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Investigations in drilling of difficult-to-cut materials using twist drills with solid binderless diamond tips

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Abstract

The application of difficult-to-cut materials typically entails significant challenges in machining, for example due to high strength and hardness as well as the presence of abrasive reinforcing ceramic phases. For drilling of non-ferrous materials good abrasion resistance preventing excessive tool wear can be achieved with binderless diamond. A reliable chip removal inhibits premature tool failure by chip jamming, especially considering the lower tool robustness of micro tools compared to macro tools. Nonetheless, most of the available diamond-tipped drills are realised with Polycrystalline diamond (PCD) containing cobalt as binder material. Furthermore, the drills are normally only partially tipped and they primarily provide geometries without helical flutes. Based on the current state of science, it is derived that the performance of micro tools can be increased significantly by using binderless diamond grades in the form of solid diamond tips representing the entire cutting part. Laser machining allows for helical flutes that enable reliable chip removal and prevent both jamming and early unsystematic tool failure. Double-edged micro drills with a nominal diameter of the binderless diamond tips of 1 mm are used for experimental investigations in blind hole drilling of cemented carbide, ZrO_2, and carbon fibre reinforced plastics. The cutting speed is 40 m/min and feeds of 2 µm or 4 µm per revolution respectively are applied. All cutting tests are realised with pressurised air for chip removal. The evaluation of the tool wear beahaviour and the machining results is based on tool wear progression, feed forces, the roughness values of the drill hole wall surfaces, and the occurring imperfections at the tool entrance area. The results show comparably low roughness values, a limited generation of imperfections, and a controllable tool wear progression. This indicates a good suitability of the binderles diamond-tipped drilling tools for broad industrial application.

Keywords: Diamond; Drilling; Machining; Tool

1. Introduction

Manufacturing of advanced systems increasingly involves machining of difficult-to-cut materials with high hardness or strongly abrasive behaviour affecting tool wear and the formation of surface imperfections. Furthermore, in drilling there are unstable conditions during drill entrance and exit due to locally varying cutting speeds thus requiring further research for efficient processes. Subsequently, current investigations primarily focusing on drilling of cemented carbides, technical ceramics and carbon fibre reinforced plastics (CFRP) are presented.

1.1. Machining of cemented carbides

Uhlmann, Protz, and Sassi [1] investigated drilling processes with and without ultrasonic vibration assistance. The machining experiments were based on two different specimen grades of cemented carbides with cobalt contents of 12 % or 6 %. The first grade exhibited average particle sizes of 0.2 µm to 0.5 µm, whereas the second material contained particles with diameters of about 0.8 µm. Moreover, chemically vapour deposited diamond (CVD-D)-coated twist drills with a nominal diameter of 1 mm were used. The cutting parameters were defined by a cutting speed of 30 m/min and a feed velocity of 10 mm/min. Ultrasonic vibrations were superimposed with an amplitude of about 0.5 µm and a frequency of about 21.5 kHz. It was found that ultrasonic assistance allowed for reduced process forces, increased tool life, and higher productivity. Okada et al. [2] investigated the drilling of a cemented carbide with a proportion of 7 % to 10 % of cobalt binder and WC-particles with an average size of 2 µm. For the experimental tests, CVD-D-coated twist drills with a nominal diameter of 1 mm and a coating with a thickness of about 20 µm were used. Applying feeds of 0.75 µm to 3 µm, blind holes with a depth of 4 mm were realised. It was found that a combination of a low rotational speed, thus resulting in a low cutting speed and high feed values entailed insufficient tool life. The researchers indicated appropriate drilling results despite partial failure of the coating and minor chipping at the cutting edge. Almeida et al. [3] investigated the drilling of a WC-Co cemented carbide with a proportion of about 6 % binder. The experiments addressed uncoated and CVD-D-coated twist drills. The tool substrate contained between 8 % and 10 % of cobalt binder and WC-particles with an average grain size of about 1 µm. The cutting tests were realised in cemented carbide blocks with about 5.5 % cobalt binder and WC-particles in pre-sintered state. The findings indicate that coated tools allowed for slower tool wear progression and reduced imperfections in the form of chipping despite applying significantly higher feed speeds. Okada et al. [4] applied a diamond-coated two-fluted milling cutter with a diameter of 2 mm and a corner radius of 0.1 mm in milling of a cemented carbide. The tool coating provided a thickness of 20 µm. The results indicated the possibility to achieve mirror-like surfaces with *Ra*-values in the range of 0.03 µm to 0.07 µm by cutting.

1.2. Machining of technical ceramic materials

Shin and Song [5] investigated the drilling of Si_3N_4-BN and AlN-BN ceramics. The specimens were machined using cemented carbide twist drills with a nominal diameter of 0.1 mm. Cutting speed and feed velocity were varied in a range of 3.1 m/min to

12.6 m/min and 0.5 mm/min to 15 mm/min.The investigations aimed for the qualitative assessment of imperfections represented by chipping in the area of tool entrance. The results indicate that if specific ratios of feed velocity and spindle rotational speed and thus cutting speed are exceeded, the formation of imperfections is benefited. Saini et al. [6] addressed the realisation of holes in yttria stabilised zirconia (YSZ) based on laser beam machining. The investigations focused on the generation of micro through holes within specimens consisting of a YSZ with a thickness of 2 mm. For the laser drilling process a 250 W Nd:YAG laser was used. The results show an inverted tapering of the laser drilled holes with a larger diameter at the bottom of the hole. Moreover, lower pulse widths and a higher number of pulses are found to be advantageous for YSZ machining.

1.3. Machining of carbon fibre reinforced plastics

A number of research activities adressed the drilling of carbon fibre reinforced plastics with diamond-coated and diamond-tipped tools. Xu, Lin, and Davim [7] applied diamond-coated brad point and step drills for their investigations. It was found that the cutting temperature can be reduced by using brad point drills combined with low cutting speeds and feeds. Nonetheless, step drills entailed a better drill hole wall quality and reduced surface roughness values, which was attributed to reaming effects. Hrechuk et al. [8] among other things investigated drilling of a CFRP using PCD-tipped and CVD-D-coated drilling tools. It was found that the PCD-tipped tools allowed for an improved abrasion resistance compared to the coated drills. When applying tipped and coated tools in the initial tool state, there were no significant differences with regard to imperfections such as pulled-out reinforcing fibres. However, the PCD-tipped tools allowed to meet the defined hole quality criteria for a significantly higher number of drill holes compared to the CVD-D-coated tools. Henerichs et al. [9] addressed different twist drill geometries and nanocrystalline diamond coatings with regard to tool wear resistance. The results indicated a significant tool life prolongation with suitable machining results up to 400 holes.

1.4. Inferences

The current state of science only presents insufficient research activities and results on machining of difficult-to-cut materials based on micro drilling tools. Currently, tools are primarily either realised with CVD-D-coatings or tipped with PCD as cutting material. Investigations on drilling with tipped micro tools incorporating binderless diamond grades are unavailable or rather limited. However, there is a significant technical potential in drilling with binderless diamond grades in the form of twist drills in order to improve wear resistance and stability preventing premature tool failure.

2. Materials and methods

Accordingly, the presented experimental investigations aim for drilling processes with diamond-tipped tools focusing on three different difficult-to-cut materials represented by cemented carbide, a ceramic material, and a CFRP. The influence of the cutting material is researched based on two binderless diamond grades. The aim is to depict different aspects of machining behaviour defined by brittle or ductile machining characteristics. In terms of the process parameters, primarily the influence of the feed is taken into consideration.

2.1. Specimen materials and geometry

The material selection aims for a spectrum of machining challenges referring to high strength or hardness, and highly abrasive effects. The cemented carbide of the grade G30 consists of 85 % tungsten carbide with particle sizes in the range of 0.7 µm to 1 µm. Cobalt is used as binder with a proportion of 15 %. The ceramic material Z-700E is a partially stabilised ZrO_2 with proportions of yttrium trioxide, aluminium trioxide, and others. The investigated CFRP provides an internal structure consisting of unidirectional carbon 0°/90° oriented prepregs incorporating 35 % of Epoxid E800 resin and fibres of the type Carbon-HT. The top and bottom cover layers are represented by a carbon fabric using fibres of the type Carbon-HT-3k-200 tex.

The investigations on tool wear progression are based on prismatic specimens manufactured from the cemented carbide grade. For each cutting material, a pattern of 12 × 5 drill holes is realised using separate specimens. The specimen geometry for the machinability tests is represented by a cylindrical section with a diameter of 12 mm and a length of 10 mm for all investigated materials. For each specimen only one centred hole is realised. This concept allows for a precise and reproducable positioning of the stylus in subsequent tactile measurements within the drill holes.

2.2. Diamond cutting materials and tool characteristics

The investigations address binderless diamond grades represented by polycrystalline CVD-D and binderless polycrystalline ultra diamond (UD). Figure 1 illustrates the geometry of the tools used for the experimental investigations.

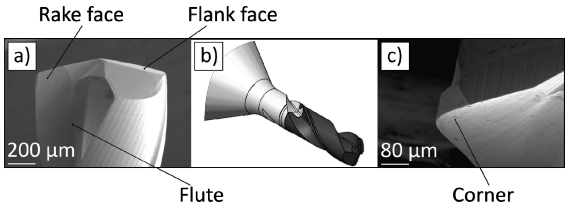

Figure 1. Tool geometry with a) SEM image of the tool tip, b) CAD-model with overview of the cutting part, and c) SEM image with detailed view of the tool corner exemplarily for an UD-tipped tool.

The investigated twist drills are characterised by two cutting edges, a nominal diameter of 1 mm, a drill point angle of 150°, a helix angle of 30°, and a corner radius of 0.03 mm. The edge radii are in a range of 2 µm to 4 µm with typically slighty higher values for CVD-D compared to UD.

2.3. Experimental setup and drilling process conditions

The cutting tests aim for different aspects of the drilling process. On the one hand, the binderless diamond grades are applied in wear tests. These experiments are solely based on the cemented carbide grade due to the highly abrasive behaviour of the inherent ceramic particles. On the other hand, machinability tests are realised for all cutting materials, combined with each specimen material, and two different feeds. The main goal is to test the prototypical tool design and to investigate the resulting surface properties of the generated drill hole walls. Moreover, the appearance and formation of imperfections in the area of the tool entrance is assessed. The different experiments require separate experimental setups, that are presented in figure 2.

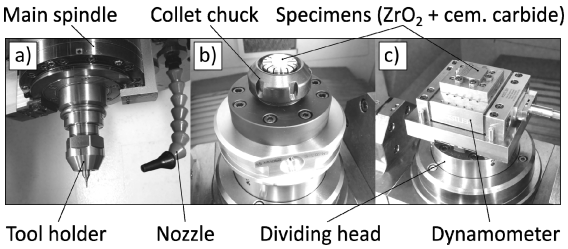

Figure 2. Experimental setups for cutting experiments with a) Tool integration within the machine tool, b) Device for machinability tests based on a collet chuck system, and c) Setup and device for drilling experiments with process-related feed force data acquisition.

For the wear progression tests a 3-axes dynamometer is integrated into the experimental setup in order to record the feed forces. Concerning the machinability tests, the specimens are clamped in a collet chuck, without logging the force data. For all the experiments a cutting speed of 40 m/min is applied, the feed is determined with 2 µm per revolution for the wear progression tests and with 2 µm or 4 µm per revolution for the machinability tests. In general, the experiments are realised in dry condition using pressurised air for chip removal.

2.4. Evaluation methods

The tool wear progression with an increasing number of drill holes is documented based on 3D-measurements using an optical coordinate measuring machine of the type Bruker Alicona µCMM. A dynamometer of the type Kistler MiniDyn 9256A2 is used to gather the resulting feed force data during the drilling process. The determined force values represent an indication of the tool wear progression. The feed force signals are acquired with a sampling rate of 5 kHz. For the qualitative and quantitative evaluation of the drill hole quality, different measuring instruments and devices are used. The acquisition of the primary surface profiles is based on a stylus system of the type Mahr LD120. Figure 3 represents the measuring setup exemplarily for a CFRP specimen.

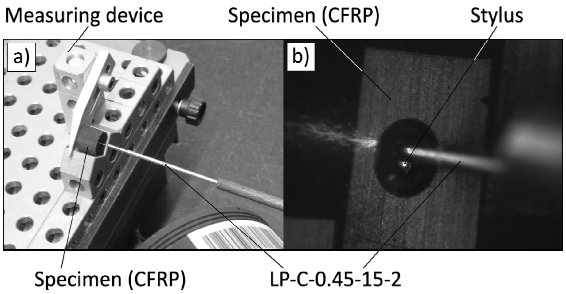

Figure 3. Measuring setup for tactile profile acquisition with a) Overview of the measuring device with specimen and probing arm and b) Detailed view of the specimen with drill hole and stylus exemplarily for CFRP.

In order to realise measurements within the generated drill holes a special probing arm of the type Mahr LP-C-0.45-15-2 is used. It enables surface profile data acquisition without the necessity of cutting the specimens. The depth of the drill holes required the selection of a standardised traversed length of 0.56 mm. Referring to that, a nesting index of the L-filter of 0.08 mm is applied to separate roughness and waviness profile. The average surface roughness values *Rz* are determined for each parameter combination based on three separate tactile measurements. Moreover, the area of tool entrance is assessed qualitatively using a 3D laser scanning microscope of the type Keyence VK-9700. Referring to the acquired images, imperfections such as edge chipping can be identified.

3. Results and discussion

The subsequently presented results aim for two different aspects. On the one hand, the investigations address the tool wear behaviour of the binderless diamond grades. On the other hand, the resulting surface roughness values of the generated drill hole walls and the appearing imperfections in the area of the tool entrance are assessed.

3.1. Investigations on tool wear progression

In order to determine the tool wear behaviour, the tool wear state was acquired and documented for a number of up to 60 drill holes in a cemented carbide specimen after every fifth drilling operation. Figure 4 exemplarily represents the tool wear progression in drilling of cemented carbide with a CVD-D-tipped tool.

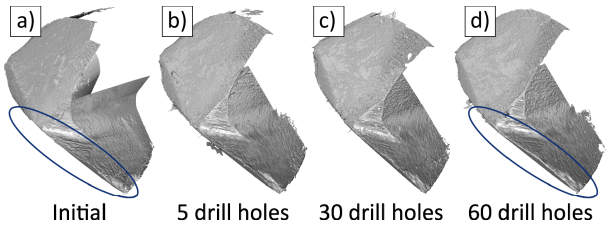

Figure 4. Qualitative imaging of tool wear progression at the primary cutting edge (blue marker) of a CVD-D-tipped twist drill with a) Initial state, b) Tool state after 5 drill holes, c) Tool state after 30 drill holes and d) Tool state after 60 drill holes (v_c = 40 m/min, f = 2 µm, pressurised air, cemented carbide).

The imaging mainly aims for the primary cutting edge (blue marker) and the front section of the cutting part. In general, the results indicate a high wear resistance with a stable and controlled tool wear progression when using the investigated binderless diamond grades. In case of the presented CVD-D-tipped twist drill, there are only quite limited changes of the tool geometry represented by a small increase of the cutting edge radius. Minor chipping in the area around the tool corner was already present in the initial state and was not caused by the machining process.

Figure 5 presents the feed force data acquired throughout cutting tests in cemented carbide. Results are shown for tools tipped with both binderless cutting materials after the 20th, 40th, and 60th drill hole.

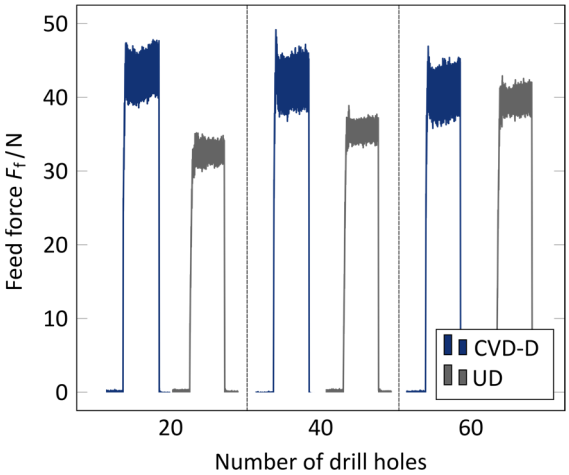

Figure 5. Feed force signals acquired for selected drill holes (v_c = 40 m/min, f = 2 µm, pressurised air, cemented carbide).

The force data confirm a stable tool state of the CVD-D-tipped twist drill without significant changes in the absolute values of the feed force. The slight decrease could possibly be attributed to run-in effects which have to be subjected to further investigations. In some cases a force overshoot can be identified during the tool entrance, which is attributed to the unstable cutting conditions when the tool enters the specimen. In case of the UD-tipped tool there is a slight but steady increase of the feed force values with an increasing number of drill holes up to a maximum value of about 40 N. This effect may be explained by different assumptions. On the one hand, differences in the initial cutting edge radius of the diamond-tipped tools can affect the tool wear progression. Based on previous investigations it could be assumed that a lower cutting edge radius is subjected to stronger rounding effects and a more significant increase of the feed forces. On the other hand, inherent differences in the properties of the cutting materials could result in a distinguished tool wear behaviour, although both materials represent binderless diamond grades.

3.2. Investigations on the machinability of difficult-to-cut materials

The generated drill holes were investigated quantitatively by surface roughness measurements on the drill hole wall surfaces. Figure 6 represents the mean values of the average surface roughness *Rz* with the calculated standard deviations.

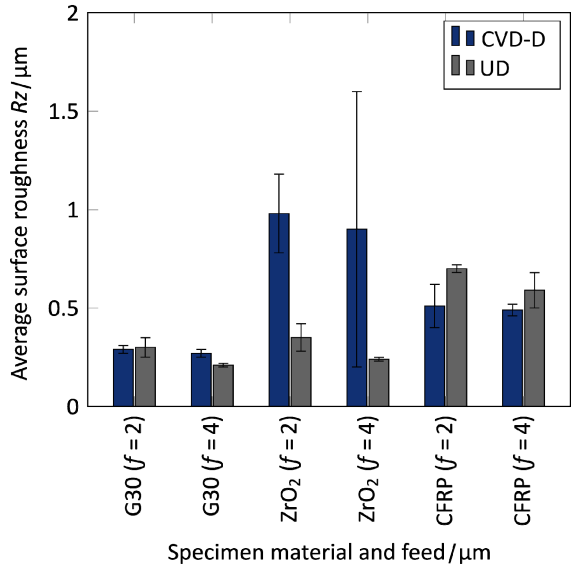

Figure 6. Surface roughness values based on investigations on the machinability of difficult-to-cut materials applying different feeds and cutting materials (v_c = 40 m/min, pressurised air).

Firstly, the results indicate that machining of the cemented carbide entailed the lowest average and absolute roughness values of all investigated specimen materials. This is mainly attributed to the ductile behaviour of the cobalt binder matrix reducing the appearance of imperfections in the form of unsystematic chipping at the drill hole walls. The strongest fluctuations appeared in drilling of the ceramic specimen material due the strongly brittle material characteristics fostering chipping effects. In case of the cemented carbide, only a limited effect of the cutting material was found, but the higher feed led to a lower average roughness value and apparently reduced the process fluctuations. Concerning the sintered ceramic, for both feeds, the application of UD as a cutting material resulted in significantly lower average roughness values and fluctuations. Drilling with CVD-D-tipped tools resulted in roughness values and fluctuations in comparable ranges. Drilling of the CFRP specimens with a CVD-D-tipped tool entailed slightly lower roughness values compared to machining with UD for the lower feed. When respecting the fluctuations of the *Rz*-values, there were no significant differences between the two addressed cutting materials when applying the higher feed.

In addition to surface roughness values of the drill hole walls, there is a qualitative assessment of the entrance area of each drill hole. Figure 7 represents images based on 3D laser scanning microscopy of the tool entrance area when machining the investigated ZrO_2 with all combinations of the focused diamond cutting materials and feeds.

In general, the results indicate a neglectable formation of imperfections in the area of tool entrance for the majority of specimen materials and investigated cutting parameter combinations. As a consequence the qualitative laser scanning images were not presented for all of the materials. However, a comparably strong formation of chipping can be found when machining ZrO_2. Especially, the application of the CVD-D-tipped tool in combination with the lower feed of 2 µm resulted in chipping effects. These effects led to visual irregularities on the edge at the entrance of the generated drill hole that can be found according to figure 7a (white marker). In difference to that, less distinct imperfections are found with an increase in feed or the application of UD as cutting material.

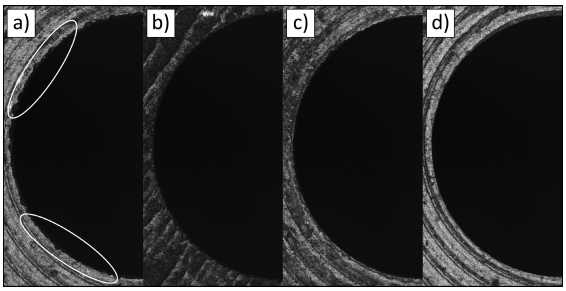

Figure 7. Resulting tool entrance areas of drill holes realised for ZrO_2 using different diamond grades and feeds a) ZrO_2, CVD-D, f = 2 µm; b) ZrO_2, CVD-D, f = 4 µm; c) ZrO_2, UD, f = 2 µm; d) ZrO_2, UD, f = 4 µm (v_c = 40 m/min, pressurised air).

4. Summary and conclusions

The presented research addresses the applicability and experimental testing of twist drills tipped with binderless diamond grades for machining of difficult-to-cut materials. The investigations focus on the machining of a cemented carbide, ZrO_2, and a CFRP with different feeds. First of all, the results provide a general prove of concept and functionality of the introduced tool design. Twist drills with solid binderless tips consisting of CVD-D and UD respectively are realised. A stable and steady tool wear progression is achieved in the investigated range of up to 60 drill holes generated within the cemented carbide. Suitable machining results are derived for all specimen materials based on the acquisition of tactile profile measurements within the drill holes and qualitative imaging of the tool entrance areas. While there are no significant differences for both diamond grades for the majority of combinations, UD proves advantageous for ZrO_2 machining. Upcoming activities will address the further development and maturation of the developed tools in order to prepare for tool market entrance and enable broad industrial application. Moreover, further research activities will investigate the effects of ultrasonic assisted drilling to enhance machinability of the focused difficult-to-cut materials.

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