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Model System Studies of Wear Mechanisms of Hard Metal Tools when Cutting CFRP

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Abstract

Within the publicly-funded ZAFH research project SPANTEC light, the Competence Center for Tribology in Mannheim, Germany, examines the wear mechanisms of hard metal tools when cutting carbon-fiber-reinforced plastic in drilling and milling processes. The research project includes a test series with a tribological model test.

The development of a new tribological simulation model system, a modified pin-on-disc system respectively called as edge-on-disc system, for cutting CFRP with hard metal composites is systematically analyzed and presented in this work. With this model system, a new method for tool wear analysis of the tool materials against CFRP is described.

As result, there are further findings on the wear mechanism of the hard metal tungsten carbide in cobalt matrix (WC-Co) compared with carbon-fiber-reinforced plastic (CFRP). Research parameters for the tribological system in this paper are the WC-Co materials, with their WC-grain size and cobalt content, and the carbon fiber orientation.

This study introduces a first approach to determine WC-Co wear compared with a CFRP-specimen, unlike most hard metal wear tests. Furthermore it is shown, that properties of the drilling and milling processes can be adapted by altering the model systems rotating speed and normal force. The results originality is also provided by using a variety of WC grain size classes (sub-µm to approximately 7-9 µm grain size) and cobalt contents far above usual CFRP-machining properties to show the wear process between carbon fibers and WC-Co in detail.

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Keywords: Wear; tribology; hardmetal; pin-on-disc; machining; CFRP

1. Introduction

When cutting CFRP, tools suffer high stress loads, the intensity of which clearly depends on the structure of the CFRP workpiece. These loads cause strong abrasive tool wear on uncoated hard metal tools. As the cutting edges of the worn tools become increasingly rounded, they load increasing mechanical stress on the cutting zones and cause damage to the workpiece. The damage caused is delamination of the top coat near the surface and of the surface-near coating layers, fiber protrusion or matrix degeneration. The quantification and the method of quantification of the delamination damage by the tool wear-states are shown by Lissek [9].

A limit to the quantified CFRP work piece damage can be set and a correlating tool life for a drill or miller can be estimated. Tool life predictions for CFRP drilling were done by Iliescu [7]. The Method described is depending on the tool geometry and leads to good results in tool life predictions for known geometries. A geometry independent tool life prediction therefore is not described. But common loading conditions, like thrust force estimations through wear prediction can be adapted to basic edge geometry.

When modeling the tribological system at the cutting contact, the optimization parameter for qualitatively good cutting results is an optimally sharpened cutting edge which suffers minimal wear while also being resistant to load changes without fracturing.

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Models systems with coatings sometimes need to be viewed critically as qualitatively good coating requires a small cutting edge radius. It is also possible to use cutting edge geometries which are intended to remain sharp through the wear process [2].

One key objective in the analysis of a tribological system is the determination of the type of wear. In steel machining applications, the tools suffer chipping and metal adhesion, as shown by Chinachanikar [4]. Also built-up edges and mild abrasion are common, shown in the tool life determination of Krolczyk [5]. Hard coated tools also suffer chipping in CFRP machining due to high dynamic loads when cutting the fibers [7]. The wear mechanisms mostly depend on the tool's material and surface structure and, of course, the counter body. In the hard-metal-/ CFRP- system as shown and described later on, the wear mechanism tends to be purely abrasive to both, the cobalt and WC-phase.

The objective of this work is to provide a more detailed description of the complex system of primary stress loads and the incurred wear mechanisms on the tools. This insight into the wear mechanisms of the commonly used WC-Co hard metals provides ideas for improvement and optimization of the hard metal composition.

This paper is divided into three chapters: a description and analysis of the tribosystem, a description of the wear mechanisms and the results. The chapter on the results outlines, interprets and quantifies the most significant influencing factors of the system.

2. Wear mechanisms and wear testing for CFRP-machining applications

For the state of the art of wear testing for CFRP-machining applications, the application itself, e.g. drilling or milling of CFRP-pieces is used to derive the wear, mechanisms and the propagation of tool wear and workpiece damage.

Approaches for single elements of the tribological system are done in various works. For example, the WC-Co wear depending on different WC-grain sizes and Co contents is described in [8]. The mating counterbody used in the system is a hard body of silicone-carbide. The system itself is described in the ASTM G65.

By now, a CFRP-counterbody for wear testing is by doing drilling and milling tests with complex tool shapes. This demands higher efforts than model testing. Furthermore it is especially important for the screening of fine-tuned system compositions in statistically relevant quantities. For the geometric dependencies of the tool shapes, the application-like testing often leads to special shapes of the cutting tool.

As a first combined approach for the development of a CFRP-machining model system is therefore described in the following parts.

Nomenclature

CFRP	carbon-fibre-reinforced plastic
WC	tungsten carbide
Co	cobalt / cobalt volume fraction [%]
HM	hard metal
MD	multidirectional (laminate)
UD	unidirectional (laminate)
WC-α	tungsten carbide grain size [µm]
p	pressure as surface load [MPa] or line load [N/mm]
v	velocity / speed
s	sliding distance
G	geometry (as a state variable)
p_m	intermediate pressure as stress load on cutting edge [MPa]
W	wear (once used as a state variable)
W	wear rate as volume loss [mm³] per pressure load [N mm^{-2}] and sliding distance [mm]; Short Unit: [mm^4 N^{-1}]

3. System Analysis

Following the common systematic approach of Czichos [10, 11] and Habig [11], the system is divided into two structural elements – the HM tool as base body and the CFRP workpiece as counterbody. The system is an open system as the set feed and speed of the tool results in a continuous and nearly constant amount of material wear on the CFRP workpiece. The abrasive effect of the CFRP surface is constantly renewed in the cutting process. Atmospheric influences on the tribosystem are normally a negligible factor in real systems as long as the chips do not remain in the friction point because real systems normally rarely use liquid cooling lubricants and have cycle times that do not allow temperature-induced increase in the oxidation of the hard metal used.

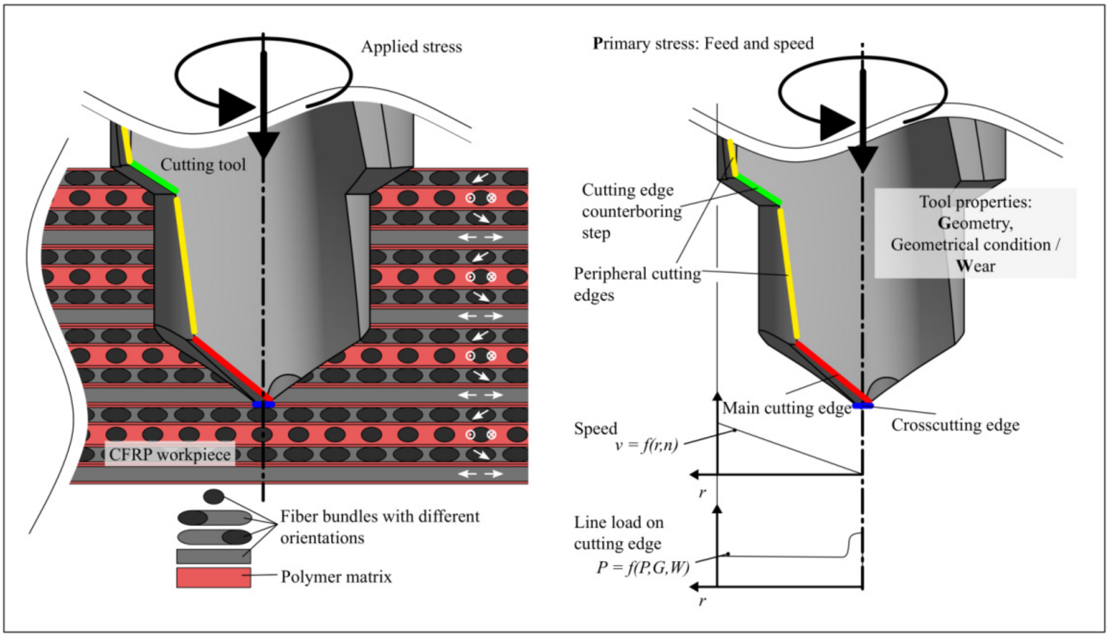


Fig. 1. Sketches of tool-CFRP contact and load collective

In order to present the system of CFRP cutting in more detail, the sketches in Figure 1 provide a schematic illustration of a drilling tool in contact with a fiber-composite multidirectional laminate (MD). The figures illustrate the geometry-specific cutting features of the tool and the possible cutting direction modes of the fibers.

The primary stress applied is normally set by the pre-determined feed and speed values. These set values are based on benchmarks for the workpiece quality used and the tolerable mechanical and thermic stress load for the tool and workpiece tested. The loads occurring on the tribosystem cutting edge-CFRP can be regarded as secondary stress loads, their value basically depending on the primary stress, the basic geometry of the cutting edge, the state (of wear) of the cutting edge and the CFRP workpiece.

The pressure applied through the main cutting and counterbore part of the cutting edge results in different sliding speeds, which depend on the correlation of the rotational speed and the distance between the sliding area and the axis of rotation of the step drill presented in the model. With peripheral cutting edges the sliding speed is proportional to the tool speed. The forces are described by comparing the line load data as the edge dimension in the cutting direction is essentially smaller than the cutting edge length.

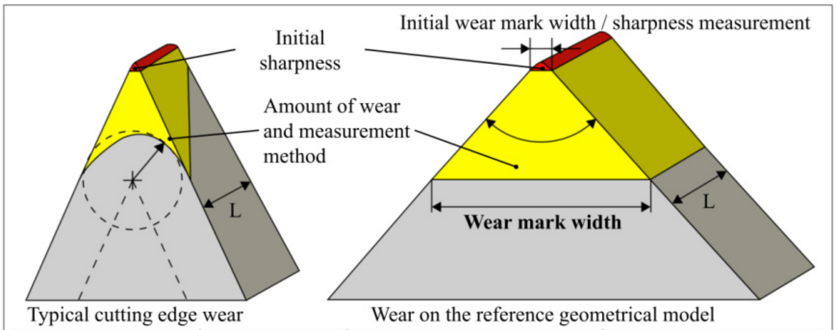
The possible fiber cutting modes depend on the type of application. For example, in drilling processes, the main cutting edge can produce all possible fiber cutting directions if the axis of the drill is perpendicular to the spatial plane. The exact cutting angle however also depends on the angle of the drill bit. In milling and trimming operations, the fiber cutting mode in relation to the circumpheral cutting edge is nearly identical to the original laminate fiber direction. Therefore, with UD laminate (unidirectional) it is possible to achieve one uniform cutting mode for all fibers.

In a to-scale perception of the detail dimensions, an individual fiber has a diameter of approximately 5 - 6 µm and newly-sharpened cutting edges have cutting radiuses in the range of approximately 5 - 10 µm. The cutting/fracture properties of the fiber depend on its mechanical properties, the flexibility of the material mix and of the adjacent fibers. If the cutting direction of the fiber is off-perpendicular, the fiber can also be separated by torsional buckling or tearing. Another possibility is elastic buckling or the fiber bending without tearing. These outcomes lead to higher forces and local stress loads on tool edges and surfaces.

This and the following paragraph describe and analyze the system as regards to wear mechanisms, as this is the subject of the present paper. For a more general system analysis which provides additional information and also focuses more on the materials, we would like to refer to the work of Keller [1].

4. Description of the Amount of Wear

The wear amount occurring in the real system is normally cutting edge rounding. This amount of wear can be expressed through the radius of an approximately circular construction, with the circle center being the intersection point of lines running parallel to the free area and cutting area. The rate of cutting edge rounding can vary along the cutting edge. Normally, cutting edge rounding increases with the distance from the center, due to the increasing sliding distance and sliding speed. The same applies to trimming operations, where different rounding rates are to be expected along the cutting edge as the CFRP laminate structures have different abrasive potentials in the direction of the cutting edge and the laminate thickness direction. This is caused by the different density of the fibers and rovings and their layer structure.



Aspect	Real system	Edge-on-Disc	Block-on-ring
(Line) pressure	2 – 10 N/mm	1 – 6 N/mm (low resonance)	10 - 100 MPa
velocity	100 m/min	81.6 m/min (low resonance)	9.42 m/min
Temperature hard metal	Up to 400 °C	approx.. 110 °C near contact	60 - 80 °C
CFRP contact ratio	0 (open system)	$>10^{-7}$ (partially open system)	$\sim10^{-2}$

Fig. 2. Geometrical wear parameters and tribological system data

On the modified pin-on-disc system, subsequently referred to as edge-on-disc, the amount of wear on the hard metal base body is expressed as the directly measurable width of the wear mark.

When comparing typical parameters of the real system and the substitute model system developed in the present project, it turns out that the edge-on-disc system reflects the real conditions well. The systems are sketched and compared in Figure 2, which also includes a comparison of the system data in a table. Figure 2 also indicates which wear parameters are relevant.

The mere comparison of the geometrical dimensions of the real and the model systems makes clear that the model allows more flexibility in the choice of dimensions. Besides the model geometry, Figure 2 also lists other comparative aspects in a table at the bottom of the illustration. This shows that the model system chosen illustrate the real life system well. The edge-on-disc system is the most suitable model to illustrate the parameters. The values in the table allow a successful test run on the type of tribometer used. It is also possible to test other parameters, while taking into account the low excitation energy through the transient friction and cutting forces in the HM-CFRP contact. The block-on-ring model, which is used to examine cobalt phase removal, illustrates a very different load collective. It also presents a particularly high contact ratio of the CFRP body (as a ring), which very much differs from the contact ratio in real system conditions.

5. Test Set-up

The test set-up on a rotational tribometer which runs automatized test programs consists of a stationary adaptation of a prepared HM test specimen with a set edge length, a wedge angle of 90° and a CFRP disc which is set into contact on its front side. The radial symmetric adaptation models the edges at a “negative” wedge or free angle of each 45°. The line contact is oriented radially to the drive axis of the CFRP disc and can be set in relation to the disc surface by a tangential axis (perpendicular to the cutting edge). Unstable running of the CFRP discs are leveled out by a gimbal suspension. Waviness is removed by a first dressing of the CFRP disc. The CFRP disc is used several times as each run renews the CFRP surface.

The hard metal test piece is prepared by grinding for angle and flatness with the edge state of the HM specimen being ground sharp. After preparation the edge dimensions in the direction of the sliding and cutting are smaller than the biggest WC crystal size (<9 µm) used. Because of edge stability and the manual grinding process, finer grinding is not possible. Also, a sharper edge would not be practically useful. The load collective used is derived from typical applications with known wear areas and thrust forces, from earlier works of Lissek [9], to calculate edge loads over time. Knowing the thrust forces and torques on the tools is necessary to derive the load collective. An appropriate method of measuring the tool loads is shown by Nieslony in [10].

6. Hard Metals and Carbon-fiber-reinforced Materials

For the investigation on wear mechanisms, the terms shown in figure 3 were used. Hard metals are presented as points on the graph showing the volume of cobalt and the mean WC grain size (WC-α). As can be seen, apart from particularly fine-grained types, coarser types, which are not used in real CFRP cutting, are also investigated because the results contribute to a wider knowledge base of wear mechanisms.

For a later comparison the hard metals G10 and G30 are used because of their different cobalt content. Another pair of metals studied is G50 and GT50 with their different grain size and roughly equal cobalt content. EMT 100, which has not been tested yet, could in the future be used with G10 and G30 because of the variety of grain size.

The hard metals U08, F10 and U40 were used in the hardness correlation study by Keller [1].

All hard metal types are commercially available and the trade names are used in this paper.

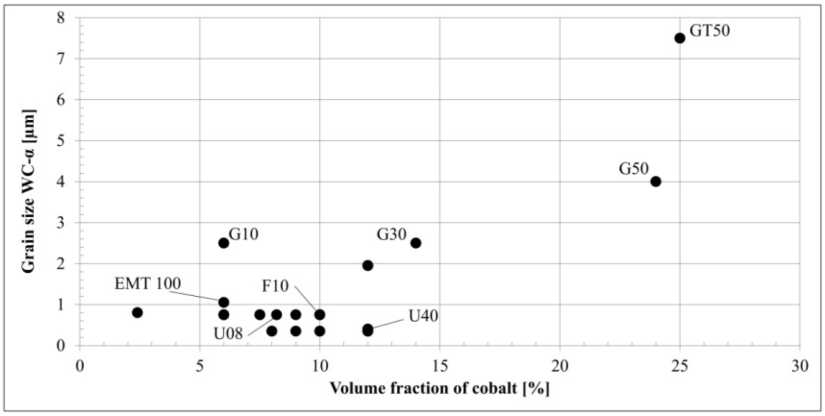


Fig. 3. Hard metal grain size and Co content in the ZAFH research project SPANTEC light

The CFRP discs used are autoclave-multidirectional, hot press-multidirectional and unidirectional structures from UD-prepregs MT21/T800S of the company Hexcel. The fiber type has an intermediary module, 24000 filaments per bundle, a fiber volume of 57% and is set in epoxy resin. The single filaments have a 5 µm diameter.

For the investigation on different fiber orientation, hot press plates are prepared as discs so that we can determine the direction of the fiber within the orbit in the edge-on-disc test. The section with results on the amount of wear for different fiber orientations will provide more details.

7. Wear Mechanisms in Hard Metals

Figure 4 provides the basis for the analysis of wear mechanisms in the investigation. Top left is hard metal G10 with G30 on the top right. In the lower row, G50 is on the left with GT50 on the right. Additionally, mean WC grain size, cobalt content, Vickers hardness (in HV10), with the observed wear mark width (in µm) are shown. The CFRP object used is a woven laminate. The prismatic WC grain is presented as lighter than the surrounding cobalt even through secondary-electron contrast, because of the great differences in the material properties of tungsten carbide and cobalt.

In the investigation a sliding speed of 81.6 m/min is set. The normal stress load of the edge as a linear load starts at 1 N/mm and increases in a linear fashion to 6 N/mm within 15 minutes to ensure a specific minimum pressure on the edge and slight wear on the CFRP body. The load of 6 N/mm is then held for a further 15 minutes. A specific constant pressure over the entire time period cannot be ensured as the available online wear measurement is a total wear value and does not distinguish, among others, the thermal expansion of the tribometer as a measured value.

The principal mechanism of primary cobalt removal becomes clear in the comparison of the test pieces in the first row, G10 and G30. With the same WC grain size the cobalt content of G30 is roughly 2.3 times that of G10. The result is a wear pattern with clear void volume on the surface. In both cases the remaining WC grains on the surface are the sole-supporting or load-resisting body. Doubling of the wear mark-width indicates a higher rest load on the remaining WC grains on the surface in G30.

Depending on the fiber contact there is also more exposure to stronger forces because the empty spaces between the grains on the fiber fraction surface mean additional exposed contact and wear surface.

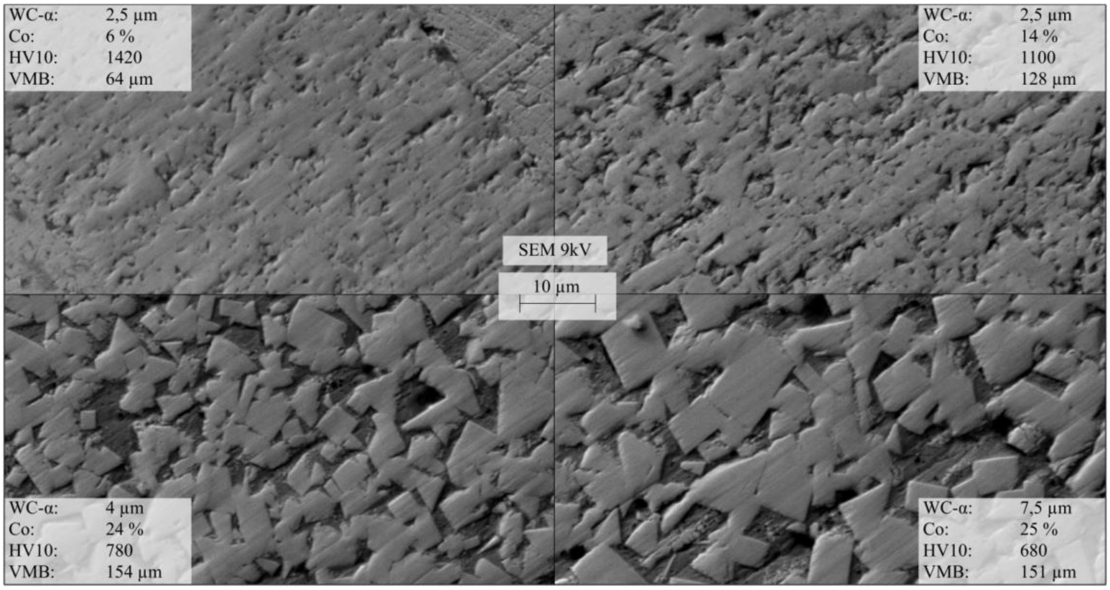


Fig. 4. SEM images of worn HM cutting edges

The wear on the WC grains is particularly evident in test pieces G50 and GT50. The scoring marks running over the grain show the sliding direction of the edge. In the pictures the CFRP composite runs from bottom left upwards towards the right. The wear marks clearly illustrate the transgranular purely abrasive wear of the WC grains. This removal of matter is very finely structured in relation to the dimensions of the counter body, the approximately 5 µm diameter carbon fibers. It thus seems that particularly the fracture areas of the cut fibers and the lateral area of the uncut fibers are responsible for this wear.

Because of the roughly equal cobalt content of G50 and GT50 the WC grain size has no noticeable influence on wear mark width; differentiation is hardly possible. Regarding repeatability and reproducibility of test conditions, both wear width measurements are at the same level. The left side of Figure 7 a) shows the minimum and maximum wear width marks as bars. In combination with composite hardness values there is a tendency for a reversal of the correlation between hardness and amount of wear, which is also visible with G10, G30 and G50. The reason for this reversal could be the coherent WC grain areals which are visible in GT50. There is a mechanical contact between the fiber area of the counterbody and a rather large surface of the HM composite, which has a lower edge to surface ratio than fine-grained sorts. Statistically, there is a lower frequency of high loads on WC grain edges. Evidence for this is the visible rounding towards the WC edges or the WC grain areals in SEM images for each hard metal.

To establish what influence stress loads applied or the test set-up have on the wear pattern and thus the active wear mechanisms, randomly sampled extreme tests were conducted on HM G50. The results can be seen in the surfaces shown in Figure 5.

In this, it becomes clearer that with higher stress loads, there is a more course abrasive removal of cobalt and WC grains, and a breaking off and to an extent a reembedding of WC grain fragments. In detailed comparison with the images of G50 and GT50 in Figure 5 (for comparison, stress load – 40 MPa, sliding distance 2580 m) reembeded WC grain fragments in the cobalt are clearly visible in Figure 5 at 90 MPa and 430 m. The rounding of the WC grain areals also appears more strongly pronounced. Whether finer-grain metals show similar wear mechanisms still needs to be clarified, as probably finer WC grains in cobalt are worn off as full grains before intracrystalline forces break the grain.

Also evident at 200 MPa is higher cobalt removal at the cutting area because the higher forces of the hard metal edge can apply more pressure onto the CFRP metal.

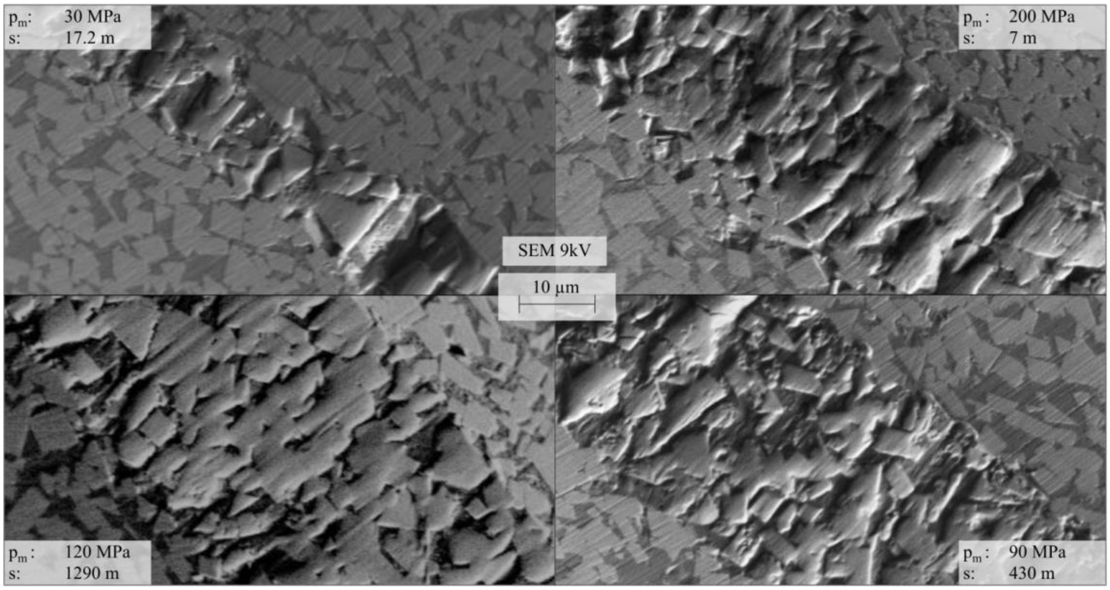


Fig. 5. SEM images of worn HM cutting edges in different load scenarios

8. Wear Rates with Different Fiber Orientations

Figure 7 b) shows the results of the investigation into the wear rates of hard metal F10 (10% Cobalt, 0.75 µm WC-α) with varying CFRP fiber orientation. Figure 6 shows a graphical explanation of fiber orientation. Fiber orientation nomenclature is related to Sheikh-Ahmad [6]. In the images the cutting edge runs in a circular orbit in the image plane, the orientation here is always radial to the orbit center. The wear rate here is calculated as a quotient of the volume of wear removal from the wear width, the sliding distance and the surface pressure.

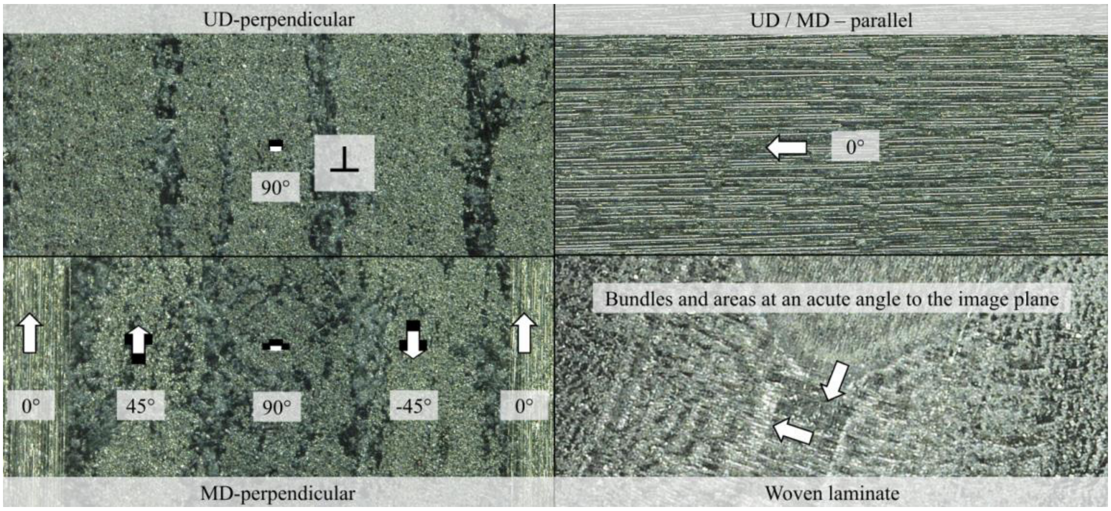


Fig. 6. Light microscopy of CFRP surface and description of fiber orientation

In determining different surface loads, the test is halted three times after a specific sliding distance, and the wear width is measured. The wear rate in Figure 7 b) is here the mean value of the rates calculated, with the bars representing minimum and maximum values from a duplicate determination.

The measurements confirm the stronger abrasive effect of the fibers oriented oblique to the sliding or cutting direction. This abrasive effect is also observed in trimming applications in real systems. Apart from the primary wear on the hard metals, CFRP surfaces are of lower quality (stability and fiber protrusion) after the cutting process at oblique angles. The fiber orientation dependency of the damage mechanisms of the CFRP work piece are further described by Sheikh-Ahmad [6].

The reason for the stronger abrasive effect could be the pronounced higher forces for a non-perpendicular fiber cut. In the case of an oblique cut, the fibers can bend or buckle in the cutting process before breaking. The reaction forces on the hard metal surface thus increase.

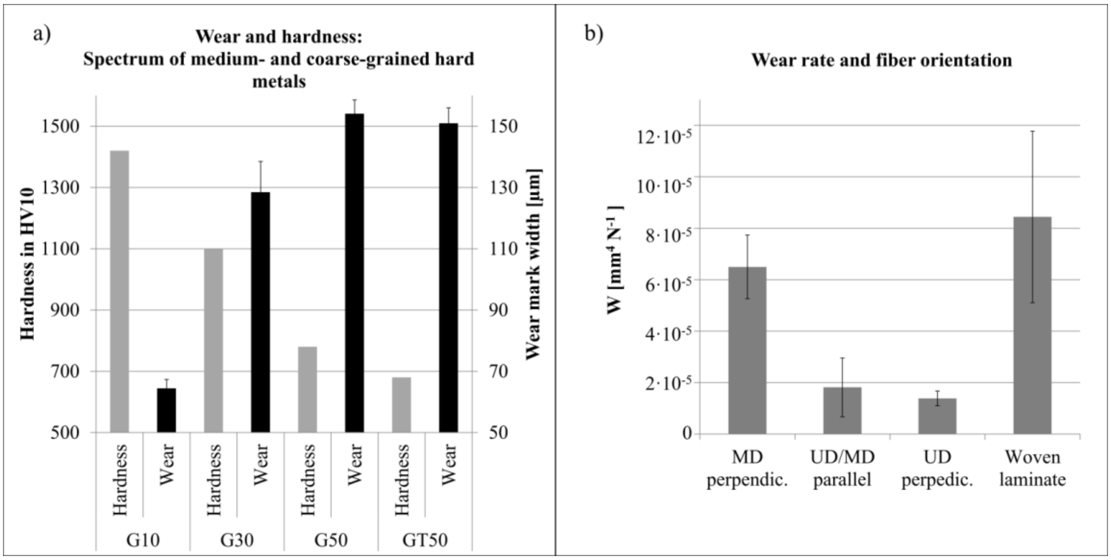


Fig. 7. a) Wear mark width and hardness of coarse grained hard metals, b) wear rates for different fiber orientations

9. Outlook

Apart from the investigation into other correlations between wear mechanisms, which can be conducted, amongst others, by testing further types of HM, future project plans include studies with other cutting materials and coatings.

Another objective is to develop specific CFRP samples for the analysis of the influence of the direction of the fiber cut. Within the joint project, the model systems developed are also tested for their applicability for thermoplastic CFRP.

Another possible project could be a theoretical model and simulation of the fiber-breakage resistance at the cutting edge contact. Test results on the forces working on the cutting material could provide information on the load conditions in the cutting contact.

10. Summary and Conclusion

The wear mechanism of HM tools when cutting and/or making contact with CFRP is mainly characterized by the cobalt phase removal. Depending on the cobalt content of the HM the surface formed by the WC grains is the resistance body against the fibers. The cobalt content is the main influencing factor for wear. The lower the cobalt content, the lower the wear. When using identical cobalt content and significantly different WC grain sizes, the measurable wear parameters are not very differentiable. Overall WC-Co compositions, it is shown, that the WC grains suffer transgranular abrasion due to the fiber contact.

The new developed model system is suitable for the differentiation of hard metal tool materials in contact with CFRP specimens. Furthermore, the model system allows a statement for the wear rate dependence on different fiber directions and CFRP laminate structures.

Wear rates of HM materials for different laminate structures and the resulting different directions of the fiber cut can be determined in the designed model system. For the specific wear rates on different fiber directions and laminate structures, it is shown, that CFRP specimens with oblique inclined fibers relative to the cutting edge produce more wear than specimens with perpendicular or non-inclined fibers.

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