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Characterization and investigation of binderless nanopolycrystalline diamond turning tools for precision machining

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Abstract
Cemented carbide is used in a wide range of industrial applications as a wear-resistant material, e.g. in mould making and forming industry. At state of the art, the machining of cemented carbide is severely limited because of the hardness, high strength and the resulting wear resistance of the material. Due to the brittle-hard character cemented carbide materials suffer from surface cracks during the machining. The brittle-hard character and the related phenomena result in high tool wear. A promising approach for the machining of cemented carbide is the use of the novel cutting material binderless nanopolycrystalline diamond (NPD) with a dedicated cutting edge design. Within this work, laser machined tools with a corner radius of $r_\varepsilon = 400$ µm are fully characterized, investigated by Raman spectroscopy regarding the condition of the diamond and applied for first cutting experiments. Cutting investigations were carried out using specimens 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 these investigations, the condition of the diamonds and possible changes due to the lasered cutting edges were examined by Raman spectroscopy. During the cutting investigations, the brittle-ductile transition as well as the minimum chip thickness were identified by scratching tests. It could be shown that a hydrostatic stress state can be used to achieve ductile chip formation using cemented carbide as workpiece material.

Keywords: cemented carbide; nanopolycrystalline diamond; Raman spectroscopy

1. Introduction

Cemented carbide materials are used in a wide range of industrial applications. Especially for stamping operations of e-mobility parts, as mould material for precision glass moulding of complex optics or as wear resistant parts in offshore applications precision cemented carbide components are of utmost importance. Due to the high strength and hardness characteristic, cemented carbide shows even more a great potential as wear resistant material in future applications. Therefore, the efficient machining of cemented carbide with high complexity and precision and low surface roughness is required from industry.

For precision machining of cemented carbides a great number of research activities were carried out [1, 2, 3]. At state of the art industrial relevant cutting tools are made of single crystal diamond (SCD), polycrystalline diamond (PCD), cubic boron nitride (cBN) and fine grain cemented carbide tools with dedicated chemical vapour deposition (CVD) or high power impulse magnetron sputtering (HIPIMS) coatings made of diamond, cBN, different oxide and nitride based or diamond like carbon (DLC) materials. Nevertheless, available cutting tools still suffer from fast and random tool wear during cutting of cemented carbide materials resulting in low precision and poor surface quality, even though there is a great progress for polycrystalline cutting materials and coatings.

Nanopolycrystalline diamond (NPD) as cutting material for machining hard-brittle materials like cemented carbide is a promising approach to overcome state of the art challenges [1, 3]. Beside the tool wear phenomena different major challenges for machining of cemented carbide like dedicated cutting edge design, workpiece related surface cracks and poor surface quality still exist at state of the art.

2. Experimental Setup and Results

Within this work, cutting edge macro- and micro geometries of novel NPD cutting tools for turning and the fundamental cutting mechanisms for machining cemented carbide were investigated. To overcome state of the art challenges 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 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 [2].

The cutting edge macro-geometry of the NPD cutting tools with a corner radius of $r_\varepsilon = 400$ µm were ground and polished with a rake angle $\gamma = 0$ ° and a clearance angle $\alpha = 15$ °. The cutting edge macro-geometry design is dedicated to efficient tool manufacturing and maximised stability of the tools for cutting hard-brittle materials. Ductile cutting of hard-brittle materials is enabled by a specific cutting edge micro-geometry and related cutting conditions. Due to the extreme hardness of the NPD a customized cutting edge preparation for the micro-geometry were carried out by laser machining. Preparation of cutting edge macro- and micro-geometry were done by Sumitomo Electric Hardmetal Corporation, Itami, Japan. The cutting edge radius r_β, the maximum chipping of the cutting edge $R_{S,max}$ as well as the K-factor K influence the fundamental cutting mechanisms strongly. For machining hard-brittle materials in ductile regime the ratio of the cutting edge radius to the chip thickness needs to be $r_\beta > h$ to induce hydrostatic pressure state. For efficient cutting of cemented carbide in ductile regime cutting edge radius of $r_\beta > 10$ µm are intended. Therefore, manufactured cutting edge micro-geometries were measured by the focus variation microscope Alicon InfiniteFocus G4 of the Company ALICONA MAGING GMBH, Graz, Austria. For tools with a corner radius of $r_\varepsilon = 400$ µm a cutting edge radius of $r_\beta = 13.1$ µm ± 1.64 µm, a maximum chipping of the cutting edge of $R_{S,max} = 0.20$ µm ± 0.02 µm and a K-Factor of K = 1.06 could be identified. To investigate a possible modification of the diamond structure by laser machining Raman spectroscopy were carried on a WiTEC ALPHA 300 of the company WITEC WISSENSCHAFTLICHE INSTRUMENTE UND TECHNOLOGIE GMBH, ULM, at BUNDESANSTALT FÜR MATERIALFORSCHUNG UND -PRÜFUNG (BAM), Berlin (figure 1). For all investigated tools modified diamond structures and even distributed graphite on the rake face A_γ and the cutting edge could identified that may influence the wear behavior.

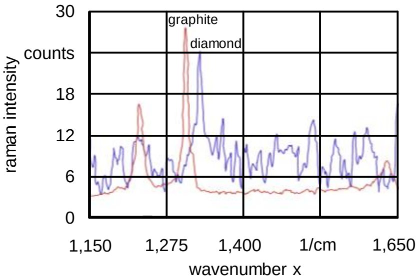

Figure 1. Raman spectroscopic examination of the investigated cutting edge

Scanning electron microscope (SEM) images of an exemplary turning tool with a corner radius of $r_\varepsilon = 400$ µm are shown in figure 2. The polished rake face A_γ shows a smooth surface finish for improved chip evacuation, whereas the flanke face A_α shows remaining grinding structures for alle investigated tools. A polishing process of the flank faces A_α of all tools were explicitly avoided, because of the oudstanding hardness of the cutting material. Figure 2 b) depicts exemplary the uniformity of the cutting edge radius with a constant smooth chipping of the cutting edge R_S. All investigated tools showed a comparable structure with low spread.

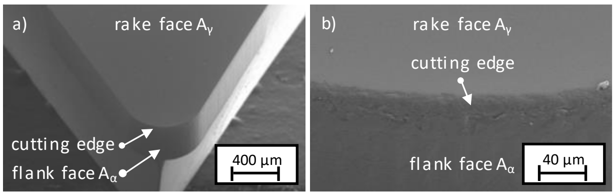

Figure 2. NPD turning tool, a) overall view and b) cutting edge detail view

To identify fundamental cutting mechanisms and ductile cutting regime of hard-brittle cemented carbide scratch tests were carried on the machine tool Nanotech 350 FG of the company MOORE NANOTECHNOLOGY SYSTEMS, LLC, Swanzey, USA. As workpiece material cemented carbide with a carbide content of $c_C = 88$ %, a cobalt content of $c_{Co} = 12$ % and a grain size of $d_g = 0.5$ µm was used. Scratch tests were done with a cutting speed of $v_c = 0.1$ mm/min on a circular path with a radius of $r_c = 12$ mm on a length of $l_c = 25$ mm and a maximum depth of cut of $a_{p,max} = 25$ µm. Fundamental cutting mechanisms could be identified by scratch tests with a minimum chip thickness h_{min} at a depth of cut of $a_p = 1.8$ µm, a ductile cutting regime with great chip formation in the range of $a_p \leq 20$ µm and a transition to hard-brittle material behavior for $a_p \geq 25$ µm and a force measurement in a range of $14 \text{ N} \leq F_p \leq 16 \text{ N}$ for cutting tools with a corner radius of $r_\varepsilon = 400$ µm. Figure 3 shows SEM images of workpiece surfaces in ductile cutting regime with a depth of cut of $a_p = 20$ µm and the transition zone to hard-brittle material behavior at $a_p = 25$ µm. For a ratio of the cutting edge radius to the depth of cut $r_\beta/a_p \leq 0.524$ surface cracks occur and dominate the structure. Chip formation during scratch tests of cemented carbide at different depth of cut a_p is shown in figure 4 to illustrate fundamental cutting mechanisms exemplary.

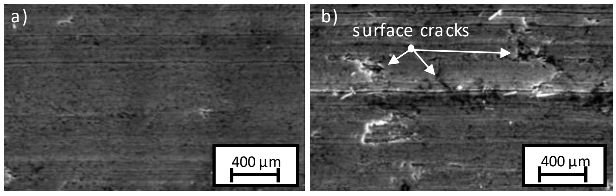

Figure 3. Workpiece surface after scratch tests,
a) ductile cuttinge regime, b) transition zone to hard-brittle behavior

Up to a depth of cut of $a_p \leq 1.8$ µm elastic and plastic deformation of workpiece material dominate and only plastified workpiece material can be found, see figure 4 a). For a depth of cut in the range of $a_p \leq 20$ µm uniform and ductile chip formation could be observed, see figure 4 b) & c). For the whole ductile regime chips show a segmented and regular structure with a plastified characteristic. Hard-brittle material behavior with whole material outbreaks correlates to surface structures in figure 3 b), see figure 4 d).

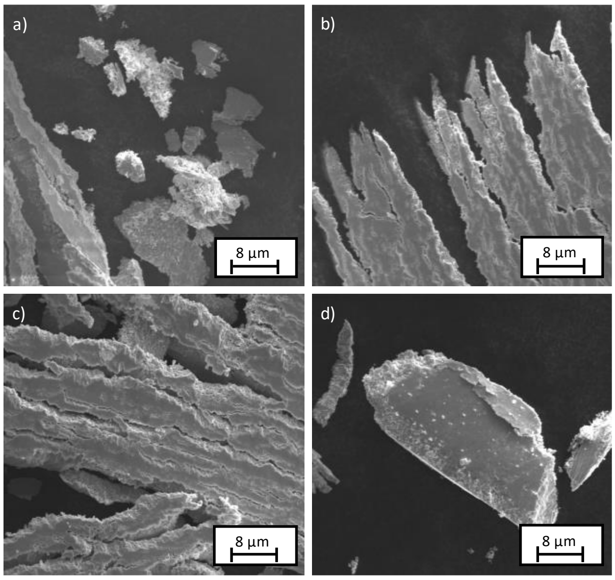

Figure 4. Chip formation during the scratch tests,
a) plastified workpiece material, b) & c) chip formation in ductile regime, d) material outbreaks in hard-brittle regime

3. Conclusion

For the novel cutting material NPD tools with uniform cutting macro- and micro-geometry could be characterized, successfully applied for scratch tests and fundamental cutting mechanisms were identified. For the dedicated cutting edge micro-geometry an industrial relevant range for ductile cutting of cemented carbide could be proofed for a depth of cut $a_p \leq 20$ µm. A ratio of the cutting edge radius to depth of cut $r_\beta/a_p \leq 0.524$ leads to hard-brittle material behaviour with material outbreaks and occurring surface cracks. Further investigations address the influence of the feed f and the cutting speed v_c on the chip formation during face turning and the related wear behavior. This work was funded by the GERMAN RESEARCH FOUNDATION DFG.

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