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Low Damage Drilling of CFRP/Titanium Compound Materials for Fastening

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Abstract

Fiber-metal compound materials are characterized by excellent mechanical properties and enable innovative and new designs, which are increasingly used e.g. in the aircraft industry. Boreholes for riveting and bolts or fasteners are required to join the initially separated material layers. Due to the considerably different machining properties of fiber reinforced plastics and metallic materials the drilling process of compound stacks is a very challenging task. High cutting temperatures and insufficient chip extraction lead to damages and disturbances of the surface integrity especially in the anisotropic and inhomogeneous CFRP layer. In the present study, low frequency assisted vibration drilling was applied for a CFRP/Ti6Al4V [10/10 mm] material stack. The axial oscillations cause an interrupted cut, which leads to small chip segments in the metallic material (Ti6Al4V). It was found that the distinctive mechanical damage of the CFRP borehole surface could be significantly reduced due to the improved extraction of the small chip segments. Thermographic images of the drilling process in the titanium alloy are showing that the cutting temperatures can be reduced by more than 40 % when using low vibration assisted drilling compared to conventional drilling. Consequently thermal damage of the matrix material was not found when applying low frequency assisted vibration drilling.

Keywords: damage; temperature; composite; vibration assisted drilling

1. Introduction

Fiber-metal compound materials are mainly used in high-tech components of modern aircrafts like the Airbus A350 or Boeing 787 (Dreamliner). The hybrid construction utilizes the advantages of both material types and results in excellent mechanical properties with a relatively low weight at the same time [1, 2]. This helps to reduce the emission and even allows new designs and part dimensions [3]. To join the initially separated material layers by rivets or bolts it is necessary to manufacture boreholes with very high requirements [3]. Based on the growing market in the aeronautical sector, reliable drilling operations for automated manufacturing are gaining importance. However, the drilling process of fiber-metal stacks is a quite challenging task since both materials are showing completely different machinability properties [4]. In the present study, CFRP and titanium which both belong to the group of heavy to cut materials are investigated. Machining of these materials in a hybrid stack leads to additional difficulties. While the cutting parameters can be adapted to the actual material layer, a compromise needs to be found for the tool geometry, cutting material, and coating respectively [5]. Cutting edge rounding due to the hard and brittle nature of the carbon fibers leads to a considerable raise of cutting forces and temperature in the titanium alloy [6]. This facilitates Ti-adhesions and as a consequence catastrophic tool failure as well as excessive burr formation at the borehole exit [7, 8]. Looking at the surface integrity, insufficient chip extraction is a major concern in drilling CFRP/Ti-stacks. The hot and sharp metallic chips lead to damages and disturbances of the surface especially in the anisotropic and inhomogeneous CFRP layer [9, 10]. Diameter variations of up to 600 µm have been found as well as thermal damage of the epoxy resin matrix. To avoid these damages, usually peck drilling

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strategies are applied and lubrication is highly recommended. Janssen [9] could show positive results when using step drills with different coatings. Excellent surface integrity was achieved by orbital drilling due to better chip extraction and lower cutting temperatures [10, 11]. However, all mentioned methods are characterized by a significant increase of the cycle time. Additionally stability problems occurred for orbital drilling with unfavourable aspect ratios (length/diameter). In the present study, the effect of low frequency vibration assisted drilling (LFVAD) to the surface integrity of CFRP/Ti6Al4V compound material is investigated. For LFVAD the axial tool movement is superimposed by a sinusoidal oscillation (in this case 1.5 per revolution) which is provided by the tool holder. Compared to ultrasonic assisted drilling, the frequency is much lower (about 125 Hz) and amplitudes up to 0.2 mm are applied, which allows an interrupted cut. The purpose is to improve the extraction of metallic chips [12] due to the generation of small chip segments and hence to prevent damage of the CFRP surface without an increase of cycle time. Also lower cutting temperatures compared to conventional drilling were found [13]. Investigations on the kinematics of LFVAD have been conducted in [14].

2. Experimental setup

The primary objective of the present study was to investigate the influence of LFVAD to the surface integrity of CFRP/Ti6Al4V compound stacks compared to conventional drilling. Defects in the machined surface are usually caused by a various amount of reasons. In order to separate and clearly identify the single damage mechanisms, different drilling trials have been carried out. The following test setup descriptions are valid unless denoted otherwise in the figures of the results chapter.

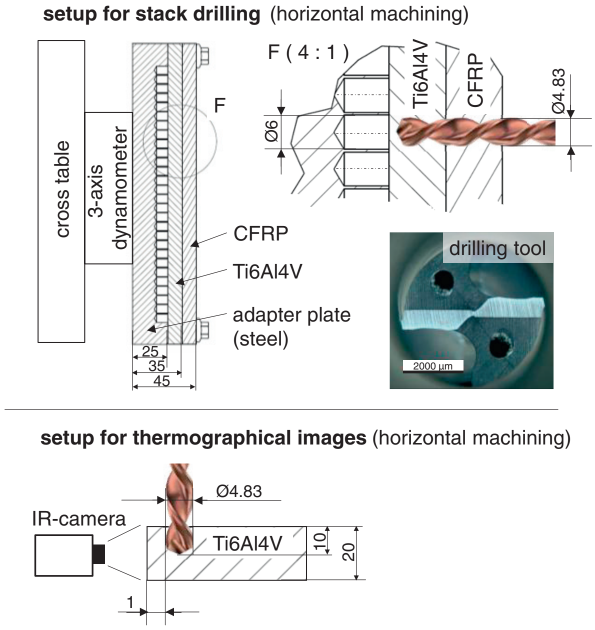

Fig. 1. Experimental setup for stack drilling trials (top) and temperature measurements in Ti6Al4V (bottom)

All drilling trials have been carried out on a three-axis CNC machine Schmid SE341 with a HSK63A chuck and ER32 collet. Axial oscillations were generated by a "Sine Holing" tool holder of Mitis-Engineering with an adjustable amplitude of 0.01-0.20 mm and a fixed frequency of 1.5/rev.

Figure 1 shows the schematic setup of the drilling experiments. The CFRP and titanium test sheets with dimensions 200 x 200 x 10 mm were screwed on a steel adapter plate. To prevent bending of the test sheets due to the thrust forces during the drilling process the adapter plate was predrilled which ensures an optimal supporting surface. These boreholes were slightly enlarged compared to the drill diameter to ensure an unobstructed burr formation in the moment of tool exit. Detailed information about the tool, workpiece and process parameters are given in Table 1. Cutting temperatures in Ti6Al4V have been measured indirectly with an Optris P1400 infrared camera. For this purpose, boreholes were drilled in a distance of 1 mm to the edge of the titanium sheet (see Figure 1/bottom). The inspected surface has been face milled in the actual test setup to maintain a precise exact distance of 1 mm to the borehole surface for all conducted temperature measurement trials. Additionally the inspected surface was painted with varnish for which a temperature dependent emissivity progression has been determined. For all experiments internal minimum quantity lubrication with fatty alcohol was applied.

Table 1: Specifications of tool, workpiece and process

Cutting tool:	
cutting material/coating	tungsten carbide / AlCrN*
diameter d	4.83 mm
point angle σ	120°
helix angle δ	30°
tool manufacturer	Walter AG
tool model	3A3399-6503003
Process Parameters:	
cutting speed v_c	15 m/min
feed f	0.075 mm*
amplitude A	0.115 mm*
frequency F	1.5 oscillations/rev
coolant	MQL (AccuLube5000)
Workpiece and conditions:	
CFRP	multi-unidirectional layer, 60% fiber volume, HTS fiber, epoxy resin matrix
titanium alloy	Ti6Al4V (material number 3.7164) R_m = 900 N/mm², 368 HV
stack thickness	CFRP: 10 mm / Ti6Al4V: 10 mm*

*: *variations according designations in the figures*

3. Results and Discussion

3.1 Temperature measurements in Ti6Al4V

Machining of titanium alloys usually implicates relatively high process temperatures in the local area of the cutting zone. This is mainly caused by a poor thermal conductivity but also by the unfavorable relation between the elastic modulus and the fracture toughness of the material which causes an extended frictional area between the tool flank and the newly generated surface at the bottom of the borehole. The cutting temperatures are a limiting factor for the process parameters, specifically the cutting speed, and often cause bad surface qualities and alterations of the metallic structure as well as excessive tool wear. From literature it is well known that the heat in the cutting zone is mainly dispatched by the hot metallic chips which need to be carried along the initially drilled borehole surface. This causes a potential risk of thermo-mechanical damage to the sensitive epoxy resins matrix material of the CFRP (glass transition temperature ≈ 180°C). Figure 2 shows thermographical images of the drilling processes in Ti6Al4V (setup according Fig.1/bottom). Applying vibration assisted drilling, the measured temperatures are about 43 % lower compared to conventional drilling at the same cutting speed and feed (same material removal rate). It needs to be considered that these measurements are showing the temperature in a distance of 1 mm to the borehole surface which means that the temperature differences should be even higher in the actual cutting zone.

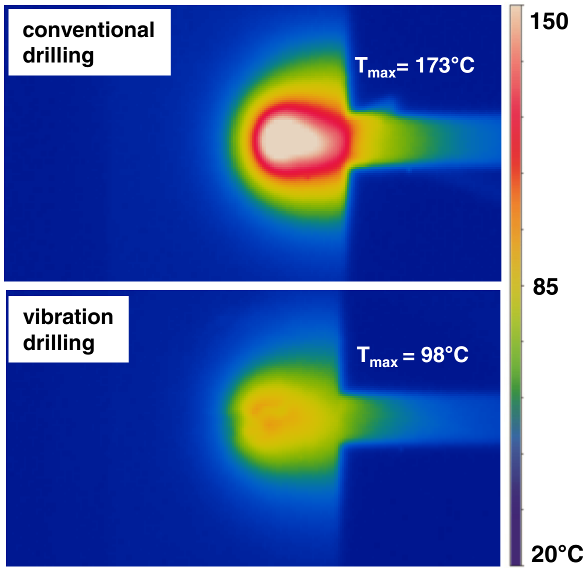

Fig. 2. Thermographical images for conventional drilling (top) and vibration assisted drilling (bottom) in Ti6Al4V

There are several approaches to explain this behavior:

1. Due to the axial oscillations an interrupted cut is gen-erated which leads to a cooling of the tool during the non-cutting time (for the given parameters, the actual contact time is reduced by about 55%). 2. The tool lifting enables a moistening of the borehole bottom with lubricant which reduces the frictional heat. 3. The small metallic chips which comprehend most of the heat are quickly evacuated from the cutting zone.

The results from Figure 3 are showing that a certain minimum value of amplitude is required to initiate the effects leading to a temperature reduction. It is assumed that this value corresponds to the amplitude which is necessary for an interrupted cut; once small chip segments are generated, the temperature drops significantly. This is also confirmed by the steplike sudden temperature change. From a theoretical point of view, the geometrical cutting conditions are dependent on the amplitude, feed, and frequency [14]. This explains why the cutting speed does not have an influence on the qualitative progression of the temperature. However, the theoretical minimum value of amplitude necessary for an interrupted cut is 0.055 mm at a feed of 0.1 mm and 0.04 mm at a feed of 0.075 mm and therefore lower compared to the actual required value of 0.075 mm. This might be caused by an elastic deflection of the material due to the relatively high axial forces (up to 1300 N).

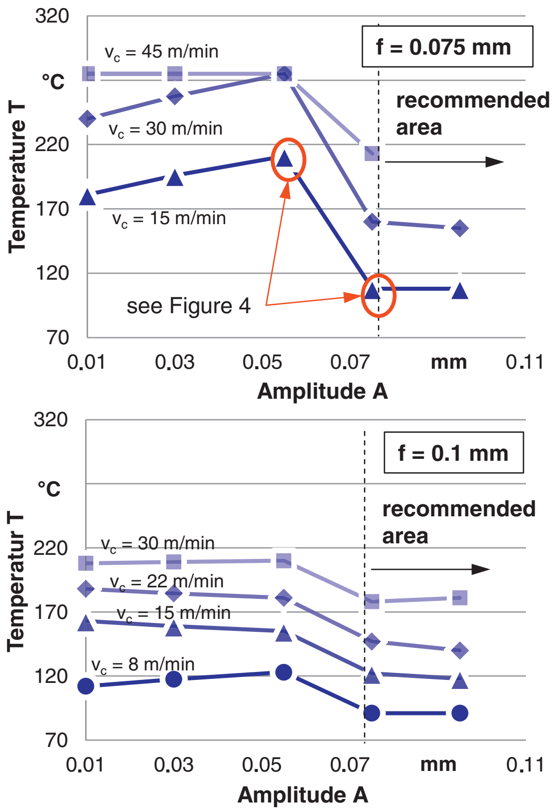

Fig. 3. Dependency of the measured temperature to the amplitude

For a better understanding of the effects which lead to a temperature change, thermograhic images for amplitudes close before and after the sudden decrease of temperature have been analyzed (encircled measure points in Fig.3). Figure 4 is showing the corresponding images in the moment of tool retraction. For the lower amplitude of 0.055 mm a large amount of chips are released which have been gathered in the drilling tools flutes, whereas no chips are found for an amplitude of 0.075 mm. However, in both processes separated chip segments have been generated. This indicates that an interrupted cut alone does not guarantee a sufficient chip evacuation. A calculation of the theoretical chip geometry shows that the size of the segments is decreasing with increasing amplitude (acc. [14]: chip radian 137° for A = 0.055 and 120° for A = 0.075 mm) which could be a reason for an improved evacuation at higher amplitudes. Anyway, a sufficient chip extraction seems to be the key for low cutting temperatures in the titanium layer.

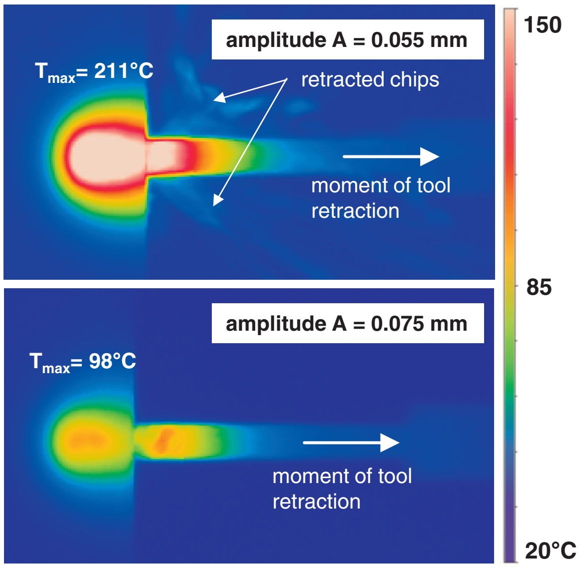

Fig. 4. Thermographical images at the moment of tool retraction for A=0.055 mm (left) and A=0.075 mm (right)

3.2 Drilling of CFRP/Ti6Al4V stack material

In the next step CFRP/Ti6Al4V [10/10 mm] stack material was machined with and without vibration assisted drilling. The borehole quality was evaluated by the bore diameter, surface roughness and exit burr height. In the CFRP layer, the diameters have been measured in three different depths in order to specify the area of expected damages due to reaming of metallic chips. In general, the diameters of each level are measured in 0 and 90° orientation (radial). Two different tool coatings were used for the vibration drilling trials in the stack material; AlCrN and TiAlN. Furthermore, vibration drilling trials were conducted in the separated materials (CFRP and Ti6Al4V). Each material was drilled with a new TiAlN coated tool. The same parameters compared to stack drilling have been applied. The results of these separate drilling trials were taken as a reference for the achievable borehole quality under the given conditions.

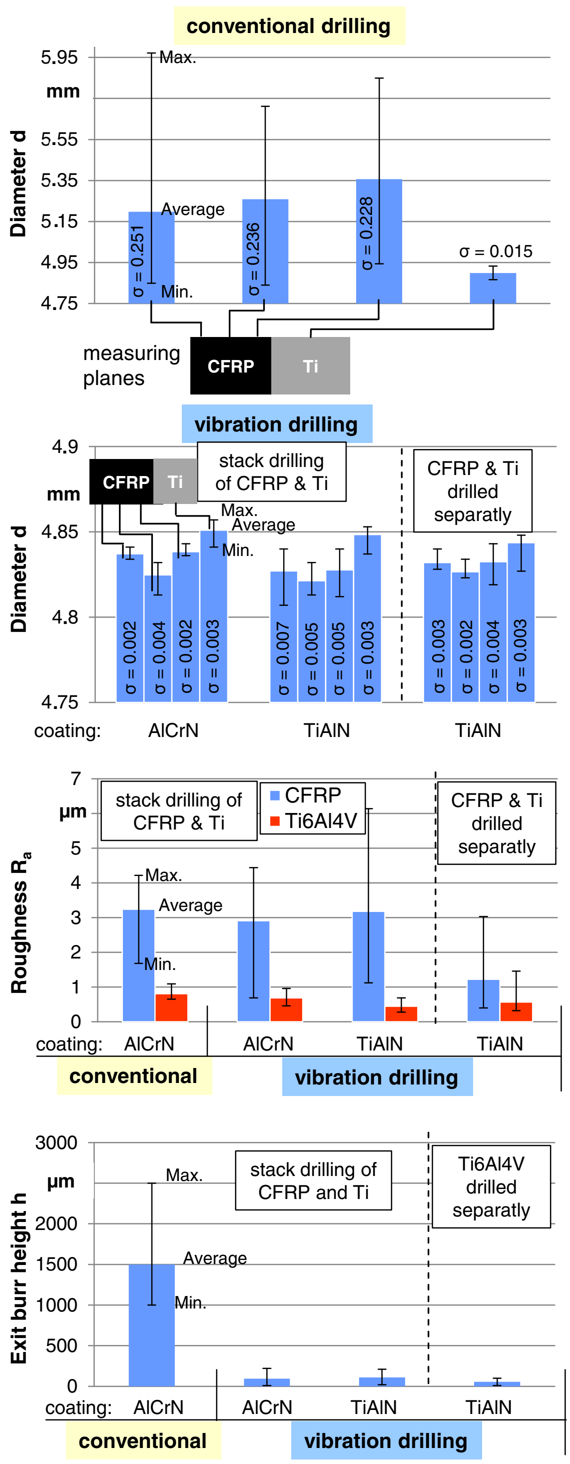

Fig. 5. Bore borehole quality for conventional and vibration drilling in CFRP/Ti6Al4V stack material

Figure 5 is showing the results for stack drilling with and without vibration assistance and for the separated materials. Since large diameter variations were found for conventional drilling these are shown in a separate diagram. The measurements are based on a series of 34 holes for conventional drilling and 100 holes for vibration assisted drilling. These different path lengths are caused by excessive tool wear in conventional drilling. The average diameters are indicated by beams with error bars for minimum and maximum measured values of the series which correlate to the primary axis. The standard deviation σ is written to the beams.
For conventional drilling excessive diameter expansions up to 5.9 mm (drill diameter 4.83 mm) have been found in all measured depth levels of the CFRP layer. A visual inspection of the CFRP layer revealed chips being reamed into the machined surface and even breaking through into the adjacent boreholes (web thickness 3 mm, see Fig. 6). These results underline the mechanical load to the borehole surface which is induced by metallic chips and which also causes frictional heat due to reaming. Compared to the CFRP-layer, much more stable diameters were found in the titanium layer. A total number of 34 boreholes have been drilled until the trial was aborted due to excessive tool wear. Thermal damages were found in the CFRP layer especially for the last few boreholes of the series. High process temperatures for conventional drilling are also indicated by the partially very large exit burrs in Ti6Al4V.

Although all vibration drilling trials are based on series of 100 boreholes the diameter deviations as well as the standard deviations are much smaller compared to conventional drilling. For both tool coatings (AlCrN and TiAlN), the diameters are within a range of 40 µm which corresponds to IT10 quality. The slightly larger diameters in the titanium layer correlate to most results from literature (e.g. [2]). This effect is either caused by thermal expansion of the titanium or an elastic spring back effect of the CFRP material during the drilling process. Due to the lower process temperature, thermal damage of the matrix material was not found. Also the exit burr is much lower compared to conventional drilling. As a consequence of the tool wear, it raises from 50 to 250 µm with an increasing number of drilled boreholes.

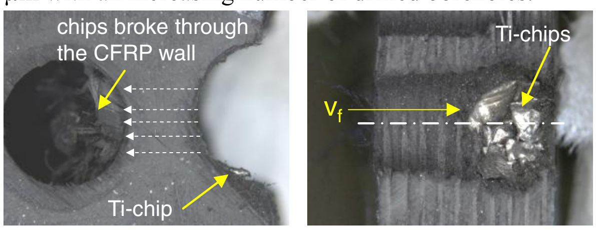

Fig. 6. Damages of the CFRP-layer by metallic chips for conventional drilling

Drilling of the separated materials with TiAlN coated tools only shows negligible differences in the bore diameters compared to stack drilling while the average roughness and the exit burrs slightly decrease. The lower burr height in titanium is based on less tool wear due to the absence of the abrasive CFRP while the lower roughness values in CFRP are caused by the lack of metallic chips. This proves that the influence of the metallic chip extraction on the surface integrity in the CFRP layer is restricted to the roughness values if vibration assisted drilling is applied while huge diameter variations are caused in conventional drilling.

3.3 Blind hole drilling in CFRP/Ti6Al4V stack material

Because of these damages in practice, conventional drilling is supplemented by peck drilling strategies to assure a sufficient chip removal, however the borehole surface in the CFRP layer is generally still showing visible scratches in the transient region to the metallic layer. In the test setup according to Figure 7, a blind hole of 13 mm depth was drilled in a CFRP/Ti6Al4V stack so that only the tool tip enters the titanium layer.

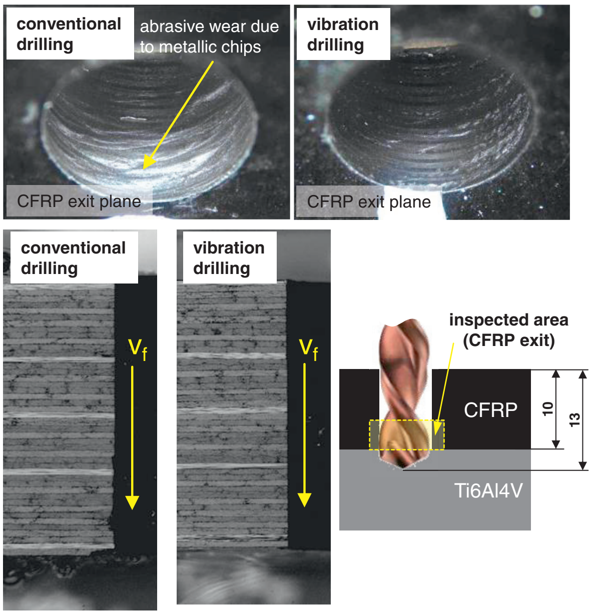

Fig. 7. Damages of the CFRP-layer by metallic chips for conventional drilling

Figure 7 is showing images and micrographs of the borehole in CFRP. Scratches and material disruptions are clearly visible in the area of the bore exit if conventional drilling is applied. By this test setup it is proved that the damages are caused by the initially generated chip of the tool tip. Assuming a free entrance side (no CFRP layer), the initial metallic chip is usually growing sideways to the tool axis. In contrast, when drilling stack material a free deformation of the chip is inhibited by the CFRP borehole surface which bends the chip in axial direction. This causes a reaming of the chip at the borehole surface and subsequent abrasive wear of the CFRP surface.

A smooth surface without visible interruptions of the surface integrity is found if vibration assisted drilling is applied which is caused by early chip separation.

4. Summary and conclusion

In the present study low frequency assisted vibration drilling (LFVAD) of CFRP/Ti6Al4V compound material was investigated with a focus on the borehole quality. Solid carbide twist drills with different coatings were used for the experimental tests. To analyze the borehole quality microscopic images and micrographs were used as well as measurements of the bore diameter, surface roughness and exit burr height. Additionally, the temperatures close to the cutting zone were measured with an infrared camera in Ti6Al4V. The application of LFVAD showed considerable advantages regarding the borehole quality compared to conventional drilling. In the following the most important findings and hypothesis are listed:

- Thermo mechanical damages of the CFRP layer and high cutting temperatures in titanium are mainly caused by insufficient extraction of metallic Ti-chips which are reaming at the newly generated bore surface.
- The chip extraction could be significantly improved by the application of LFVAD, subsequently damages due to reaming chips and high process temperatures are avoided. The cutting temperature in titanium could be decreased by about 43%.
- A sufficient chip extraction is requiring an interrupted cut and chip should not exceed a certain maximum size (chip radian) which is dependent on the amplitude, frequency and feed.
- Two different mechanisms were found which lead to damages due to metallic chips in the CFRP layer:
  1. Accumulated chips in the drill flutes which typically results in diameter expansions along the entire borehole
  2. Damages at the CFRP exit site due to the initially generated metallic chip (prohibition of the free chip deformation).

  Both types of damage could be avoided by the application of LFVAD.
- The exit burr height in Ti6Al4V is significantly decreasing due to lower process temperatures in LFVAD.
- Drilling trials in the separate materials revealed that relatively high surface roughness values in the CFRP layer are caused by the metallic chips, even if a sufficient chip extraction is found.

In conclusion, under the given cutting conditions LFVAD leads to a significant improvement of the borehole quality in CFRP/titanium stack materials compared to conventional drilling. A sufficient chip extraction, which can be achieved with LFVAD, was found to be the key for the prevention of thermo-mechanical damages at the borehole surface. However, further investigations are planned to better understand and describe the trajectories of the chips in the tools flute and their interactions with the tool and workpiece during the extraction process.

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