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Precise cutting of cemented carbide with nanopolycrystalline diamond in ductile regime

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Abstract

Today´s demands on technical applications require the precise machining of high-performance materials. Cemented carbide is used as a wear-resistant material in a wide range of industrial applications, e.g. tool and mould making, mobility and medical engineering. Due to the brittle material characteristics and the resulting high hardness and wear resistance, the machining of the cemented carbide is severely limited. Long machining times and high tool wear are remaining challenges at state of the art. A novel approach for the machining of cemented carbide is the application of binderless nanopolycrystalline diamond (NPD) as cutting material for precise turning. Based on investigated fundamental cutting phenomena, within the scope of this work, the application of the novel cutting material was further investigated by comprehensive turning experiments. Turning tests were carried out with cemented carbide samples with a tungsten carbide content of $C_C = 88$ %, a cobalt content of $C_{Co} = 12$ % and a grain size of $d_g = 0.5$ µm. Prior to the turning tests, the brittle-ductile transition as well as the minimum chip thickness were determined by dedicated spiral cutting tests as a function of the feed. In subsequent turning tests, the influence of the cutting speed, feed velocity and depth of cut were investigated. Process forces were evaluated and specimens were analysed regarding surface roughness and topography. In the course of the investigations, it could be shown that a dedicated set of process parameters enable cutting in ductile regime with great chip formation. Thus, the great potential of the novel cutting material NPD in turning of cemented carbide could be demonstrated.

Keywords: cemented carbide; nanopolycrystalline diamond; turning

1. Introduction

In a broad range of industrial applications precision cemented carbide parts are required. At state of the art precision cemented carbide parts are mostly manufactured by electrical discharge machining or grinding. Conventional cutting materials for turning cemented carbide suffer from chipping, delamination and random tool breakage due to the high hardness and wear resistance of cemented carbide. These material characteristics enabled great innovations in toolmaking, medical engineering, forming and optics. Nowadays, diamond coated cemented carbide tools, various polycrystalline diamonds (PCD) and cubic boron nitrides (cBN) with different grain sizes d_g as well as single crystal diamond tools (SCD) are known for cutting cemented carbide.

2. Experimental Setup

To overcome state of the art challenges the Sumitomo Electric Hardmetal Corporation, Itami, Japan, developed the NPD using a dedicated sintering process and technology with a pressure of $p \geq 15$ GPa and a temperature of $\vartheta \geq 2{,}200$ °C to convert graphite directly into diamond. The novel nanopolycrystalline diamond (NPD) cutting material shows a polycrystalline structure with a grain size of $d_g \approx 30$ nm, a hardness of $H \leq 150$ GPa and isotropic characteristic without any binder phase [1]. On the basis of investigated basic cutting phenomena by Uhlmann et al. [2], the use of the novel cutting material NPD was further investigated in this work by means of spiral cutting and turning tests.

The used NPD turning tools are exemplary shown in Figure 1.

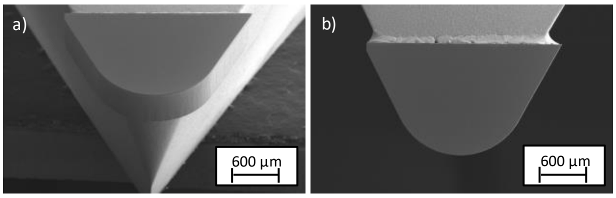

Figure 1. NPD turning tool, a) overall view and b) view of the rake face A_γ

The macro- and micro-geometry of the cutting tools were manufactured by Sumitomo Electric Hardmetal Corporation, Itami, Japan. The macro-geometry of the cutting edges of the NPD cutting tools have a corner radius of $r_\varepsilon = 800$ µm and were ground and polished with a rake angle $\gamma = 0$ ° and a clearance angle $\alpha = 15$ °. Due to the extreme hardness of the NPD a customized cutting edge preparation for the micro-geometry were carried out by laser machining.

The cutting edge micro-geometry was analyzed by using the optical measuring device InfiniteFocus type from the company Alicona Imaging GmbH, Graz, Austria. 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 were identified. The experiments were performed on the machine tool Nanotech 350 FG of the company Moore Nanotechnology Systems, LLC, Swanzey, USA. In this work, a cemented carbide material from the company Gerhard Ihle e.v., Königsbach-Stein, Germany, with a carbide content of $C_C = 88$ %, a cobalt content of $C_{Co} = 12\ \%$ and a grain size of $d_g = 0.5\ \mu m$ was used.

The arithmetical mean deviation Ra and average surface roughness Rz were investigated with a white light interferometer NewView 5010 from ZYGO CORPORATION, Middlefield, USA, with a measurement length of $l_m = 1.25$ mm. The scanning electron microscope (SEM) from LEICA ELECTRON OPTICS, Wetzlar, Germany, was used to capture the SEM-images. For statistical validation, each study was repeated three times. Within the experimental investigations, the process parameters cutting speed v_c, depth of cut a_p, feed f and the use of the cooling lubricant were varied. The feed f was determined by the theoretical surface roughness at $R_{th} = 5$ nm and $R_{th} = 35$ nm using Formula 1. ISOPAR H from EXXONMOBILE, Hamburg, Germany was used as cooling lubricant.

$$R_{th} = f^2 / 8{*}r_{\varepsilon} \qquad \text{(Formula 1)}$$

The cutting experiments were carried out according to design of experiments (DoE) with an experiment plan $2^{4\text{-}1}$ shown in Table 1.

Table 1 Investigated process parameter

Process parameter	**Set 1**	**Set 2**
cutting speed v_c	50 m/min	200 m/min
depth of cut a_p	5 µm	15 µm
feed f	2.5 µm	14.9 µm
cooling lubricant	ISOPAR H	dry

3. Cutting results

Prior to the turning tests, the ductile-brittle transition as well as the minimum chip thickness were determined by dedicated spiral cutting tests as a function of the feed f to gain extensive knowledge about fundamental cutting mechanisms for cutting cemented carbide with binderless NPD. Great chip formation with a dominating cutting mechanism could be observed for a ratio of the chip thickness to cutting edge radius $h / r_\beta = 0.718$.

Based on the investitagions concerning the fundamental cutting mechanisms face turning tests were carried out according to Table 1.

Due to the typically dominating carbide content C_C in general cemented carbide shows a brittle behaviour during the cutting process with related excessive tool wear. By applying a hydrostatic stress condition during machining, ductile cutting of carbide is made possible. A hydrostatic stress condition can be achieved during the cutting process by an effective negative rake angle γ, which is defined by a ratio of the chip thickness to the cutting edge roundness of $h / r_\beta < 1$.

Figure 2 shows the surfaces generated during the turning tests. While Figure 2a) shows the lowest value with a surface roughness of $Ra = 0.012\ \mu m \pm 0.001\ \mu m$, Figure 2b) shows the highest surface roughness achieved with $Ra = 0.099\ \mu m \pm 0.013\ \mu m$.

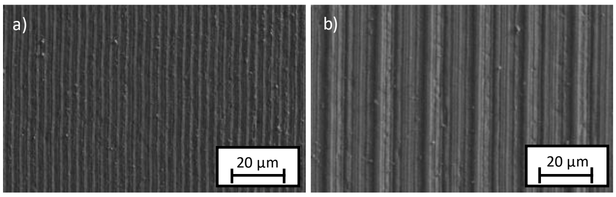

Figure 2. SEM-images of machine surfaces, a) finish cut and b) rough cut

From the surface images it can be seen that in both the finish cut and the rough cut the workpiece material was machined ductile. This applies to both the brittle carbide phase and the ductile cobalt phase. The effective chip thickness h_e increases along the cutting edge in the feed direction. At a feed of $f = 14.9\ \mu m$, the ratio of the chip thickness to the cutting edge roundness of $h / r_\beta < 1$ required for exclusively ductile cutting is exceeded along the cutting edge and results in crack and fracture behaviour, which can be seen from the exemplary chip in Figure 3b). Figure 3 shows the chips for both finish cut at a feed $f = 2.5\ \mu m$ and the rough cut at $f = 14.9\ \mu m$.

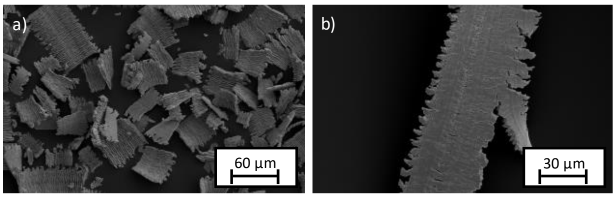

Figure 3. Chips, a) finish cut an b) rough cut

Figure 4 shows the main effect of the DoE study concerning the surface roughness Ra and Rz. The results show that the feed f has major influence on the surface roughness Ra and Rz with statistical relevance. Lowest surface roughness values of $Ra = 12.0$ nm and $Rz = 47.9$ nm could be achieved using a cutting speed of $v_c = 50$ m/min, depth of cut of $a_p = 5\ \mu m$ and a feed of $f = 2.5\ \mu m$ with Isopar H as cooling lubricant.

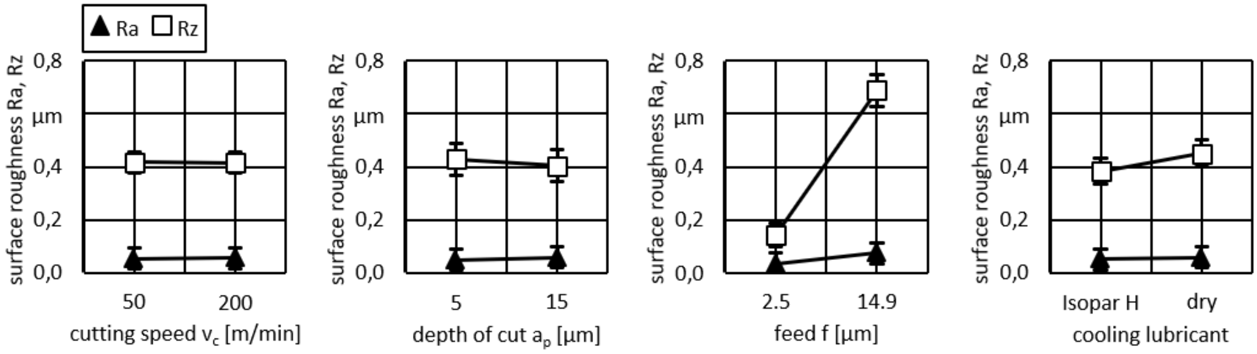

Figure 4. Cutting results, main effects of the DoE study

4. Conclusion

The results show investigations by means of the spiral cutting tests and subsequent turning tests. The surface roughness Ra and Rz and the chip formation were evaluated. The lowest surface roughness $Ra = 0.012\ \mu m$ could be achieved for a cutting speed of $v_c = 50$ m/min, a depth of cut of $a_p = 5\ \mu m$ and a feed $f = 2.5\ \mu m$. Future investigations will address the detailed investigation of the significant process parameters on the cutting result. Tool will also be investigated in further research activities. This work was funded by the GERMAN RESEARCH FOUNDATION DFG.

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