

## High Performance Cutting

# Comparison of ground and laser machined polycrystalline diamond (PCD) tools in cutting carbon fiber reinforced plastics (CFRP) for aircraft structures.

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### Abstract

The extended use of carbon reinforced plastics (CFRP), especially in aircraft industries, requires efficient machining solutions due to superior mechanical properties with a lower weight compared to metals. This material is highly abrasive, requiring very hard cutting materials and additionally only a sharp cutting edge provides a sufficient surface quality on the workpiece. Ultrashort laser pulses and the focusability of high brilliance laser systems enable diamond processing without relevant graphitization or other material deteriorating effects for polycrystalline diamond (PCD). This study focuses on a comparison of conventional and laser machined PCD cutting tool inserts and a characterization of their machining characteristics. Conventional processing of the PCD tools is done using grinding processes on five axis machining centers. Laser manufacturing is done using a five axis CNC machine with additional three axes for beam delivery. Comparable values in terms of surface roughness on flank and rake face as well as edge curvature radii are achieved. The comparison of machining characteristics is done machining CFRP in a continuous turning process with a single fiber orientation at cutting velocities of 200 m/min. Machining forces and the cutting edge radii are measured to evaluate tool wear. The resulting work piece quality is analyzed by measuring surface roughness and integrity using tactile surface roughness measurement (Taylor Hobson PGI 1240) and scanning electron microscopy (SEM).

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Laser micro machining; Cutting; Composite; Tool Wear

### 1. Introduction

This study consists of two interconnected parts, one deals with the manufacturing of cutting tool inserts using ultrashort laser pulses. The second part focuses on turning experiments of ground and laser treated cutting tools. Laser processing of composite materials as well as cutting edge generation technology based on ultrashort laser pulses has drawn a lot of attention in the past few years. Main current process strategies in cutting CFRP are milling, drilling, waterjet machining and laser processing. The first major introduction of CFRP appeared within the aircraft industry. As milling and drilling are well established processes within this industry, early research focused on these topics [1].

The authors found that uncoated carbide tools and nitride or carbide based coatings showed an insufficient wear resistance. Available diamond coatings showed a very poor ply adhesion. In combination the authors recommended PCD-tools. Nevertheless the authors mention high tool costs in combination with a low geometrical flexibility. Recent studies show a sufficient tool lifetime of coated carbide tools due to a good ply adhesion of the diamond coatings in combination with high geometrical flexibility [2-3]. In result diamond coated carbide is being used for the majority of the drilling tools and to increasing portions of milling tools. CFRP is described as technically challenging to machine. Defects like delamination, uncut fibers, fiber pull-out

and thermal damages occur [4]. A sharp cutting edge is one of the indispensable prerequisites for a flawless work piece surface [5-6]. Rounded cutting edges lead to increased delamination, uncut fibers and thermal damages [7]. Carbide tools with a diamond coating of 5-10  $\mu\text{m}$  thickness in general show a higher cutting edge radius ( $r_p$ ) than PCD tools, where the PCD layer is at least 500  $\mu\text{m}$  in thickness and thus like a cutting insert. Ground PCD tools are very limited in the geometrical flexibility and limited to small grain sizes. Laser manufacturing of PCD tools promises a better work piece quality due to better adaptable cutting tool geometry and higher lifetime due to larger grain sizes. This first study compares ground and laser machined PCD tools of identical material and geometry to evaluate their general tool quality. Main fields of application for CFRP are aerospace and the sports industries. Automotive and machine tool industry have increased their application of CFRP due to reduced material costs [5].

## 2. State of the Art

### 2.1. Laser manufacturing of cutting tool inserts

Generating a defined cutting edge in PCD on a carbide substrate is mainly executed with good quality using lasers in pulsed regimes of nano- to femtoseconds [8]. Weikert et al. analyzed the influence of laser parameters, especially pulsed influence, laser power, repetition rate and process gases such as nitrogen, helium, argon and ambient air on cutting edge generation of cutting tools, from PCD, and monocrystalline diamonds (MCD). Feed rates for 200 micron thick layers are in the range of 1 mm/s using a repetition rate of 8 kHz and a pulse energy of 350  $\mu\text{J}$  at a pulsed width of 5 ps [9]. Harrison et al. presented results for laser cutting and laser polishing of PCD on tungsten carbide (WC) using nanosecond laser pulses at 1.064 nm wavelength with a pulsed width between 20 and 200 ns as well as a coaxial laser cutting head with an assist gas jet and an intensity of 120  $\text{MW}/\text{cm}^2$  [10]. Assist gases did not show an essential improvement in cutting tool quality. Hu et al. investigated three types of cutting tool materials, nanocrystalline (NCD)-, MCD and PCD diamond structures by machining an Al-matrix and an A390 alloy. Regarding roughness values, PCD tools achieve the best results, in terms of performance NCD reaches similar values than PCD tools [11].

### 2.2. Cutting of CFRP

Machining of CFRP has attracted considerable attention in literature. The research on machining the

material has been widespread including turning, milling, drilling, waterjet cutting and laser machining for applications in the aerospace industry [1,5,12-13]. Up to now riveting of joints is the most important joining technology in aerospace industry making drilling an important technology in this field. Most research focuses on the required geometry of drills [14-16]. CFRP causes massive tool wear when drilling, making ultrahard coatings like diamond or PCD inserts necessary. The most severe damage to the work piece observed is delamination, which is getting worse for increasing tool wear. The second important operation for CFRP parts, contour trimming, is mainly done with coated carbide tools, PCD tools and water jet cutting [5,17]. Uncoated carbide tools face intensive wear during the milling operation. Diamond coatings show sufficient wear resistance. Main work piece damage when milling CFRP with coated carbide tools is delamination at the material edge [18]. The authors have tried most complex tool geometries to ensure a permanent pressure from the work piece edge to the mill axis center. PCD tools face fewer problems with delamination even though these are limited in the achievable geometrical complexity. The smaller cutting edge radius yields lower forces on the work piece, resulting in lower susceptibility to delamination. Water jet cutting has found a lot of attention in literature in the past years [5,13]. Work piece damage like delamination and uncut fibers can be eliminated. Nevertheless a starting hole is still required, and the cutting operation is too time consuming, when cutting CFRP using waterjet technology, making the latter inefficient for drilling operations. Laser machining of CFRP is reported using pulsed widths from continuous wave down to ultrashort laser pulses [12,19-21]. In direct laser processing of CFRP thermal damage and the cut kerf quality in terms of geometry and surface roughness properties represent the main challenges. Pulsed lasers enable damage free machining of CFRP in a pulsed width range of nano- to femtoseconds.

## 3. Objectives and experimental condition

### 3.1. Laser system and processing setup

The setup is depicted in Fig. 1. It utilizes a picosecond laser source operating at a pulsed width of about  $t_p = 10$  ps. The beam guiding setup consists of three linear and two rotary axes as mechanical and of two galvanometer driven rotary axes for beam guidance in the x-, y- plane as well as one focus shifter system which is employed for focal spot shifting in z-direction. The focal length of the plane field correction lens is  $f = 163$  mm. Furthermore a  $\lambda/2$ - and a  $\lambda/4$ -plate

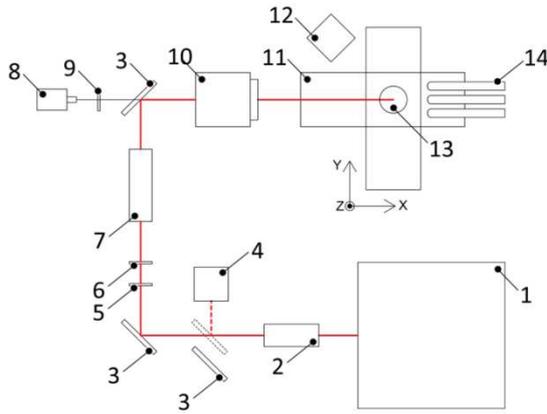


Fig 1. Experimental setup laser system. (1) Laser source. (2) Beam expansion system. (3) Mirrors. (4) Power meter. (5)  $\lambda/2$ -plate. (6)  $\lambda/4$ -plate. (7) Focus shifting unit. (8) Online camera. (9) Iris diaphragm. (10) 2D scan unit. (11) 5-axis CNC system. (12) 3D-measurement device. (13) Work piece. (14) Auxillary gas nozzles.

is employed which allows for polarization control in vertical, horizontal or circular states. Cutting edge generation is done via guiding the laser beam along the desired final geometry on the work piece with a scanning hatch width of 500 microns. The used laser parameters for edge generation are depicted in Table 1. Graphitization effects on the diamond surfaces using picosecond laser radiation below a pulse duration of  $t_p = 10$  ps are neglectable [22-23] and therefore have not been under consideration for this study. In case of graphitization effects tool life is expected to be drastically reduced. In a first step the cutting tool insert is cut to shape within tolerances of about 100 microns, a second step generates the final surface finish as well as cutting edge radius geometry with laser irradiation at different inclination angles to the work piece.

Table 1. Used laser parameters

Pulse duration	10	ps
Wavelength	1.064	nm
Focal spot diameter	35	$\mu\text{m}$
Fluence	0,179	$\text{J}/\text{cm}^2$
Pulse energy	47,5	$\mu\text{J}$
Scanning speed	2.000	$\text{mm}/\text{s}$

Table 2. Constant cutting parameters on Okuma LB15-II for turning experiments for all work pieces under consideration.

$\alpha$	$\gamma$	$v_c$	$f$	$v_f$	$a_e$	$Q_w'$	$V_w'$
deg	deg	$\text{m}/\text{min}$	$\text{mm}$	$\text{m}/\text{min}$	$\text{mm}$	$\text{mm}^3/\text{mm}/\text{min}$	$\text{mm}^3/\text{mm}$
7	0	200	0,1	0,032	1	20	47.124,0

### 3.2. Cutting test condition

The conducted machining tests are turning tests using unidirectional CFRP-material. The constant cutting conditions for all tests are depicted in Table 2, these are the flank angle  $\alpha$ , face angle  $\gamma$ , cutting velocity  $v_c$ , feed rate  $v_f$ , feed per rotation  $f$ , depth of cut  $a_e$ , inclination angle  $\lambda = 0^\circ$  and a setting angle  $\kappa = 90^\circ$ . The cutting inserts are PCD-tools with a fine grain size of 2-4  $\mu\text{m}$  in average and a diamond content of 90%. Each CFRP-work piece is laminated using 20 layers in a single fiber orientation. The nominal work piece thickness is 5 mm, the tested fiber orientations are  $30^\circ$ ,  $90^\circ$  and  $150^\circ$  in the direction of cut. The work piece material is an IMA-12K fiber in combination with M21E matrix material as being used in the upcoming Airbus A350. The fiber volume content is 60%. The process forces are measured using a Kistler dynamometer Type 9121.

### 3.3. Measurement condition

For surface metrology of the cutting inserts a 3D optical microscope is used. Measurement parameters are a twentyfold magnification, vertical resolution of 0,2  $\mu\text{m}$ , lateral resolution of 1  $\mu\text{m}$  using polarized light at a  $90^\circ$  inclination. Measurements are carried out on unused and used cutting inserts after a removed material amount of  $V_w' = 47.124,0 \text{ mm}^3/\text{mm}$ . After each cutting operation an imprint cast of the cutting edge was made by using epoxy resin. These imprints are used for measurements on cutting tool radius development. The used measurement setup consists of a Taylor Hobson Talysurf PGI 1240, with a resolution of 270 nm in the measuring direction and a diamond measuring tip with a cone angle of  $60^\circ$  and a tip radius of 2  $\mu\text{m}$ . Evaluation of the measured cutting edge profiles is carried out by using a robust circle fitting method from Wyen et al. [24].

## 4. Experimental results

### 4.1. Laser preparation of cutting tool inserts

The resulting cutting edges can be seen as SEM images in Fig. 2. Laser treated cutting edges have cut diamond grains and exhibit a homogeneous surface throughout the cutting radius geometry. Ground tools tend to have broken out grains due to the inability to cut these grains directly. Processing of large grain sizes using grinding machines poses the problem of achieving very large chipping values on the cutting edge and cannot be done effectively, therefore grains are torn out of the surface, leaving holes in the binding material, which on the laser treated tools is inexistent.

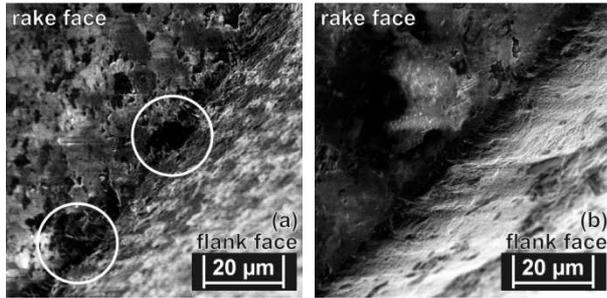


Fig. 2. SEM images of unused cutting tool inserts. (a) ground and (b) laser treated cutting edge. Torn out grains are marked by circles.

Resulting cutting edge radii (ground and laser treated tools) are shown in Fig. 3. The unused tools have similar edge radii in the range of  $r_{\beta} = 5$  to  $5,3$  microns in case of the ground, and  $r_{\beta} = 4,3$  to  $6,5$  microns in case of the laser treated cutting tools. On such small radii measurement uncertainties and circle fit errors cannot be neglected. On the shown measurements the uncertainties are up to  $3,9$  microns. With respect to that the cutting tool geometries are well comparable. Achieved processing times are about  $t = 8$  minutes on ground and about  $t = 6,5$  minutes on laser treated edges for the complete cutting edge generation process.

#### 4.2. Comparison of ground and laser treated cutting edge behavior on turning experiments.

The tool wear for ground and laser machined PCD cutting inserts is alike. As can be seen in Fig. 3 the wear for machining CFRP under a fiber orientation angle of  $150^{\circ}$  is very low, increasing the cutting edge radius from about  $r_{\beta} = 5 \mu\text{m}$  to  $r_{\beta} = 8 \mu\text{m}$  (ground) and  $r_{\beta} = 7,5 \mu\text{m}$  (lasered) respectively. After a specific material removal of  $V'_w = 31.416,0 \text{ mm}^3/\text{mm}$ . When machining with a fiber orientation of  $90^{\circ}$  or  $30^{\circ}$  the wear is considerably increased. The cutting edge radius increases from about  $r_{\beta} = 5 \mu\text{m}$  to values of  $r_{\beta} = 31$  to  $37 \mu\text{m}$  for the tested tools. Major differences in respect to the cutting edge radius between ground and laser machined tools cannot be observed, this clearly indicates, that there is no measurable graphitization due to laser machining. Fig 4 shows the profiles of each tool after a specific material removal of  $V'_w = 31.416,0 \text{ mm}^3/\text{mm}$ . The shape of cutting inserts machining CFRP with a fiber orientation of  $150^{\circ}$  are closest to the shape of new cutting tool inserts. The tools machining CFRP with a fiber orientation of  $90^{\circ}$  and  $30^{\circ}$  show intensive wear on the flank face, displaying a waterfall profile. Ground tool machining at a fiber orientation of  $30^{\circ}$  shows largest wear on its flank face. The feed force shows a good

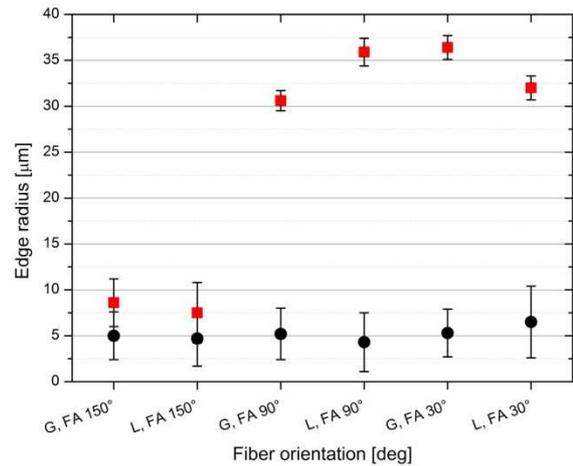


Fig. 3. Cutting edge radius comparison between ground (G) and laser treated (L) cutting tool edges. Black circles show cutting edge radius on new inserts, red squares after a material removal of  $V'_w = 47.124,0 \text{ mm}^3/\text{mm}$  at fiber matrix orientations relative to cutting direction of  $150^{\circ}$ ,  $90^{\circ}$  and  $30^{\circ}$ .

correlation to the increasing tool wear. As can be seen in Fig. 5 the feed force almost doubles during all experiments. When machining CFRP with fiber orientations of  $90^{\circ}$  and  $150^{\circ}$  the feed force for ground and laser machined tools is almost identical and work piece roughness has equal values for the  $90^{\circ}$  machining operation, as depicted in Fig. 6. A surface roughness value of about  $R_a = 2 \mu\text{m}$  is achieved in both cases and does not change with increasing wear. However, the resulting work piece roughness for machining CFRP with a fiber orientation of  $150^{\circ}$  is about 20% lower for the work piece machined with the laser machined tool ( $R_a = 5-7 \mu\text{m}$ ) compared to the ground tool ( $R_a = 7-12 \mu\text{m}$ ). The feed force is highest for  $30^{\circ}$  CFRP fiber orientation, whilst the

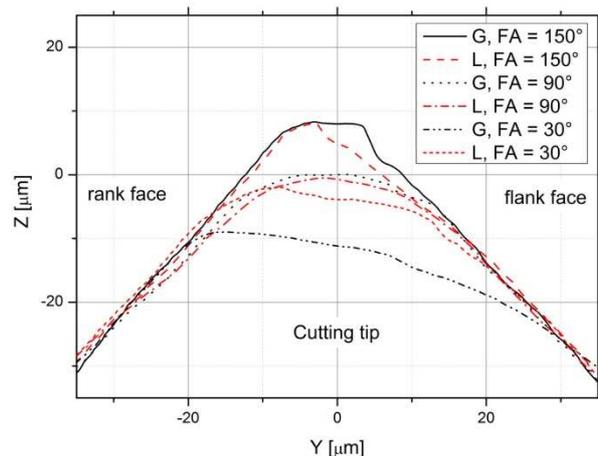


Fig. 4. Cutting edge analysis of ground (G) and laser treated (L) cutting edges after material removal for fiber orientation angles of  $150^{\circ}$ ,  $90^{\circ}$  and  $30^{\circ}$  of  $V'_w = 31.416 \text{ mm}^3/\text{mm}$ . The rake face is displayed on the left, the flank face is shown on the right.

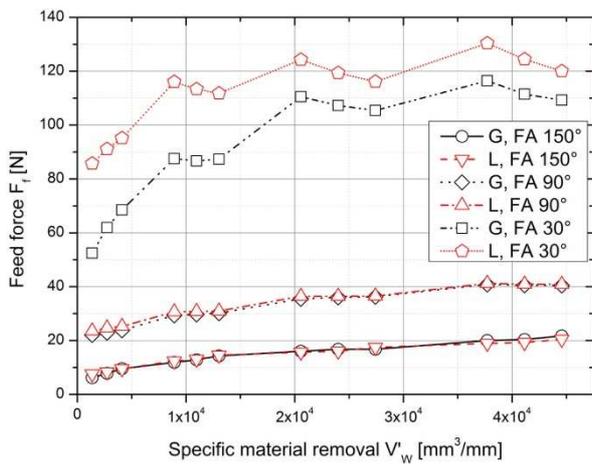


Fig. 5. Feed force comparison of ground and laser treated cutting tool insert on cutting CFRP.

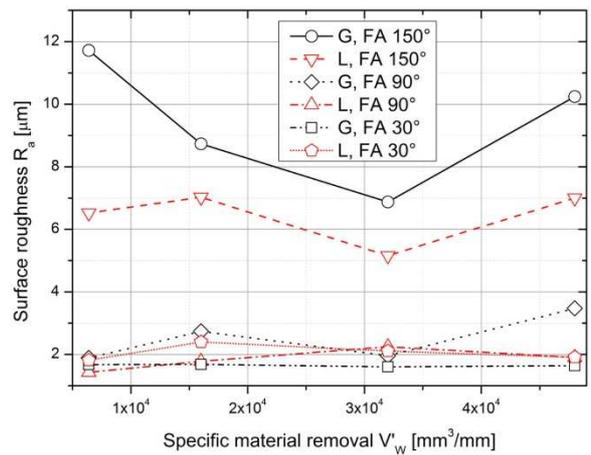


Fig. 6. Surface roughness of CFRP work piece. Comparison of turning results of ground and laser treated cutting tool inserts.

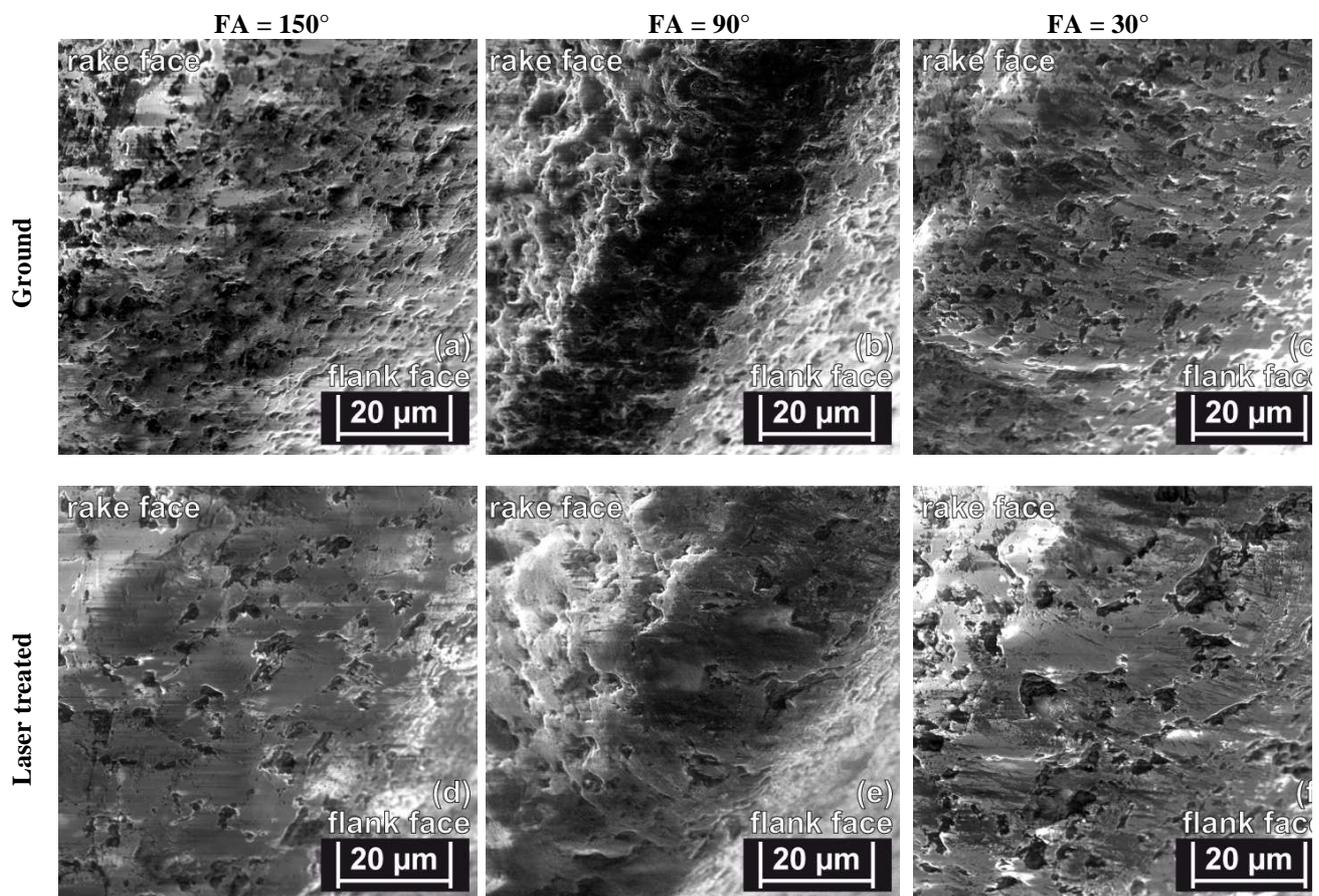


Fig 7. SEM images of cutting edge comparison after  $V_w = 47.124,0 \text{ mm}^3/\text{mm}$  work piece from left to right. The images show wear on the cutting edge at a fiber orientation angle (FA) relative to cutting direction of 150° (a,d), 90° (b,e) and 30° (c,f). Top row images are ground, bottom row images laser treated cutting edges.

resulting work piece roughness remains at about  $R_a = 2 \mu\text{m}$ . The laser machined tool processes CFRP with significantly higher feed force, but the resulting work piece roughness is nearly identical to the previous

one. Currently the varying feed forces cannot be explained, these will be part of ongoing studies as well as work piece roughness studies. Delamination as well as work piece surface analysis using a SEM are

important for determining work piece quality. Within this study a measurement was not possible but will be dealt with in future work. Fig. 7 shows SEM images of the cutting edges for the tools after a specific material removal of  $V'_w = 47.124,0 \text{ mm}^3/\text{mm}$ . Upper row images depict ground, lower row images show laser machined tools after machining of CFRP with fiber orientations of  $150^\circ$ ,  $90^\circ$  and  $30^\circ$ . Ground tools appear to be more structured on a microscopic scale, meanwhile the laser machined cutting inserts seem to have a smeared surface. Although the tools that machined CFRP with an angle of  $150^\circ$  show a small increase in the cutting edge radius (Fig. 3), the SEM picture of the laser machined tool looks like its undergone intensive tool wear. The images for  $90^\circ$  fiber orientation angle show regular wear. Machining with tools at  $30^\circ$  fiber orientation angles exhibit extensive wear on the flank face. Additionally ground tools show grooves in cutting direction.

## 5. Conclusions and Outlook

Similar results for ground and laser machined PCD-tools are presented, demonstrating that laser machining of the PCD-inserts does not cause considerable damage to the tool. In regard of resulting work piece quality, wear resistance and process forces, both technologies can be rated equal. It is shown that fiber orientation has a significant influence on resulting tool wear. The amount of wear is similar, although the tool surface topography differs. As next steps firstly it needs to be proven if the possible geometric adaption of laser machined PCD tools to the requirements of CFRP machining results in superior work piece quality. Secondly it needs to be proven if the usage of grain sizes larger than  $10 \mu\text{m}$  for laser machined PCD tools lead to the expected longer lifetime compared to ground PCD tools.

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