



6th CIRP International Conference on High Performance Cutting, HPC2014

Tool wear analyses in low frequency vibration assisted drilling of CFRP/Ti6Al4V stack material

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Abstract

Drilling of fiber-metal compound materials is one of the most challenging machining operations. Besides frequently occurring damages of the borehole surface tool wear is a major concern when drilling compound stacks. The significantly divergent cutting conditions of fiber reinforced plastics and metallic alloys require compromises in the tool geometry as well as the cutting materials and coatings. Excessive cutting edge rounding due to the brittle and abrasive fibers leads to increasing cutting forces and temperatures in the metallic alloy. This usually results in a catastrophic failure of the tools. In the present study low frequency vibration assisted drilling (LFVAD) of CFRP/Ti6Al4V [10/10 mm] was investigated in terms of tool wear and compared to conventional drilling. Solid carbide drills with a diameter of 4.8 mm and different CVD and PVD coatings have been tested. The flank wear as well as the adhesions at the cutting edges have found to be significantly lower when using LFVAD. The tool life could be increased by more than 300 % compared to conventional drilling. This is based on considerably lower process temperatures and an improvement of the process stability which could be proved by cutting force measurements. Additionally the chip extraction was found to be more efficient due to the generation of small chip segments which is a consequence of the interrupted cut. Best results in terms of tool wear and borehole quality have been achieved with an AlCrN coating.

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Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting

Keywords: vibration assisted drilling; tool wear; composite; CFRP; titanium

1. Introduction

Compound materials made from carbon fiber reinforced plastics (CFRP) and lightweight metals, often titanium and/or aluminium alloys, are utilizing the individual advantages of the single materials. These hybrid structures provide excellent mechanical properties like high tensile strength, stiffness, and corrosion resistance with a relatively low weight at the same time, which makes them especially interesting for structural components in the aircraft industry or other high tech applications [1, 2]. Modern aircrafts like the Airbus A350 or Boeing 787 (Dreamliner) contain more than 50 % CFRP in mass, often build up in compound stacks with lightweight metals [3]. To join the initially separated material layers, usually rivets or bolts are used, which require a drilling process throughout the entire material stack. Based on the growing market in the aeronautical sector, reliable drilling operations for automated manufacturing are gaining importance [4]. However, the drill-

ing process of fiber-metal stacks is a quite challenging task since both materials are showing completely different machinability properties [5]. While the cutting parameters allow to be adopted according to the actual material layer, compromises have to be made for the choice of tool geometry, cutting material, and coatings [6]. This usually results in excessive tool wear, especially for the material combination CFRP/titanium [7,8]. The hard and brittle carbon fibers of the CFRP causing abrasive wear in the form of cutting edge rounding. This leads to increasing process forces and cutting temperatures in the titanium layer [9]. As a consequence, thermally activated diffusion and titanium adhesions at the cutting edges are causing edge chipping and catastrophic tool failure respectively [10]. In the present study the influence of low frequency vibration assisted drilling (LFVAD) to the tool wear of tungsten carbide drills with different coatings is investigated and compared to conventional drilling. In LFVAD the feed rate is superimposed by axial sinusoidal oscillations, comparable to

ultrasonic assisted drilling but with much lower frequencies (1,5 oscillations per revolution) and higher amplitudes (up to 0.2 mm) [11]. The kinematic of the process can be described by the parameters: cutting speed v_c , feed f , amplitude A , and frequency F in oscillations per revolution (for more information regarding the kinematics of LfVAD refer to [12]). Under certain cutting conditions LfVAD leads to an interrupted cut, which results in a considerably improved extraction of the metallic chips but also in high dynamic loads to the cutting tool which might result in edge chipping or tool fracture.

2. Experimental setup

The primary objective of the present study was to analyze the tool wear of tungsten carbide drills with different coatings for LfVAD in CFRP/Ti6Al4V stack material and the comparison to conventional drilling.

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 0.01-0.2 mm and a fix frequency of 1.5/rev.

Figure 1 shows the schematic setup of the drilling trials. The CFRP/titanium test sheets with dimensions 200 x 200 x 10 mm were screwed on a pre-drilled steel adapter plate. This ensures an optimal support at the backside of the test sheets and prevents them from bending due to the high thrust forces during the drilling process. 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.

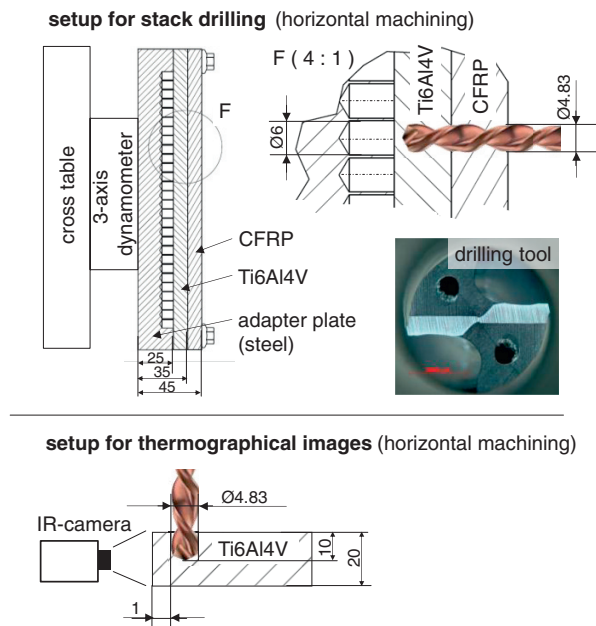


Fig. 1. Experimental setup for stack drilling trials (top) and temperature measurements in Ti6Al4V (bottom)

The tool wear was determined by microscopic images of the flank wear, measurements of the cutting edge radius via structured light projection, and SEM micrographs. The cutting forces were measured with a Kistler 4 component force/torque dynamometer Type 9272. Additionally the cutting temperatures in Ti6Al4V have been measured indirectly with an Optris P1400 infrared camera. Therefore 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 guarantee an 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 trials internal minimum quantity lubrication with fatty alcohol was applied.

Cutting tool:	
cutting material/coating	tungsten carbide
coatings	AlCrN, AlTiN, TiAlN/TiSiN, NHC*
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) $R_m = 900 \text{ N/mm}^2$, 368 HV
stack thickness	CFRP: 10 mm / Ti6Al4V: 10 mm*

* variations according designations in the figures
 **New Hard Carbon

Due to the application of vibration assisted drilling, the complexity of the cutting kinematics and also of the geometrical cutting conditions are considerably increasing. The large variability of cutting parameter settings and the fact that there are no guidelines or recommendations in the literature yet, makes it difficult to find suitable cutting parameters. In the present study the following approach was used: 1. Identification of the most difficult to cut material (in that case titanium, since catastrophic tool failure is expected due to the high process forces) 2. Selection of cutting speed and feed according to recommendations in the literature. 3. Step-wise increase of the amplitude, until a sufficient chip extraction is achieved (to avoid high dynamic loads to the tool, the amplitude should be kept as low as possible). The choice of suitable cutting parameters is a challenging task which depends on several factors including the material being cut and will be part of further investigations.

Cutting parameters in table 1 have been selected according to this procedure.

3. Results and Discussion

Drilling of fiber-metal compound materials always results in a cumulative tool wear, which represents a combination of the wear in each material, additionally supplemented by interaction effects (tool wear from material A influences the progression of wear in material B). This prohibits a simple addition of the tool wear from material A and B. However, a determination between the wear caused by the separated materials, CFRP and titanium is reasonable for a systematic tool development e.g. choice of cutting material, coating, and geometry. Therefore, besides stack drilling, machining of the separated material layers has been performed, using the experimental setup as described in Figure 1/top.

Figure 2 shows the flank wear of AlTiN coated tools for LfVAD after a series of 100 boreholes in CFRP and Ti6Al4V respectively. As expected, the hard and brittle carbon fibers of the CFRP caused considerable abrasive flank wear, which correlates to literature e.g.[5]. In contrast nearly no changes of the cutting edge were found for LfVAD in Ti6Al4V. Since only LfVAD was applied for the machining of separated materials in the present study, a comparison to conventional drilling is not possible. However, compared to most literature, the tool wear in titanium appears to be extremely low for LfVAD. Not even adhesions are found, which are usually quite common for conventional drilling after a certain cutting length.

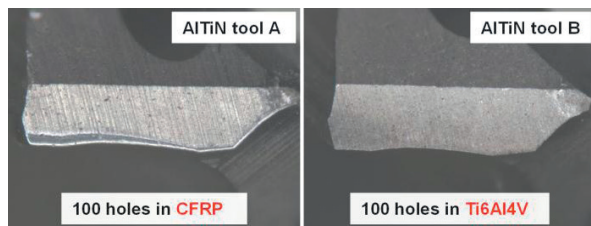


Fig. 2. Flank wear of AlTiN coated tools in LfVAD of CFRP and Ti6Al4V

Figure 3 shows the evolution of the cutting edge radius over the cutting length of both tools from Fig. 2 (for a comparison, also the results of stack drilling are added). Looking at the evolution of the cutting edge radius over the cutting length, the initial radius of 6 μm is only marginally raised by about 1 μm for the drilling in Ti6Al4V, while an increase of over 10 μm was found for the drilling in CFRP. These results also correlate to the evolution of the axial feed force and torque shown in Figure 3/bottom. Marginal changes are found for the drilling in titanium, while in CFRP the force and torque are significantly increasing. However, even with a blunt cutting edge the axial force and the torque are much lower when drilling in CFRP compared to titanium. To identify the effect of the significant tool wear in CFRP to the force and torque in titanium, an additional borehole was drilled in Ti6Al4V with tool A. The axial force increased from 1000 to 1400 N and the torque from 1.7 to 2.6 Nm (not shown in the diagrams). That means that the tool loads in titanium are significantly increased due to the tool wear in CFRP. Figure 3/top is also showing the cutting edge radius for LfVAD of CFRP/Ti6Al4V stack material. In the last 2/3 of the total

cutting length, the radius is significantly increased compared to the cumulative wear in the separated materials. It is assumed that this is a consequence of the high process forces in the titanium layer, caused by the considerable tool wear in CFRP.

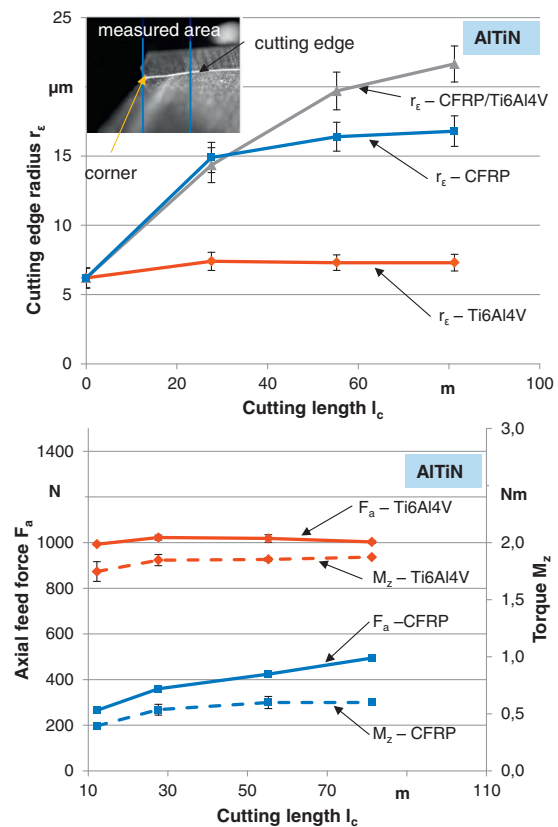


Fig. 3. Cutting edge radius (top) and axial feed forces/torque (bottom) of AlTiN coated tools in LfVAD of CFRP and Ti6Al4V

Machining of titanium alloys 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. Figure 4 is showing the measured cutting temperatures in Ti6Al4V for LfVAD and conventional drilling according to the experimental setup shown in Figure 1/bottom. Compared to conventional drilling, a significant decrease in temperature of about 43% is found when LfVAD is applied. Considerable investigations regarding this effect were done in [13]. It was concluded that the temperature drop is mainly effected by an improved extraction of the hot metallic chips, but also due to the interrupted cut which involves cooling of the tool during the non-cutting times. These results are significant since the cutting temperatures do have a considerable influence on the diffusion wear of tungsten carbide drills.

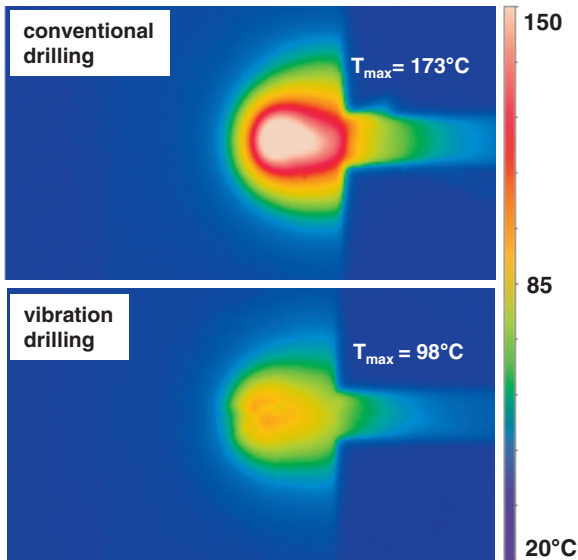


Fig. 4. Thermographical images for conventional drilling (top) and vibration assisted drilling (bottom) in Ti6Al4V

A comparison between the tool wear for conventional drilling and LFVAD in CFRP/Ti6Al4V stack material is shown in Figure 5. Microscopic images and SEM micrographs of the tool flank and cutting edge respectively were taken. For the conventional drilling process, already after 15 drilled bore-holes, large erosive wear as well as titanium adhesions were found on the flank face and also in the surrounding region of the cutting edge corner, most probably caused by high temperatures in combination with abrasive wear in the CFRP layer. In contrast, for LFVAD only marginal tool wear and titanium adhesion are visible. Even after a series of 100 bore-holes, a very smooth progression of the flank wear is found along the cutting edge (SEM image in the bottom-right corner). Edge chipping or thermally induced diffusion wear is not indicated.

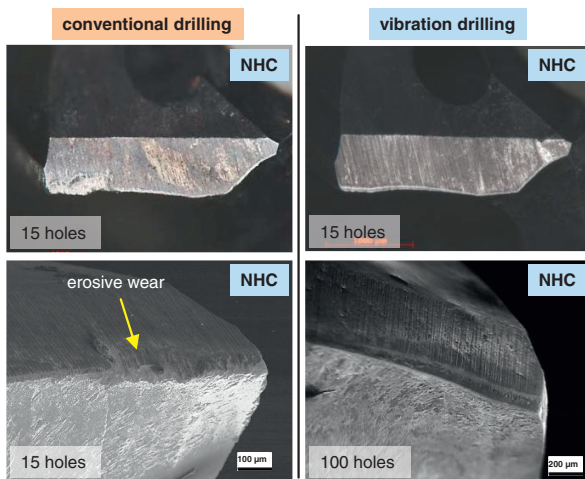


Fig. 5. Flank wear of NHC coated tools for the drilling in CFRP/Ti6Al4V stack material. Conventional drilling (left), LFVAD (right)

In this context it is noticeable that the measurements of the axial feed force and the drilling torque (in Figure 6) are showing a much higher mechanical load for LFVAD compared to conventional drilling, although the tool wear is significantly lower.

It is also remarkable that the torque progression over the process time is very uniform for LFVAD (high process stability), whereas significant alterations are found for conventional drilling. Additional measurements of the torque were showing that these alterations are randomly occurring, possibly due to the generation of built-up edges.

In the moment of tool exit (marked by the black dashed vertical line) the torque is slightly increasing for LFVAD as well as conventional drilling. This might be explained by the drop of axial forces which causes an elastic spring back of the remaining material in negative feed direction. With this, the uncut chip thickness is temporarily increasing and therefore results in higher torque.

In summary, LFVAD results in higher mechanical - but at the same time decreasing thermal loads to the tool. This indicates that thermal load is the predominant influencing factor for the tool wear. From literature it is well known that high process temperatures are facilitating diffusion of cobalt atoms from the tungsten carbide substrate into the flowing chip [14]. Cobalt depletion leads to a gradual degradation of the mechanical properties and wear resistance of the tool. This could increase abrasive tool wear, especially in the CFRP layer, which would also explain the significantly higher cutting edge radius for drilling in CFRP/titanium stack material compared to separate machining of CFRP (results from Figure 3).

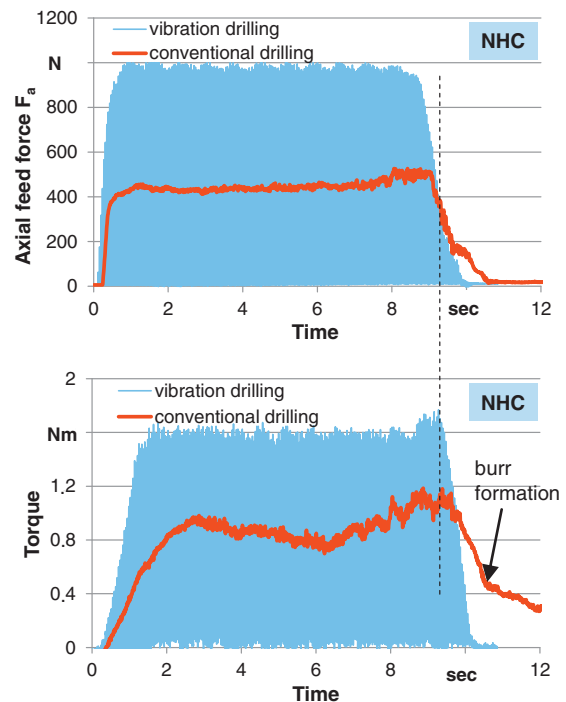


Fig. 6. Axial feed force (top) and torque (bottom) in Ti6Al4V for conventional drilling and LFVAD

In the last trial, four different tool coatings, AlCrN, AlTiN, TiAlN/TiSiN (multilayer), and NHC (carbon, sp²/sp³) as well as uncoated drills were investigated regarding the tool wear in LFVAD of CFRP/Ti6Al4V stack material. All tools exhibit the same macroscopic geometry. The cutting parameters and experimental setup are selected according to Figure 1 and Table 1 respectively.

Figure 7 is showing microscopic images of the flank wear after 100 drilled boreholes in CFRP/Ti6Al4V stack material. In general, all tools are showing a similar wear pattern with a smooth progression of wear along the cutting edge. Chipping or larger adhesions did not occur which is most probably a consequence of the low process temperatures in LFVAD.

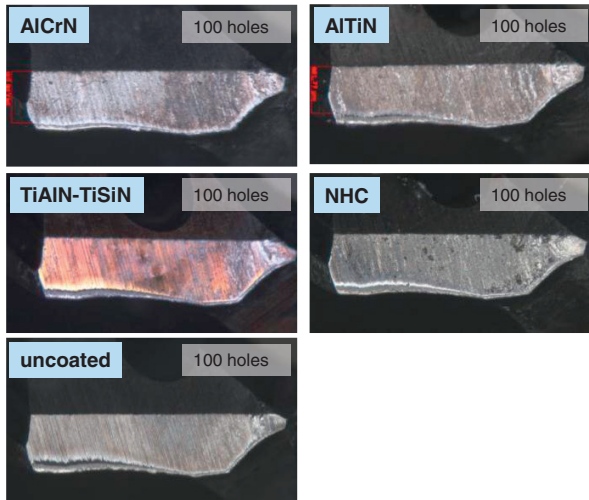


Fig. 7. Flank wear for LFVAD in CFRP/Ti6Al4V stack material for different tool coatings

Quantitative differences in the tool wear are shown in Figure 8. Looking at the maximum flank wear VB_{max} , significant differences are found for the different coatings. AlCrN and NHC coated tools are showing the lowest flank wear with 100 and 135 μm respectively, whereas the highest wear of about 220 μm was found for TiAlN coated tools. These results correspond to the measured cutting edge radius for selected tools (Figure 8/bottom).

Machining of the separate materials (result of Figure 2 and 3) has shown that the flank wear is predominantly caused by the abrasive CFRP. From literature it is well known that abrasive wear is only avoidable by hard cutting materials or coatings respectively [15]. It is strongly remarkable that a correlation between Vickers hardness HV (shown in the Figure) and flank wear was not established within these investigations. This leads to the assumption that another important material property or mechanism exists, which influences the tool wear in CFRP/titanium stack drilling. A review of the coatings material properties (provided by the manufacturer) revealed that the fracture toughness of AlCrN is about 3 times higher compared to the other coatings, and thus nearly equal to the fracture toughness of the tools substrate. Further investigations are necessary to clarify these interrelations.

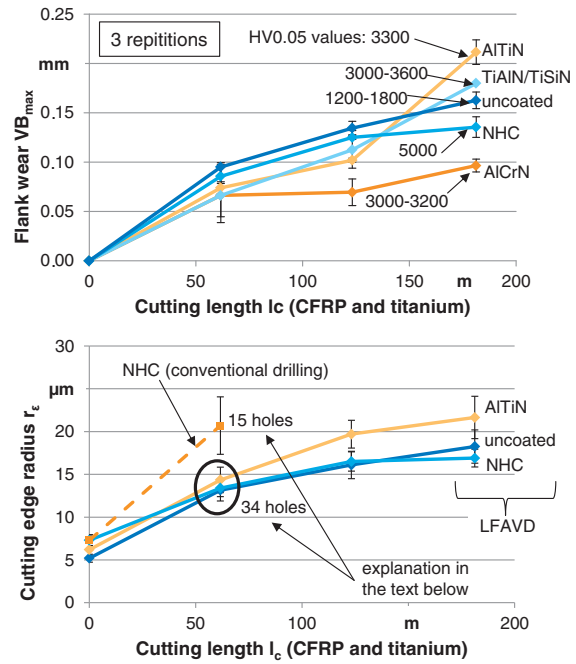


Fig. 8. Flank wear (top) and progression of cutting edge radius (bottom) for LFVAD in CFRP/Ti6Al4V stack material with different tool coatings

Note that the assignment of boreholes and cutting length differs for LFVAD and conventional drilling. This is caused by the interrupted cut in LFVAD. The non-cutting apporion was not considered as cutting length.

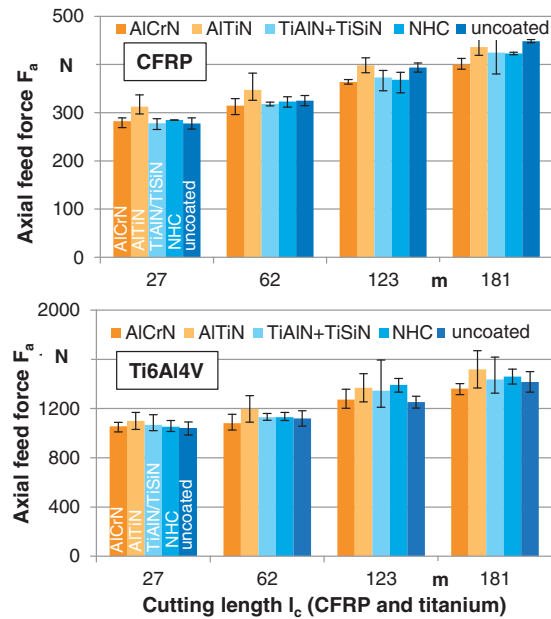


Fig. 9. Axial feed forced in CFRP (top) and Ti6Al4v (bottom) for LFVAD in CFRP/Ti6Al4V stack material with different tool coatings

The axial feed forces in CFRP and Ti6Al4V are shown in Figure 9. After a series of 100 boreholes, which equates to a cutting length of 181 m, the axial forces are increasing for about 45% in CFRP and 18% in Ti6Al4V. Marginal variations dependent on the different coatings are mostly correlating to the flank wear shown in Figure 8.

4. Conclusion

In the present study the tool wear of tungsten carbide drills with different coatings was investigated for LFVAD of CFRP/Ti6Al4V stack material and compared to conventional drilling.

It was found that the tool wear as well as the cutting temperatures are significantly decreased by the application of LFVAD, whereas the mechanical load is raised compared to conventional drilling. This indicates that the thermal load has a major impact on the tool wear, most probably due to a facilitation of diffusion processes, which further degrades the mechanical properties of the substrate.

Machining of the separated materials approved that abrasive wear due to the hard and brittle carbon fibers is predominant. In contrast negligible wear was found for LFVAD in Ti6Al4V. A comparison between the wear in the separate materials to those, caused by CFRP/Ti6Al4V stack drilling revealed the presence of interaction effects. The tool wear in CFRP influences the wear progression in titanium and vice versa. Further investigations are necessary to fully understand these interdependencies. Measurements of the axial forces and torque also proved that LFVAD results in an improved process stability compared to conventional drilling. For LFVAD the axial forces and torque varied only marginal with increasing drilling depth.

LFVAD of CFRP/Ti6Al4V stack material with different tool coatings was showing a very similar wear pattern and a smooth progression along the cutting edge. However, the flank wear for the different tool coatings was significantly different (from 100 – 220 μm , dependent on the coating). Since abrasive wear due to the carbon fibers was found to be the major reason for tool wear, a correlation between the flank wear and the Vickers hardness of the tool coatings was assumed but could not be proved. More detailed investigations regarding the wear mechanisms and interactions between the different material types (CFRP and titanium) are necessary to explain these results and to further improve tools for the drilling in CFRP/titanium stack material.

In conclusion, the results of the present study are showing that LFVAD is a promising alternative for the drilling of fiber-metal compound material. The tool wear was considerably decreased compared to conventional drilling and also time consuming peck drilling strategies are avoided. The high process stability makes it especially interesting for automated drilling operations or deep-hole drilling of heavy to cut materials.

Acknowledgements

The authors would like to thank Walter AG for the provision of drilling tools as well as professional technical advice and support.

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