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Influence of machining with defined cutting edge on the subsurface microstructure of WC–Co parts

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ABSTRACT

To machine WC–Co cemented carbides, discontinuous cutting (milling, shaping, etc.) with diamond tools can be an economical alternative to grinding or electrical discharge machining operations for finishing mechanical parts after sintering. However, the machining with cutting depths within the range of sintering allowance (≈0.2 mm) leads to high cutting forces which may influence the quality of the workpiece.

Single cuts of a shaping process of WC–Co with different rake angles and cutting depths were examined. SEM micrographs of the machined subsurface zone allow the measurement of microstructure parameters by an automated method programmed in MATLAB. The result is the determination of grain size, mean free path of the binder, contiguity and cobalt content of a selected region of interest within the subsurface compared to the according bulk properties.

Regarding the influence of the cutting conditions, it can be assumed that the damage of the subsurface zone correlates with the acting forces. Larger cutting depths and an extremely-negative rake angle of the tool, which both lead to higher loads, generate larger and further reaching damage in the subsurface. Within deeper influenced subsurface zones, parameters vary depending on the distance to the surface. Close to the surface, small fragmented grains can be found while in the deeper regions of the damaged subsurface zone only few single larger cracks were observed.

1. Introduction

The steadily growing importance of cemented tungsten carbide for wear resistant parts leads to a wide variety of part geometries and hardmetal grades. Although the metallurgical production process is already highly developed, most parts require machining following sintering, which includes removal of the sintered surface layer to achieve the dimensional accuracy. Electrical discharge machining (EDM), as well as grinding and lapping, are well-established methods for this process. In this state of the value chain, the potential for machining is limited due to high material hardness. Establishing machining with a defined cutting edge can increase flexibility. Hence, results of research on turning rotationally symmetrical geometries [1–8] and milling operations [9–11] have been published. While turning of WC–Co cemented carbides is already established in some industrial applications, machining in discontinuous cutting mode (milling, shaping, broaching etc.) is still critical due to the high static and dynamic loads on the system. In addition to challenges arising due to tool wear, aspects regarding workpiece quality are essential for process-stability of cutting in both continuous and discontinuous modes. Surface roughness values of $R_z < 1$ µm could be achieved in milling experiments, which are suitable for proximate polishing [9]. One of the most crucial aspects is the fundamental influence of the cutting process on the subsurface zone of the workpiece.

Previous analyses specify the damage of the subsurface zone by means of its depth, determined by SEM-measurements in the cross section of turned WC–Co parts [5,6,8]. In these experiments, tool wear, hardmetal grade and cutting material were found to have the most significant impact on the subsurface zone. These findings were superposed by cyclic load effects resulting from overlapping feed path. The influence of loads on the subsurface zone's microstructure in single cuts was not analyzed, nor were any other indicators, beside the depth of damage.

The analysis of microstructure has played an important role in material science for many years [12]. With the development of EBSD-analysis, new methods intended to complement the conventional standards for microstructure analysis are discussed in the scientific community [13].

An additional improvement can be attained by implementing conventional manual methods in automated image analysis programs based on SEM or optical images. Especially since the image processing toolbox is implemented in MATLAB, there is a greater possibility of applying these methods using common software. For the grain size distribution measurement of etched WC–Co hardmetals, a similar technique has already been demonstrated [15]. Other microstructure parameters, contiguity of the carbides,

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mean free path and weight content of the binder, can only be determined from polished samples without etching. Following, a suitable method and its application for characterization of machined subsurface zones will be presented.

2. Experiments

In order to analyze the influence of the mechanisms occurring in single cuts on the machined subsurface zone, a shaping process was implemented due to its simple kinematics. Sintered WC–20 wt% Co was cut with single edge tools. This hardmetal grade was selected for initial analyzes due to good results achieved in previous cutting experiments in discontinuous mode [9,16]. PCD was chosen for its superior performance in prior tests instead of thick-film CVD-diamond and CBN. Although thick-film CVD-diamond showed good wear resistance in turning of WC–Co [8], its fracture-toughness was not sufficient for milling and shaping. Contrary to PCD, CBN-tools failed at an early stage because of lower hardness properties [9,10]. Furthermore, strong differences between single PCD grades regarding wear have been observed in discontinuous cutting mode. The selected bi-modal grade performed promising in previous experiments [16]. Both tool and workpiece material properties are listed in Table 1.

Fig. 1 shows the experimental setup. On a 4-axis horizontal machining-center, the cutting insert was set in a toolholder fixed against rotation. The cutting velocity of $v_c = 14$ m/min was performed by the feed motion of the *x*-axis according to previous studies [9,10,16]. The workpiece was fixed on a three-component force measurement platform.

In hard machining, negative rake angles are commonly used to stabilize the cutting edge. Previous analyses revealed that employing extremely-negative rake angles can avoid tool failure. For this study, two negative rake angles γ_o were considered (Table 2). By inclination of the workpiece a linearly growing cutting depth a_p, ranging from 0 to 150 μm, was achieved. Hence, only the tool corner radius was in contact with the workpiece. Sections of cut are always circle segments whose size increases progressively with rising cutting depth. The contact conditions are shown in Fig. 2. Regarding the surface roughness measured in single cuts, a range of 1 μm < R_z < 3 μm can be specified for each rake angle tested.

After machining several cuts, the workpiece was sliced into single samples by wire EDM parallel to the sectional plane shown in Fig. 2. The surface of each sample was ground and polished with diamond suspension so that longitudinal sections through the middle of the machined groove were generated. These specimens allowed SEM-analysis of the microstructure of the subsurface zone machined at different cutting depths.

3. Analytical methods

Four parameters were selected for microstructure characterization: cobalt weight content (Co-wt%), average grain size of the carbides (d_{WC}), contiguity of the carbide phase (C) and mean free path of the Co-binder (λ). All of these parameters can be determined from SEM micrographs via digital image processing. Selected regions of interest from grey scale SEM-images were loaded in MATLAB as matrices, each with a number of elements according to the image resolution (pixel) and values from 0 (black) to 255 (white). The cut regions were rectangular in order to fulfill the demand of a matrix. As the carbides in WC–Co appear brighter than the cobalt binder, the two phases are easy to identify. For automated measuring, the selected region of interest had to be filtered with a low pass (median-blur) filter to reduce salt and pepper noise. Because sharp edges were needed for identification of grain boundaries, the dimension of the neighborhood matrix of this filter was set to the smallest possible size of 3 × 3 elements. Next, using a binary image generated through a threshold operation, the area of both carbides A_{WC} and binder A_{Co} can be measured by tabulating white (1-valued elements) and black (0-valued elements) pixels. The

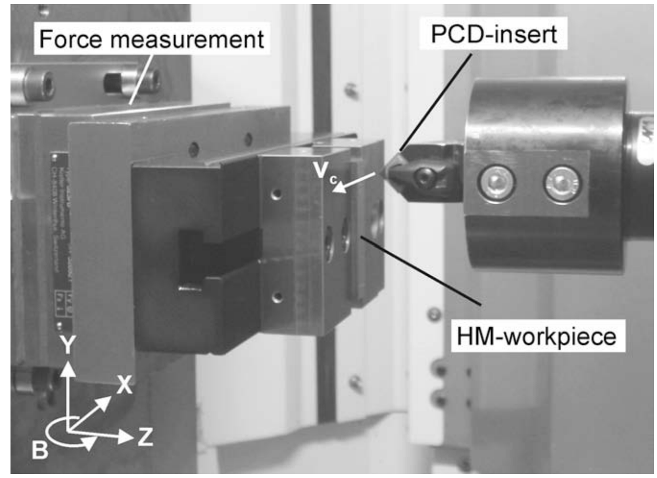

Fig. 1. Experimental setup for shaping cemented carbides.

Table 2
Tool geometry and cutting conditions.

Tool geometry	
Corner radius (r_ε)	0.8 mm
Edge radius (r_n)	<10 μm
Clearance angle (α_o)	8°
Rake angle (γ_o)	−8°/−48°
Cutting conditions	
Cutting speed (v_c)	14 m/min
Cutting depth (a_p)	0–150 μm

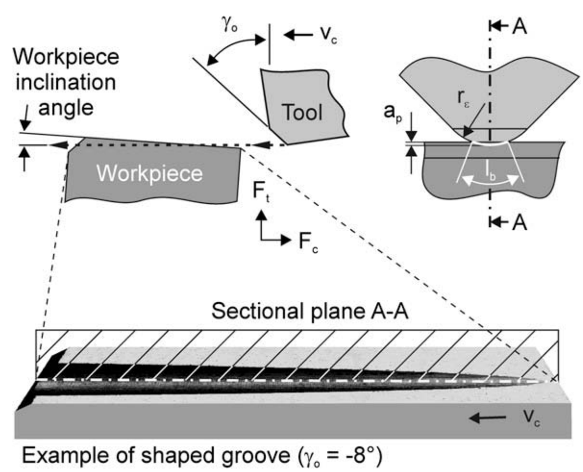

Fig. 2. Shaping with increasing cutting depth $a_p = 0$–150 μm.

Table 1
Material properties of workpiece and tool.

	Workpiece material WC–Co	Cutting material PCD
Composition	80 wt% WC, 20 wt% Co	–
Hardness	1100 HV10	–
Grain size	Fine	Bi-modal 30 μm/2 μm
TR-strength	3400 GPa	1150 GPa
Fracture Toughness	14.2 MPa*m$^{-0.5}$	11.7 MPa*m$^{-0.5}$