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Investigation of Machining Parameters for Binderless Cemented Carbide Turning Using NPD Tools

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Abstract
Today's demands on technical applications require the precise machining of high-performance materials. Due to its wear resistance, cemented carbide is used in a variety of industrial sectors, including tool and mould making, mobility and medical technology. However, due to its brittle material properties combined with the high hardness and wear resistance, the machining of binderless cemented carbide materials with geometrically defined cutting edges is strongly limited. Long machining times and high tool wear remain significant challenges in the current state-of-the-art for cutting binderless cemented carbide materials. A promising approach for machining binderless cemented carbide is the use of binderless nanopolycrystalline diamonds (NPD) as a cutting material in precision turning. Within the experimental investigations, samples of binderless cemented carbide with a tungsten carbide content of $C_C = 99.5$ %, a cobalt binder content of $C_{Co} \leq 0.5$ % and a grain size of $d_g = 0.5$ µm were machined using NPD cutting tools. Following the previous investigation of various process parameters in research works already carried out, the statistically significant parameters feed f and depth of cut a_p were analysed in detail in this study in order to determine suitable conditions for improving the surface quality for the machining of binderless cemented carbide. Furthermore, the chip formation and process forces were analysed in order to fully investigate the influence of the used NPD tools. According to the results, the significant potential of the cutting material NPD for achieving low surface roughness values of Ra = 10 nm and Rz = 57 nm could be demonstrated. Therefore, a suitable technology for the described industrial applications could be identified as part of this study.

Keywords: binderless cemented carbide; nanopolycrystalline diamond; precision turning

1. Introduction

The precise machining of high-performance materials, including binderless cemented carbide, is a cornerstone of modern industrial applications, addressing the increasing demands for advanced manufacturing technologies. Key challenges include achieving long tool life and high surface quality. Binderless cemented carbide, characterized by exceptional hardness, wear resistance, and thermal stability, plays a vital role in industries such as tool and mould making, mobility and medical technology. Conventional machining techniques, such as grinding, are commonly employed for processing binderless cemented carbide. While effective to some extent, these methods have significant limitations, including restricted design flexibility, prolonged machining times, and substantial tool wear. These drawbacks emphasize the need for alternative machining strategies that enhance productivity while achieving superior surface quality. Research on ultrasonic-assisted machining could already demonstrate its potential in the machining of hard metals. Studies showed that ultrasonic assistance increases the efficiency of machining hard metals with single crystal diamond tools by reducing tool wear and improving precision [1]. The use of binderless nanopolycrystalline diamond (NPD) tools in precision turning represents an innovative approach to address these challenges. NPD tools, with their exceptional hardness, wear resistance, and controlled cutting edge geometries, provide significant advantages for machining hard-brittle materials. Within this study, binderless cemented carbide, composed of $C_C = 99.5$ % tungsten carbide, a cobalt content of $C_{Co} \leq 0.5$ %, and an average grain size of $d_g = 0.5$ µm, was machined using an innovative cutting material to evaluate its performance through extensive investigations.

2. Experimental Setup

To address the challenges associated with machining binderless cemented carbide, NPD tools were employed, which were developed using an advanced sintering process. This process, carried out by Sumitomo Electrical Hardmetal Corporation, Itami, Japan, involved applying extreme pressures and temperatures, enabling the direct transformation of graphite into diamond. The resulting NPD material exhibits a polycrystalline structure with a hardness of H = 130 GPa and isotropic properties without any binder phase, making it ideal for precision machining [2, 3]. For the analysis of the machined surfaces, surface roughness parameters were measured using a white light interferometer NewView 5010 from Zygo Corporation, Middlefield, USA. Furthermore, the microgeometry of the cutting edge was analysed utilising the InfiniteFocus optical measurement system, manufactured by Alicona Imaging GmbH, Graz, Austria. The analysis revealed a cutting edge radius of $r_\beta = 11.13$ µm ± 1.54 µm, a K-Factor of K = 0.989 and a maximum chipping of the cutting edge of $R_{S,max} = 0.164$ µm ± 0.023 µm. Additionally scanning electron microscope (SEM) imaging was performed using a Leica Electron Optics, Wetzlar, Germany, to obtain detailed optical evaluations of the cutting edge. Figure 1 illustrates an example of an NPD tool used in the experiments. The machining tests on hard-brittle binderless cemented carbide were carried out on the Moore Nanotechnology Systems, LLC, Swanzey, USA. This comprehensive characterization ensured accurate insights into the performance of NPD tools in machining binderless cemented carbide. The experiments were carried using ISOPAR H, which provides a suitable evaporation rate and lubricity for the production of optical surfaces. This increases the efficiency of machining and extends tool life.

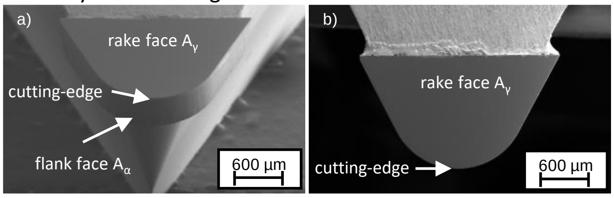

Figure 1. NPD turning tool with a) overall view and b) view of the rake face A_γ

In prior experimental investigations conducted according to a design of experiments (DoE) approach, statistical analysis revealed that the process parameters depth of cut a_p and feed f exert a statistically significant influence on the surface roughness Ra and Rz [4].

3. Cutting results

Building upon previous investigations, the present study provides a detailed examination of the effects of depth of cut a_p and feed f on the machining performance of binderless cemented carbide. A preliminary analysis of variance (ANOVA) revealed that the process parameters depth of cut a_p and feed f are statistically significant. The findings indicate that a depth of cut of a_p = 3 µm and feed of f = 3 µm yielded the most favorable surface roughness Ra and Rz within the ductile machining regime. These process parameters exhibited the best balance between reducing process forces F_C and maintaining process stability. Consequently, these parameters are implemented in accordance with Table 1.

Table 1 Investigated process parameter

Process parameter	Set 1	Set 2
cutting speed v_c	50 m/min	50 m/min
depth of cut a_p	2 µm ≤ a_p ≤ 4 µm	3 µm
feed f	3 µm	2 µm ≤ f ≤ 4 µm
cooling lubricant	ISOPAR H	ISOPAR H

Figure 2 illustrates the variation of surface roughness Ra and Rz as a function of depth of cut a_p and feed f. The results clearly demonstrate that the process parameters have a significant influence on surface quality. The investigated parameter ranges were varied between 2 µm ≤ a_p ≤ 4 µm for the depth of cut and 2 µm ≤ f ≤ 4 µm for the feed. The data reveal that a reduction in these process parameters leads to a decrease in surface roughness Ra and Rz, thereby enhancing surface quality. This effect is attributed to lower mechanical loads and reduced tool deflection, which contribute to more uniform material removal and a minimized risk of brittle fracture. The most favorable result was achieved at a cutting speed of v_c = 50 m/min, a feed of f = 3 µm and a depth of cut of a_p = 2 µm using the cooling lubricant Isopar H. Under these conditions, a surface roughness of Ra = 10 nm and Rz = 57 nm could be machined. These findings emphasize the importance of carefully optimizing process parameters to achieve high-quality machined surfaces machining binderless cemented carbide.

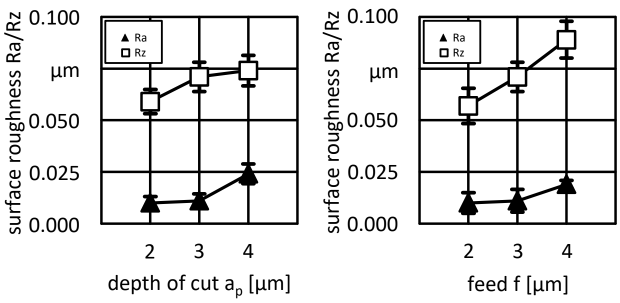

Figure 2. Cutting results of the investigated process parameters

In addition to the analysis of surface roughness Ra and Rz, the process forces F_C were also measured to assess the stability of the machining process. Force measurement ranging between 0.83 N ≤ F_C ≤ 1.35 N.

Furthermore, Figure 3 presents exemplary chip formations observed during the machining process and provides insights into the wear behavior of NPD tools.

The results indicate a consistently ductile chip formation throughout the investigated parameter range, ensuring a stable and controlled material removal process. Figure 3a) provides an overview of the chip formation, while Figure 3b) shows a detailed view of the chip formation process. The uniform chip structure and consistent shear patterns indicate that the applied cutting parameters effectively maintain process stability, leading to predictable and repeatable machining conditions.

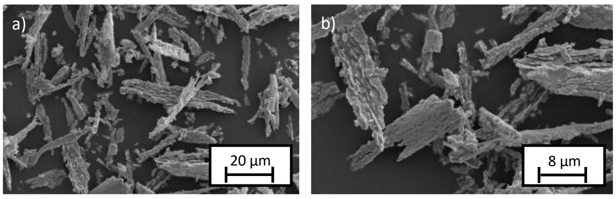

Figure 3. Chips a) overall view and b) detailed view of the chip formation

4. Conclusion

The results of this study are based on comprehensive turning experiments on binderless cemented carbide using NPD as cutting material. Building upon previously identified statistically significant process parameters, this investigation focused on a detailed analysis of feed f and depth of cut a_p to determine the optimal machining conditions for enhanced surface quality. Regarding the microgeometry of the cutting edge, the achievable limits of feed f and depth of cut a_p were extended, while surface roughness Ra and Rz further examined.

The findings conclousively demonstrate that a reduction in depth of cut a_p and feed f leads to a significant improvement in surface quality. The lowest surface roughness Ra = 10 nm and Rz = 57 nm were achieved at a cutting speed of v_c = 50 m/min, a feed of f = 3 µm and a depth of cut of a_p = 2 µm. These results underline the critical importance of precise process parameter control in achieving superior surface finishes when machining binderless cemented carbide. Future investigations will refine the incremental steps of process parameters to precisely determine optimal machining conditions and further minimize surface roughness. Additionally, the wear behaviour of NPD tools will be examined in greater detail to further assess their performance and tool life in machining binderless cemented carbide. Additionally, ultrasonic-assisted machining will be analyzed using NPD tools for its potential to enhance efficiency and tool life. This work was funded by the GERMAN RESEARCH FOUNDATION DFG.

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