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Nanopolycrystalline diamond for precision machining of binderless cemented carbide

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Abstract

In a broad range of industrial applications, the technical importance as well as the demand for the hard-brittle material binderless cemented carbide is increasing due to special material properties. Due to its high wear resistance, binderless cemented carbide is used in industries like tool and mould making, optics as well as for forming and punching dies. However, because of the brittle material properties, the machining of this material with geometrically defined cutting edges is limited by the current state of the art due to considerable tool wear. An innovative approach for machining of binderless cemented carbide is the use of binderless nanopolycrystalline diamond (NPD) as a cutting material for precision turning. As part of these investigations, the use of NPD as cutting material was examined in detail by means of extensive turning tests, starting from the basic machining phenomena. Turning tests were carried out with cemented carbide samples with a cemented carbide content of $C_C = 99.5$ %, a cobalt content of $C_{Co} = 0.5$ % and a grain size of $d_g = 0.3$ µm. Prior to the basic turning tests, specific spiral cutting tests were carried out to identify the ductile-brittle transition and the minimum chip thickness as a function of the feed. Within subsequent turning tests the influence of the cutting depth, feed, cutting speed and the use of coolant was investigated. Surface topography, roughness characteristics, chip formation and process forces were used as process criteria. The potential of the innovative cutting material NPD could be demonstrated in the course of the investigations.

Keywords: binderless cemented carbide; nanopolycrystalline diamond; turning

1. Introduction

Binderless cemented carbide is used in a wide range of applications. At state of the art, binderless cemented carbide is mainly processed using grinding or electrical discharge machining technologies. However, conventional machining results in increased tool wear and surface cracks in the component surface. Due to the hard-brittle material characteristics and the considerable tool wear, the machining of binderless cemented carbide using geometrically defined cutting edge processes is significantly limited by the current state of the art. Due to its hardness H and grain size d_g the use of binderless nanopolycrystalline diamond (NPD) as a cutting material for precision turning represents an innovative approach to overcome the current challenges. As part of the present investigations, the use of NPD as a cutting material was used to analyse fundamental machining phenomena and for extensive turning tests. The investigations were carried out with a binderless cemented carbide, which is characterised by a tungsten carbide content of $C_C = 99.5$ %, a cobalt content of $C_{Co} = 0.5$ % and a grain size of $d_g = 0.3$ µm. As part of the investigations into the fundamental cutting mechanisms, scratch tests were carried out as a function of the depth of cut a_p and spiral tests were varied as a fuction of the feed f in order to determine the ductile-brittle transistion and the minimum chip thickness h_{min}.

As part of the subsequent turning tests, the influence of the cutting speed v_c, the depth of cut a_p, the feed f and the cooling lubricant were analysed. The surface topography, roughness characteristics, the chip formation and process forces F_p were analysed in more detail as process criteria.

2. Experimental Setup

To overcome the challenges of the state of the art, the Sumitomo electrical hardmetal corporation, Itami, Japan, developed the NPD using a dedicated sintering process and a technology with a pressure of $p \geq 15$ GPa as well as a temperature of $\vartheta \geq 2.200$ °C to convert graphite directly into diamond. The novel NPD cutting material shows a polycrystalline structure with a hardness of $H = 150$ GPa and isotropic properties without any binder phase [1]. The macro- and micro geometries of the novel NPD were analysed by measurements prior to testing.

The macro-geometry of the cutting edge, which was ground and polished, is characterised by a value of $r_\varepsilon = 800$ µm with a rake angle of $\gamma = 0$ ° and a clearance angle of $\alpha = 15$ °. Laser machining was employed for customizing the micro-geometry of the cutting edge due to the exeptional hardness of the NPD material. The micro-geometry of the cutting-edge was examined utilising the optical measurement device InfiniteFocus, 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 radius of $R_{S,max} = 0.164$ µm ± 0.023 µm. The surface roughness parameters of the machined workpiece surfaces were measured in terms of surface roughness Ra and Rz using the white light interferometer NewView 5010 from Zygo corporation, Middlefield, USA, with a measuring length of $l_m = 1.25$ mm. Figure 1 shows an example of a NPD turning tool used. A scanning electron microscope (SEM) from Leica Electron Optics, Wetzlar, Germany, was used to take the SEM-images for further optical evaluation.

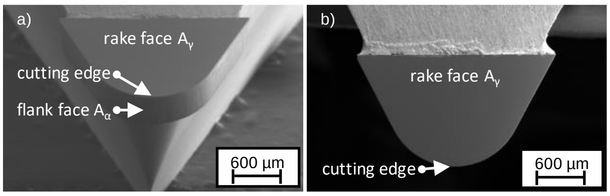

Figure 1. NPD turning tool with a) overall view and b) view of the rake face A_γ

3. Cutting results

Prior to the spiral cutting tests, scratch tests were performed to get first insights into minimum chip thickness h_{min} and the transistion point from ductile to brittle material behaviour. These tests were carried out by varying the depth of the cut a_p or the feed f to acquire comprehensive insights into the fundamental cutting mechanisms employed in the machining of cemented carbide using binderless NPD. To identify the fundamental cutting mechanisms, comprehensive turning tests of hard-brittle binderless cemented carbide were carried out on the Nanotech 350 FG of the company MOORE NANOTECHOLOGY SYSTEMS, LLC, Swanzey, USA. Fundamental cutting mechanisms could be identified with a minimum chip thickness h_{min} at a depth of cut of $a_p = 2.4$ µm and a feed of $f = 2.7$ µm. The ductile regime was observed in a range of $3\ \mu m \leq a_p \leq 8\ \mu m$ and $3\ \mu m \leq f \leq 8\ \mu m$, whereas a transition to hard-brittle material behaviour is $a_p \geq 9.5\ \mu m$ and $f \geq 8.7\ \mu m$. Force measurement ranging between $19\ N \leq F_p \leq 30\ N$.

Owing to the prevalent carbide content C_{Co}, cemented carbide commonly exhibits brittle characteristics during the cutting process, leading to associated elevated tool wear. The hydrostatic pressure condition is a requirement during machining facilitates ductile cutting of cemented carbide. This hydrostatic pressure condition can be generated by utilising an effective negative rake angle γ, defined by a ratio of the chip thickness to the cutting edge radius $(h / r_\beta) < 1$, throughout the cutting process.

In the spiral tests, a great chip formation with a dominant cutting mechanism could be observed for a ratio of chip thickness to cutting edge radius in a range of $0.269 \leq h/r_\beta \leq 0.718$. Figure 2 shows the chips during the spiral tests in ductile condition (Figure 2a) as well as in hard-brittle condition (Figure 2b).

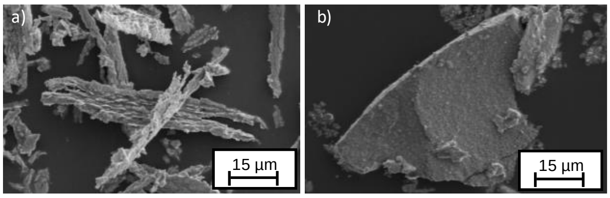

Figure 2. Chips a) finish cut and b) material breakage

The subsequent cutting experiments were conducted in accordance to design of experiments (DoE), utilising an experimental plan 2^{4-1} as illustrated in Table 1.

Table 1 Investigated process parameters for turning

Process parameter	Set 1	Set 2
cutting speed v_c	50 m/min	200 m/min
depth of cut a_p	3 µm	8 µm
feed f	3 µm	8 µm
cooling lubricant	ISOPAR H	dry

Figure 3 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. By increasing the feed f, a significant increase in surface roughness could be demonstrated. The cutting speed v_c as well as the used cooling lubricant also show an influence, especially on the surface roughness Ra. Lowest surface roughness values of Ra = 11.0 nm and Rz = 71.7 nm could be achieved using a cutting speed of $v_c = 50$ m/min, a depth of cut of $a_p = 3$ µm and a feed of $f = 3$ µm with Isopar H as cooling lubricant.

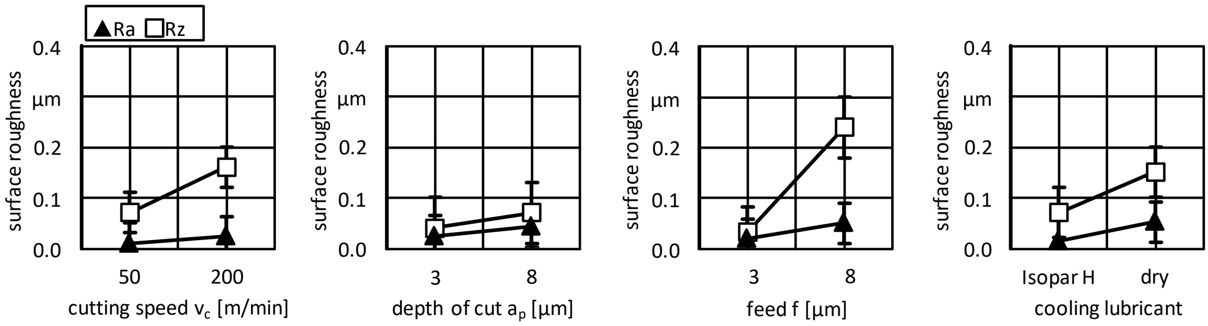

Figure 3. Cutting results, main effects of the DoE study

4. Conclusion

The results show investigations based on spiral tests and subsequent turning tests. With a fully characterised macro- and micro-geometry of the used NPD tools, the fundamental cutting mechanisms for the machining of binderless cemented carbide could be identified by specific spiral tests. With regard to the micro-geometry of the cutting edge, an industrially relevant range of $3\ \mu m \leq a_p \leq 8\ \mu m$ for ductile cutting was observed. Fundamental cutting mechanisms were identified by scratch tests with a minimum chip thickness h_{min} at a depth of cut of $a_p = 2.4$ µm and a transistion to hard-brittle material behaviour for $a_p \geq 9.5$ µm. From a ratio of chip thickness to cutting edge radius of $h / r_\beta \geq 0.718$, surface cracks and brittle material behaviour could be observed. Surface roughness Ra and Rz were further analysed during subsequent turning tests. Based on the results, the feed f showed a major impact on the surface roughness Ra.

The lowest surface roughness of Ra = 11 nm could be identified at a cutting speed of $v_c = 50$ m/min, a cutting depth of $a_p = 3$ µm and a feed of $f = 3$ µm. In further investigations, the influential process parameters that affect the machining results will be comprehensively researched. Additionally, the wear behaviour of the NPD tools will also be investigated in detail in future research works. This work was funded by the GERMAN REASEARCH FOUNDATION DFG.

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