Lasers in Manufacturing Conference 2017

Laser based surface and post coating treatment of cutting tools

Sebastian Michel[a,*], Timo Bathe[a], Ivan Iovkov[a], Dirk Biermann[a], Bastian Kuhle[b], Alexander Kanitz[b], Cemal Esen[b]

[a]*Institute of Machining Technology, Technical University of Dortmund, Baroper Straße 303, 44227 Dortmund, Germany*
[b]*Chair of Applied Laser Technologies, Ruhr-University Bochum, Universitätsstraße 150, 44801 Bochum, Germany*

Abstract

Higher demands on the workpiece quality in the mobility sector result in the necessity to extend the capabilities of cutting tools when manufacturing parts made of carbon fiber reinforced plastics (CFRP) or Inconel 718. Therefore, an approach of a laser ablation process was examined to improve the machining behavior of diamond coated tools when machining CFRP and to adjust the coolant supply of solid carbide drills when machining Inconel 718. To evaluate the wear behavior and mechanisms when machining CFRP, non-coated tools and also tools with a partly removed diamond coating were used to examine the abrasive wear mechanisms under orthogonal cutting conditions. Based on the findings of these investigations, it can be shown that the cutting edge abrades rapidly due to the high abrasiveness of the imbedded carbon fibers. As a result of this wear mechanism, the rounded cutting edges lead to diminished workpiece qualities. To improve the machining behavior of those tools, an approach of a laser ablation method, using a femtosecond based laser beam, was utilized to remove the diamond coating. Additionally, investigations with a modified flank face for drilling Inconel 718 were carried out. The modified flank face was generated by the same laser ablation process in order to increase the tool performance significantly. The integrated groove limits the width of flank wear and allows an improved cooling supply of the thermally high loaded peripheral corner.

Keywords: Cutting tools; laser ablation; CFRP; Inconel 718

1. Introduction

High demands on lightweight construction and efficiency are increasingly leading to the use of high-performance materials in the mobility sector. Advanced aerospace alloys such as the nickel-base alloy

* Corresponding author. Tel.: +49-231-755-5822; fax: +49-231-755-5141.
E-mail address: michel@isf.de.

Inconel 718 are used for thermally highly stressed turbine engine components [1]. Composite materials such as carbon fiber reinforced plastics (CFRP) are replacing conventional construction materials in lightweight applications because of their outstanding specific stiffness and strength [2]. High demands on the workpiece quality and the rapid tool wear make the machining of these difficult-to-cut materials a great challenge.

Inconel 718 is a high strength nickel-base alloy with a high corrosion resistance. The machining leads to extreme demands on the cutting tools due to the material properties. The material retains its strength up to temperatures of 650° C. The low thermal conductivity of the material and the tendency to cold hardening lead to an immense thermal load on the cutting edge. Additionally, the high content of carbides and intermetallic phases result in a rapid abrasive tool wear or material adhesion to the tool [3,4]. In the machining of CFRP, the inhomogeneous material structure combining extremely hard carbon fibers and soft polymeric matrix materials influences the processing results and the tool wear. The temperature-sensitive matrix material (thermoset, thermoplastic) requires comparatively low process temperatures for damage-free machining, the embedded fibers generate a high abrasive wear on the tools. The abrasive wear leads to a fast rounding of the cutting edge, resulting in higher cutting forces and thereby in material-typical damages like delamination, fiber fracture and fiber pull-out [5,6,7,8].

In order to reduce wear and to realize efficient machining processes with consistent process stability for these materials, adapted machining strategies and tool concepts are necessary. Modifications of the flank face of carbide drilling tools for the machining of Inconel 718 could lead to a better coolant supply of the thermally high-loaded peripheral corner of the drill and limit the flank wear [9,10]. Partially coated tools with a difference between the wear resistance of the diamond coating on the rake face and the wear resistance of the carbide substrate material on the flank face could lead to self-sharpening tools with permanently sharp cutting edges for the machining of CFRP [11,12].

Laser ablation processes are suitable for removing ultra-hard diamond coatings and for machining tools made of cemented carbide [12,13,14]. The aim is to prepare solid carbide drills with defined structures on the flank face and to partially remove the diamond coating of cutting tools for CFRP using a femtosecond laser system. The cutting tools for CFRP are examined in an orthogonal cutting process and the results are compared with an uncoated tool.

2. Laser Ablation Process

Cemented carbide and diamond coatings are difficult to machine by chip-removal processes due to their extremely high hardness. Laser ablation enables the contactless machining of these materials. Using ultra-short pulsed laser systems (USP laser), the heat affected zone is reduced significantly allowing to machine with high precision and low thermal damage to the material. The tools used to examine the abrasive wear for machining CFRP under orthogonal cutting conditions are made of cemented carbide with a CCDia® AeroSpeed® diamond coating with a coating thickness of about 9 µm. The cobalt content of the different carbide grades directly influences the coating process and therefore the layer adhesion of the diamond coating. The properties of the different cemented carbide grades are given in table 1.

Table 1. Cemented carbide

	Grade	Co (*%*)	WC (*%*)	Density (g/cm^3)	Hardness HV30 (N/mm^2)	Grain size Ø in (*µm*)	Transverse rupture strength (N/mm^2)	Diamond coating
Tool A	K10UF	6	94	14,4	1900	0,6	> 3500	CCDia® AeroSpeed®
Tool B	K34EF	9	91	14,3	1930	< 0,5	> 3900	CCDia® AeroSpeed®
Twist drill	K40UF	10	90	14,5	1610	0,6	> 3600	-

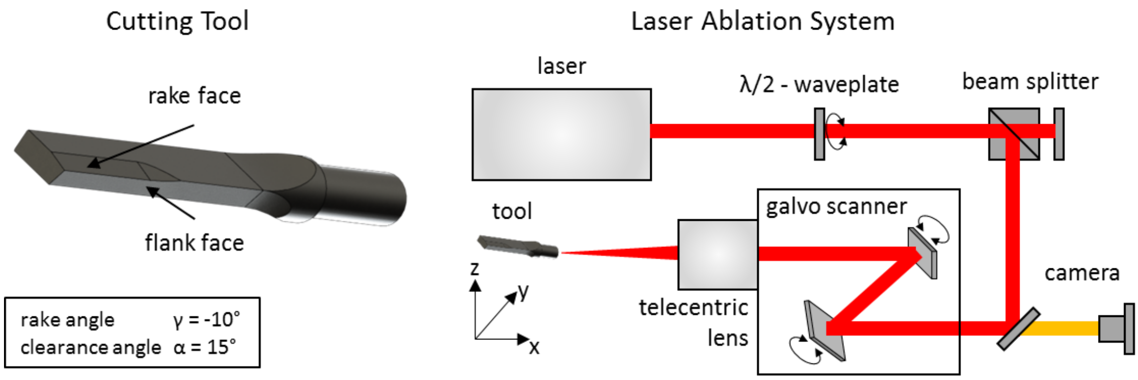


Fig. 1. Schematic representation of the cutting tool geometry and the laser ablation system

Fig. 1 shows a schematic representation of the cutting tool and the laser set-up. The cylindrical part of the tool was used to clamp the blanks during grinding, coating and laser ablation. The cutting edge geometry consists of a clearance angle of α = 15° and a rake angle of γ = -10°. The negative rake angle should increase the cutting edge stability. The USP laser system used to remove the diamond coating at the flank face has a wave length of λ = 800 nm and an output power of P = 1,6 W at a repetition rate of 5 KHz. The telecentric lens allows a focal distance of 80 mm with a spot diameter of 10 µm. The resulting fluence was 360 J/cm² with an effective ablation area of about 50 µm. The pulse duration was set to 35 fs with a line pitch of 10 µm. The area reached by the galvo scanner is relatively small and the tool has to be moved with a coordinate table to cover the whole flank face. Fig. 2 shows scanning electron microscope images of the cutting edges after the ablation process. The overlapping areas of the galvo scanner visible in the image of tool A can be found on both tools. However, the influence on the cutting process should be negligible due to the rapid wear of the cemented carbide while machining CFRP. The diamond coating in the machined area has been completely removed. The line pitch of 10 µm is clearly visible on the surface structure of the remaining cemented carbide material. The machined area has a surface roughness of Sa = 0,75 µm compared to the surface roughness of Sa = 0,5 µm of the diamond coating. While the coating on some parts of tool B has been removed to the cutting edge (fig. 2, right), a small section of the flank face along the remaining cutting edge of tool B and the whole cutting edge of tool A was not machined. At the edge of the remaining diamond coating, however, no thermal damages or cracks resulting from the ablation process can be detected even at high magnifications. The layer adhesion of the coating seems to be very good.

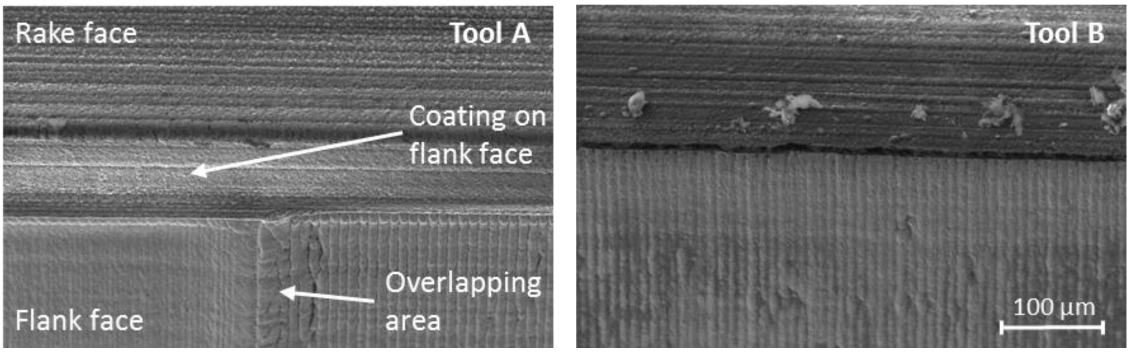


Fig. 2. Scanning electron microscope images after the laser ablation process of the diamond coating

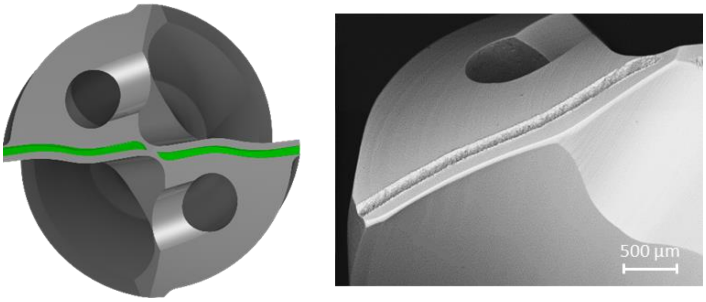
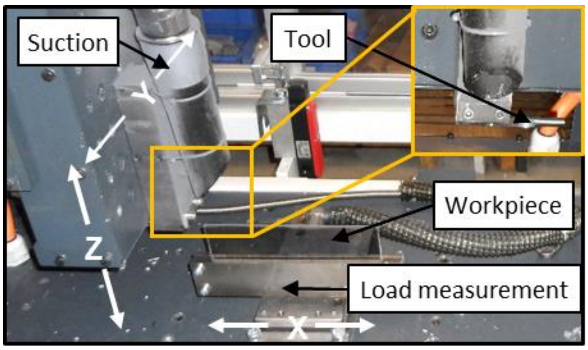


Fig. 3. Modified flank face of twist drills for drilling Inconel 718 [9,10]

Another application of laser ablation for cutting tools was studied at the Institute of Machining Technology by Beer and Özkaya with geometrical modifications of the flank face of carbide twist drills for drilling Inconel 718. A groove in the flank face in a defined distance to the cutting edge limits the maximum flank face wear width and allows a better coolant supply to the thermally high-loaded peripheral corner of the drill. The groove was machined with a 100 W Nd:YAG laser. With the modified twist drill shown in fig. 3, it was not only possible to increase the tool life considerably, but also to improve the processing result with regard to the surface integrity [9,10].

3. Orthogonal Cutting of CFRP

Due to the strong abrasive wear and the resultant cutting edge rounding of conventional tools made of cemented carbide, the tool life while machining CFRP is severely limited. Because of this, many tools are coated with wear-resistant diamond coatings. However, due to the dynamic cutting forces and the highly abrasive fibers even the diamond coating undergoes wear during the machining of CFRP. A failure of the diamond coating makes the tool unusable, since regrinding of coated tools is not possible. Supported by the concentration of the abrasive wear in drilling and milling processes on the flank face, the material removal on the tool can be specifically controlled by different wear resistances on the rake face and the flank face, thus leading to a self-sharpening effect of the cutting edge. Orthogonal cutting is ideally suited to investigate the basic wear mechanisms of the tools prepared by the ablation process due to the simplification of the cutting edge engagement and the accessibility of the contact zone. Fig. 4 shows the test-setup on the fundamental chip formation machine to realize orthogonal cutting conditions.



Fundamental chip formation machine

Traverse speed:

X	180 m/min	Y/Z	15 m/min

Work area:

X	900 mm	Y	200 mm
Z	95 mm		

Axis acceleration:

X	30 m/s²	Y/Z	15 m/s²

Fig. 4. Fundamental chip forming machine and test-setup

The workpiece material is a 3 mm thick CFRP laminate with a unidirectional fiber orientation. The matrix material consists of epoxy resin and the fiber content is 60 %. Due to the use of modern and very powerful linear drives for the fundamental chip forming machine, the table (x axis) can be accelerated by a maximum of 30 m/s^2 and realizes cutting speeds up to v_c = 180 m/min. The kinematic limits of the linear traversing motion are not suitable for high-speed processes, but correspond to usual cutting speeds of industrially used cemented carbide tools for machining CFRP. During the tests the resulting respirable fiber particles are filtered through a corresponding suction system. The process forces are measured with a Kistler 9121 3-component dynamometer and a 5017A multichannel charge amplifier. In addition to the partially coated tools A and B, an uncoated tool made of cemented carbide K34EF is used as a reference. The initial tests were carried out with an uncut chip thickness of *h* = 0,1 mm over a cutting path of l_C = 5 m. The measured process forces are shown in fig. 5. The reference tool on the one hand shows a strong but uniformly increasing normal force F_n and a slightly falling cutting force F_c over the entire cutting path. In the case of tool A and B, on the other hand, there is a sudden sharp increase in forces directly at the beginning of the cutting path which indicates an abrupt failure of the cutting edges. The different wear behavior can also be observed in scanning electron microscope images of the cutting edge. The reference tool shows a massive abrasive material removal which leads to a strong rounding of the cutting edge. The extent varies over the width of the engagement and depends on the fiber orientation in the laminate. Tool A and B are showing big breakouts at the cutting edges, explaining the strong and sudden increase of the process forces. The layer adhesion of the partially coated tools is very good. Due to the high mechanical load on the cutting edge, however, cracking occurs in the diamond coating. The cracks lead to a notching effect, which transfers the high mechanical load to the substrate material and thus leads to the large material breakouts. To reduce the mechanical load, another test run with tool A and an uncut chip thickness of *h* = 0,05 mm was carried out. The lower load prevents cracking of the diamond coating and therefore leads to very low process forces which remain constant even over a prolonged cutting path of l_C = 15 m (dotted line in fig. 5). No damage of the cutting edge was visible on the scanning electron microscope images. A self-sharpening effect could not develop because the narrow strip of remaining coating on the flank face prevented the wear of the carbide.

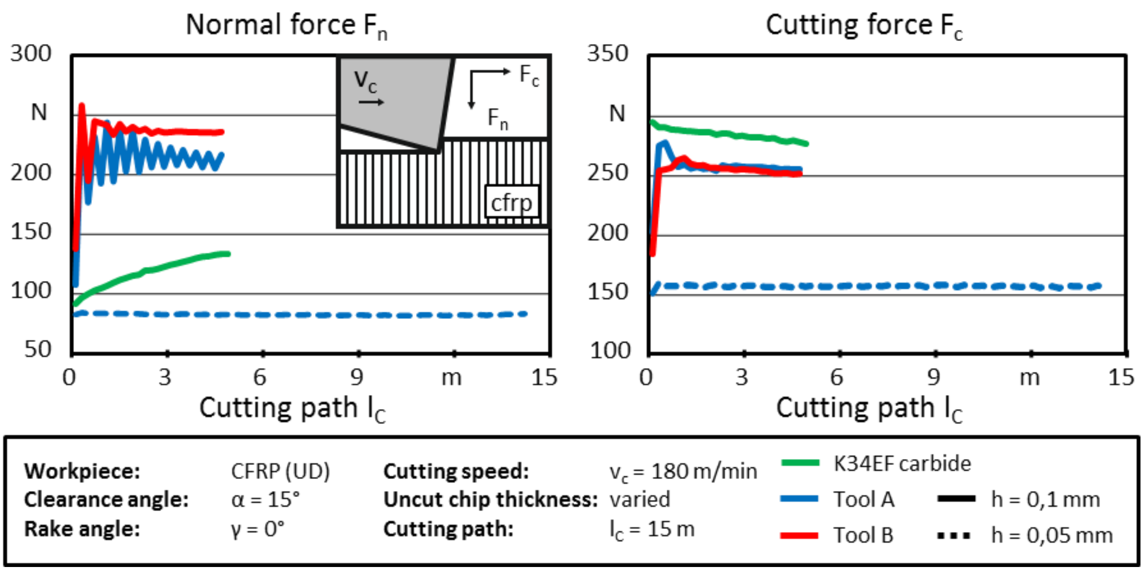


Fig. 5. Process forces of the orthogonal cutting process

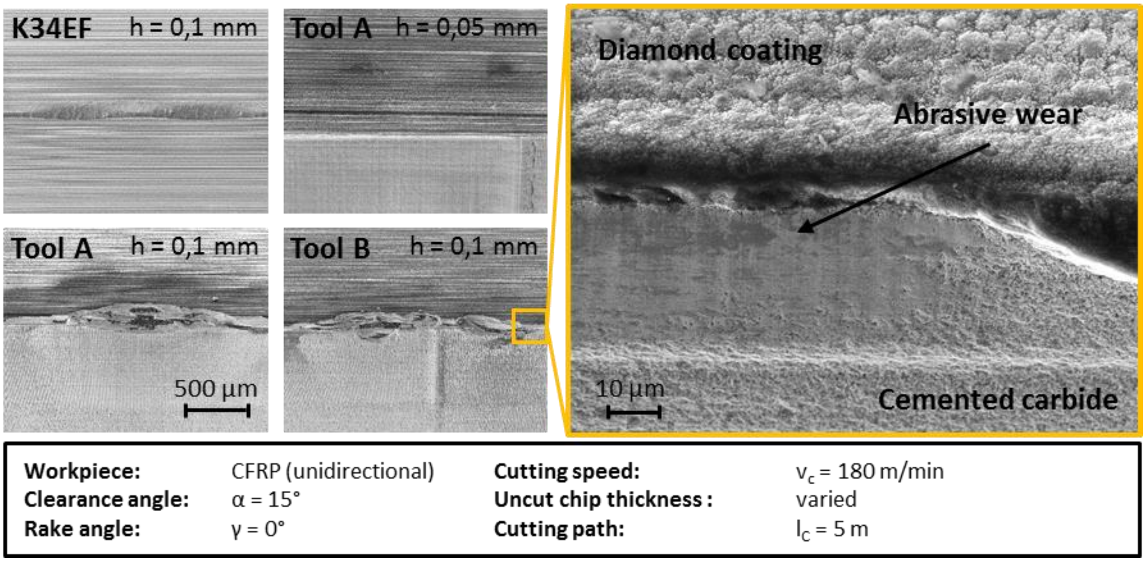


Fig. 6. Scanning electron microscope images of the worn cutting edges

However, in a more detailed examination of tool B, the scanning electron microscope images indicate the formation of a self-sharpening effect on some parts of the cutting edge (fig. 6, right). The parts of the cutting edge machining the surface layers of the CFRP are less mechanically stressed and therefore no cracks in the cemented carbide occur. The diamond coating reaches up to the cutting edge and abrasive wear can be detected on the exposed cemented carbide on the flank face forming a sharp cutting edge geometry with a low cutting edge rounding.

4. Conclusion

The presented results show that laser ablation is suitable for micromachining and microstructuring of cemented carbide tools as well as ultra-hard diamond coatings. The processing of polycrystalline diamond cutting tools is already state of the art. Especially ultra-short pulsed laser systems with a pulse duration in the femtosecond range are characterized by their precise material removal without inflicting thermal damage to the tool material and therefore enable a wide range of new applications to develop new tool concepts and to optimize the tool topology. The tool life of drilling tools for Inconel 718 has already been increased significantly, but further research is required for the development of a self-sharpening effect for the machining of CFRP. The results show that the coating removal process by laser ablation has little or no influence on the layer adhesion of the diamond coating remaining on the tool and thus enables the realization of partially coated tools with a functional diamond coating on targeted areas on the tool surface. The development of a possible self-sharpening effect is rather dependent on the process-dependent individual mechanical load of the cutting edge. The gentler cutting engagement and the altered contact situation at the flank face during drilling and milling could prove thereby to be advantageous compared to the process kinematics of the orthogonal section.

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