitride (pBN), both made of graphitic hexagonal boron nitride (hBN), can be used as starting materials [6].

The conditions with a pressure of approximately \( 10 \text{ GPa} \) and temperatures between \( 1400^\circ\text{C} \) and \( 2200^\circ\text{C} \) are realized by a Multianvil press. Because of the composite structure and the 'crystallographic interlocking' of the 3 nanoscale components (cBN/ wBN/ hBN) higher mechanical strengths can be achieved than with pure cBN [7].

Figure 1 shows the Multianvil press with the Walker-type module to realize the high pressures and temperatures for the synthesis of BNNC.

![Figure 1. Multianvil press with the Walker-type module for the HP/HT synthesis of BNNC.](image)

Table 1 shows the material properties of PCBN and BNNC. The mean grain sizes of BNNC are significantly smaller, which results in a significantly higher hardness because of the Hall-Petch relationship. The BNNC consists of pure boron nitride, of which approximately 94 vol. % have been converted to cBN and approx. 6 vol. % hBN are still present [4].
Table 1. Material properties of PCBN and BNNC [4]

| Name   | Hardness (HK₀.5) | Average crystallite size of cBN (nm) | Proportion cBN (vol. %) | Proportion hBN (vol. %) | Proportion Co-Al (vol. %) |
|--------|-----------------|------------------------------------|------------------------|------------------------|--------------------------|
| PCBN   | ≈ 3500          | 500 - 1000                         | 92 ± 3                 | -                      | 8 ± 3                    |
| BNNC   | ≈ 5000          | 50 - 100                           | 94 ± 2                 | 6 ± 2                  | -                        |

For the groove turning tests, grooving tools were manufactured with PCBN and BNNC as cutting materials. Figure 2 and figure 3 show the rake faces of the tools. With regard to the surface topography, clear differences can be seen, which are explained by the fact that the higher hardness of the BNNC results in material cutting through brittle material behavior caused by the occurrence of lateral microcracks, which only result in the smallest chip particles splitting off. This results in high cutting forces and a high tool wear during the cutting edge preparation of BNNC by grinding [4]. The same tools and the same technological setting parameters were used to create the surfaces.

![Figure 2. Surface of the rake face of the grooving tool with PCBN as cutting material.](image1)

![Figure 3. Surface of the rake face of the grooving tool with BNNC as cutting material.](image2)

This is also confirmed by the analysis of the roughness parameters Rz, Ra and Rmax on the rake face of the cutting tools (table 2) The PCBN cutting material shows significantly better surface characteristics, which significantly determine the friction conditions in the cutting zone. If the surface quality is poor, the friction coefficient increases, which promotes abrasive wear on the rake face and the free face.

Table 2. Surface parameters with standard deviation on the rake face of the tools (Lt = 1.5 mm)

| Name   | Arithmetic mean roughness Ra M ± SD (µm) | Averaged roughness height Rz M ± SD (µm) | Maximum roughness height Rmax M ± SD (µm) |
|--------|------------------------------------------|------------------------------------------|------------------------------------------|
| PCBN   | 0.12 ± 0.015                             | 0.75 ± 0.138                             | 0.91 ± 0.197                             |
| BNNC   | 0.26 ± 0.026                             | 2.07 ± 0.727                             | 2.51 ± 0.752                             |

While BNNC has promising material properties compared to PCBN, the geometric analysis of the surface shows that it does not match the quality of the PCBN cutting material after the cutting edge preparation. This is explained by the high hardness, which makes the cutting process more difficult when grinding the rake face of the cutting tool. At this point, further investigations of the cutting edge preparation of BNNC are necessary to achieve the best possible surfaces.

3. Experimental conditions

to evaluate the cutting materials for groove turning applications, grooving tools with PCBN and BNNC as cutting materials and a cutting edge width of B = 3 mm and B = 2.2 mm were manufactured (figure 4). These tools were clamped in a groove turning tool holder. These grooving tools were used for the experiments to turn grooves into a hardened rolling bearing steel 1.3505 (62 ± 2 HRC) and into
a hardened alloy tool steel 1.2379 (62 ± 2 HRC). To measure the cutting forces $F_c$, the feed force $F_f$, and the passive force $F_p$, a stationary 3-component dynamometer type KISTLER 9129AA was integrated into the tool mounting system (figure 5). A lathe of the type DMG CTX 300 Alpha was used for the technological investigations.

To assess the cutting material, a radial cut was made into the workpiece with the complete width of the tool and a radial cutting depth of $a_r = 3$ mm or $a_r = 2$ mm was defined. The cutting speed was varied while the radial feed $f_r$ was maintained constant.

### 4. Results and discussion

The evaluation of the cutting force $F_c$ (figure 6) shows that lower cutting forces $F_c$ occur up to a cutting speed of $v_c = 160$ m/min by using the BNNC cutting material than the PCBN cutting material. This is also confirmed by the results of the feed force $F_f$ measurement (figure 7). At a cutting speed of $v_c = 180$ m/min, the BNNC cutting material generates significantly higher cutting and feed forces. It is recognizable that with an increasing cutting speed the cutting forces decrease for PCBN cutting material, while they increase slightly with BNNC cutting material.

For the cutting speed of $v_c = 180$ m/min, the cutting forces (figure 8) and the feed forces (figure 9) up to a cutting distance of $l_c = 240$ m were measured at regular intervals. It clearly shows that the cutting force and the feed force of the BNNC cutting material increase continuously over the cutting length. This can be justified by the fact that at high cutting speeds, in addition to the increase of the temperature in the cutting zone, the chip velocity $v_{ch}$ also increases and also the proportion of rake face friction. Therefore, additional energy must be used to realize the separation work and to compensate the rake face friction. In addition, the friction force rises with an increasing feed force.
Figure 8. Cutting forces $F_c$ up to a cutting length of $l_c = 240$ m, $v_c = 180$ m/min.

Figure 9. Feed forces $F_f$ up to a cutting length of $l_c = 240$ m, $v_c = 180$ m/min.

As a result of the increased rake face friction, there is strong abrasive wear, as a consequence of crater wear on the rake face can quickly appear. Figure 10 and figure 11 show the rake face of the PCBN or BNNC after a cutting path of $l_c = 240$ m. At the BNNC cutting edge the crater wear is very clearly visible, whereas with the PCBN cutting edge hardly any crater wear is visible.

Figure 10. Rake face of PCBN after $l_c = 240$ m, $v_c = 180$ m/min.

Figure 11. Rake face of BNNC after $l_c = 240$ m, $v_c = 180$ m/min.

Figure 12 and figure 13 show SEM images of the flank faces of the PCBN and BNNC cutting edge. Also here it can be seen that the width of the flank wear land of the BNNC cutting material is more pronounced. Also, clear material adhesion is visible, which also indicates a higher coefficient of friction.

Figure 12. Flank face of PCBN, after $l_c = 240$ m, $v_c = 180$ m/min.

Figure 13. Flank face of BNNC, after $l_c = 240$ m, $v_c = 180$ m/min.

In a further test, grooves were also made by groove turning on a hardened alloy tool steel 1.2379 (62 ± 2 HRC). Tools with a cutting-edge width of $B = 2.2$ mm and a cutting speed of $v_c = 160$ m/min were used for this operation. Fig. 14 clearly shows that in this case the cutting forces by using the BNNC cutting material are significantly lower than by using the PCBN cutting material. The feed forces in figure 15 show higher values, which can also be explained by the poor surface topography on the rake face. With the PCBN cutting material, the cutting edge chipped after approximately $l_c = 590$
m, causing the cutting forces to increase abruptly. With the BNNC cutting material, the cutting edge chipped after a cutting length of \( l_c = 680 \) m.

![Figure 14](image1.png) \( \text{Cutting forces } F_c \text{ up to tool failure } v_c = 160 \text{ m/min.} \)

![Figure 15](image2.png) \( \text{Feed forces } F_r \text{ up to tool failure } v_c = 160 \text{ m/min.} \)

5. Summary and conclusions
The results show that the BNNC cutting material is significantly harder than the PCBN cutting material, but this also makes the cutting edge preparation much more difficult. This means that conventional processes cannot produce surfaces at the cutting edge comparable to PCBN cutting materials. This increases the chip surface friction between tool and chip, which increases the cutting forces and promotes scour wear. This is confirmed by the groove turning tests on 1.3505 (62 ± 2 HRC). Notwithstanding the lower surface quality at the cutting edge of the BNNC, the tool life increases when machining 1.2379 (62 ± 2 HRC) by using a cutting speed of \( v_c = 160 \) m/min. This confirms the potential of this cutting material for hard turning applications and high loads, such as grooving or roughing. It is therefore necessary to carry out further technological research on cutting edge preparation at the BNNC and to develop an optimum technology for this purpose.

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References
[1] Klocke F 2011 Manufacturing Processes 1
[2] Tromans D and Meech J A 2004 F Miner. Eng. 17 1–15
[3] Fujisaki K, Yokota H, Furushiro N et al 2009 J. Mater. Process. Technol. 209 5646–52
[4] Hânel A, Hasterok M, Schwarz M et al 2018 Procedia CIRP 77 493–6
[5] Bushlya V, Petrusha I, Gutnichenko O et al 2014 6th Swedish Prod. Symp. 1–10
[6] Rafaja D, Klemm V, Motylenko M et al 2008 J. Mater. Res. 23 981–93
[7] Sumiya H, Harano K and Ishida Y 2014 Diam. Relat. Mater. 41 14–9