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Tool Life Time Extension with Nano-Crystalline Diamond Coatings for Drilling Carbon-Fibre Reinforced Plastics (CFRP)

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Abstract

Carbon fibre reinforced plastics (CFRP) are delicate to machine as the material is highly abrasive and tends to show multiple workpiece damages like delamination, fibre pull out, uncut fibres and burnt matrix material. In result machining CFRP requires on the one hand tools which can withstand the massive wear, on the other hand geometrical highly adaptable tools to produce flawless workpieces. Diamond coated solid carbide tools can provide an excellent wear resistance in combination with a highly adaptable tool geometry. Nano-crystalline diamond coatings provide a good layer adhesion and can be applied to machining tools.

This study focuses on required drilling tool characteristics for a large tool life time of diamond coated carbide tools. The workpiece material used is the M21/35%/370H5/AS4C-6K from Hexcel© which finds its main application in the aircraft industry. The machining tests are being conducted using a Mori Seiki NMV5000DCG at different feed rates and cutting velocities. Two different nano-crystalline diamond coatings are being evaluated regarding wear resistance depending on the drill geometry and tool diameter. The workpiece quality is measured using a microscope. It is shown that the tool geometry influences the wear resistance intensively. A change in wear resistance depending on the tool geometry is not unique for different diamond coatings. Finally, it is shown that cutting velocity and feed have only a small influence on tool life time.

1. Introduction

Carbon fibre reinforced plastics experience extraordinary growth rates in industry. The material combines a high mechanical strength with a low density, making the material ideal for aerospace, automotive and wind turbine industry [1]. New generations of civil aircrafts contain CFRP as major structural material, such it makes up about 50% of the total weight [2]. Although the material is often manufactured near net shape, machining operations like edge trimming and drilling for riveted joints are required. Over the last years machining of CFRP has developed from a special application to a major machining task [3]. The presented study shows the coating behaviour of different diamond coatings when machining.

Carbon fibre reinforced plastics (CFRP) are extraordinary abrasive during machining meanwhile the material is chemically inert [4-5]. The fibres break after an elastic deformation. Plastic deformations appear only in the matrix material. The absence of a major plastic deformation in CFRP reduces the temperatures at the cutting edge compared to metal machining. CVD-Diamond coatings are of a superior hardness (about 10 000 HV) compared to nitride based PVD-coatings, which leads to a considerable increase in tool life time. The low maximum operation temperature of about 600°C and the reactivity of the diamond layer do not restrict

the usage for CFRP machining. In result diamond coatings are most suitable for machining CFRP.

Machining CFRP faces the two main problems of insufficient workpiece quality and high tool wear [3; 5]. Recent nano-crystalline diamond coatings show an improved layer adhesion, making diamond coated carbide tools the first choice for most machining applications in CFRP [6-7]. The development of drilling tools for machining CFRP focuses on three different characteristics of the tool: Geometry, substrate and diamond coating [8-10]. The resulting workpiece quality is mainly influenced by the tool geometry and the current tool wear. The tool geometry requires an intensive web thinning to reduce workpiece delamination. A large rake angle reduces delamination, fibre pull out and uncut fibres. A large clearance angle reduces tool wear [11-13].

Various diamond coatings with different grain sizes are available on the market, see exemplary Fig. 1. Crystalline microstructures with a coarse grain size are commonly known for their benefits in abrasive wear resistance. Therefore they are often used for the machining of graphite, as shown in Fig. 1 on the left hand side [14]. Diamond coatings with a nano-crystalline structure can have grain sizes lower than 40 nm, shown in Fig. 1 on the right hand side.
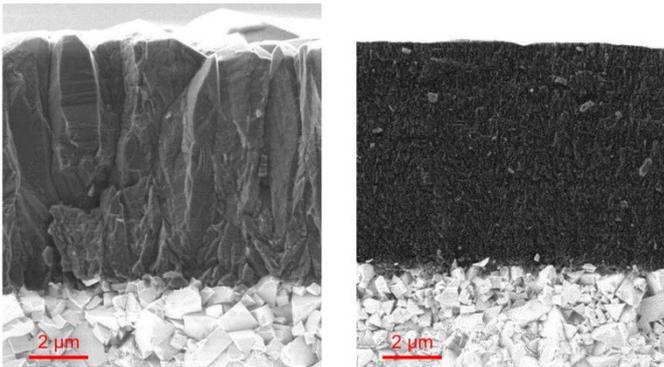

Fig. 1: Examples of diamond coatings with coarse (left) and nano-crystalline grain size (right), Source: Oerlikon Balzers Coating AG.

Without any post-treatment nano-crystalline coatings possess a lower surface roughness, as shown in Fig.1. In result the resistance against material adhesion is higher and this type of coating is recommended for example for the machining of CFRP, ceramics or aluminium with higher Si-content (>10%).

A commonly known coating process for diamond coatings with a coarse grain size is based on the DC-ARC technology. Reactive carbon species such as radicals or ions and atomic hydrogen are necessary to initiate the nucleation. They have to be produced and must be brought to the substrate surface. Controlled addition of hydrogen is commonly used to remove graphite and stabilize a sp3 carbon structure at the diamond surface [15, 16]. In general, decomposition of reactive gases for diamond growth can be initiated by hot-filament technology, microwaves, DC-plasma or plasma jets [17-20]. The use of hot-filament and DC arc for diamond coatings have been demonstrated by Karner et al. [21]. To vary the diamond layer properties the deposition conditions have to be controlled. The ratio between atomic hydrogen and carbon is one of the most important actuating variables for the diamond quality. This ratio enables to vary the coating properties and especially the grain size [22; 23]. Thereby it is possible to realize both very fine grains and smooth diamond coatings.

While the individual influence parameters for tool wear are intensively investigated, as shown above, the relation between these parameters is unknown. This study aims to point out the relation between tool geometry and coating resistance concerning tool lifetime and work piece quality.

2. Experimental setup

The presented study analyses the wear resistance and workpiece quality when drilling CFRP. Two different spiral drill geometries are tested with two different nano-crystalline diamond coatings, "version a" and "version b". The coating thickness is 6^{+2} µm for all tools. In Tab. 1 the tool models are described and visualised in Fig. 2. All angles are given in the direction of cut. M21/35%/370H5/AS4C-6K from Hexcel© is the work piece material as used in the aerospace industry, machined with a thickness of 8 mm. Each tool model is tested using three different sets of parameters, shown in Tab. 2.

Tab. 1: Tool model description.

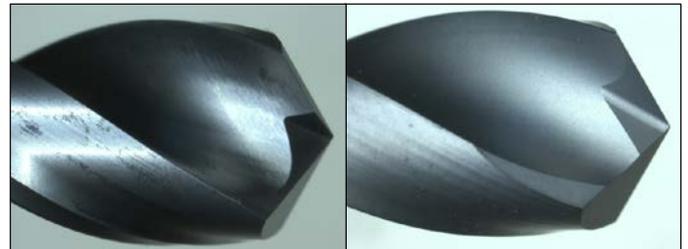| Drill Type	Diameter [mm]	Rake Angle	Clearance Angle	Coating	Carbide Material
Model Ia	6.35	25°	11°	Vers. a	EMT100
Model Ib	6.35	25°	11°	Vers. b	EMT100
Model IIa	6.35	5°	17°	Vers. a	MG12
Model IIb	6.35	5°	17°	Vers. b	MG12

Fig. 2: Drill Model I (left) and Model II (right)

Tab. 2: Process parameters for machining tests.

Process parameter	Revolution [1/min]	Feed / revolution [mm]	Cutting velocity [m/min]
Parameter set 1	7519	0.06	150
Parameter set 2	4512	0.06	90
Parameter set 3	4512	0.10	90

Tab. 3 shows the analysing schedule for force measurement and microscopy during experiments. The test rig is implemented onto a Mori Seiki NMV5000DCG, a Kistler dynamometer type 9272 is used to measure the feed force and the torque. In regular steps during the machining operation the tools are analysed using an 3D Alicona Infinite Focus and an optical microscope. Tab. 3 shows the analysing steps. For the parameters 2 and 3, the analysing steps are the same except

for the 3D analysis of the micro geometry which are omitted. Work piece quality is analysed regarding exit delamination, diameter tolerance and roundness as well as the surface roughness of the bore.

Tab. 3: Analysing schedule for coated drilling tools.

Number of Bores	0	1-3	150; 250*; 400; 600*; 800*; 1000
Analysing Method	M	F	F, M

Abbreviation	Analysing Method
F	Force Measurement with Dynamometer
M	Tool wear and Workpiece Analysis with Microscope
*	Not analysed for Model Ia

3. Results

One of the most severe damages during drilling of CFRP without glass fibre deck layer is the exit delamination. In many applications the maximum damage around the bore needs to be less than +1 mm of the nominal radius of the bore. Fig. 3 shows the bore exit from the different drills for parameter set 3. A green dot with a white check mark describes the bore as "good", being usable without any post-processing. These bores show virtually no delamination. A yellow dot with a black cambered line marks a "sufficient" quality, describing a usable bore after a post-treatment. In this case the maximum delamination can be found within a distance of 1 mm around the bore. A red dot with a white cross describes an "insufficient" bore quality. The first bore of each drill model is of a worse quality than the 150th bore. The surface roughness of new diamond coatings leads to poor drilling results. The coating smoothens within the first 10 bores. With increasing tool wear the radius of delamination increases in general.
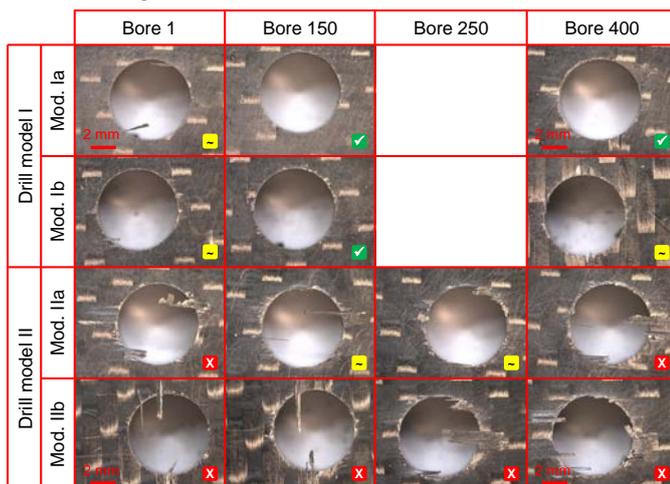

Fig. 3: Bore exit surface for parameter set 3: v_c = 90 m/min, f = 0.1 mm.

The first bore of each drill model is of a worse quality than the 150th bore. A higher surface roughness of new diamond coatings leads to poor drilling results. The coating smoothens within the first 10 bores. With increasing tool wear the radius of delamination increases in general. Model I generates a better bore exit quality than Model II. Models Ia and Ib

produce acceptable quality for the first bores with only some uncut fibres. For the 400th bore Model Ia shows slightly better results with less delamination than Ib. Model IIa shows a poor quality for the first and the 400th bore and sufficient quality for 150th and 250th bore. Model IIb produces an insufficient quality in general. The bore exits of Model IIb show massive damages already for the 150th bore, comparable to the 400th bore of IIa.

One of the most important in-process measurable value for machining CFRP is the feed force. This force increases with progressing tool wear. The feed force development during the tool life time can be divided into three segments, see Fig. 4. In Phase 1 the cutting edge is protected by the diamond coating. The coating slowly wears off, changing the micro-geometry hardly. Phase 1 can be called "coating wear". In Phase 2 a transition from coating wear to substrate wear can be observed. First small pitting areas, where the coating is gone, occur in the diamond coating on the clearance face. In Phase 3 the substrate wear is the most dominant tool wear. The outer part of the main cutting edge misses the diamond coating. The diamond coating is peeled off extensively, after short material contact. During Phase 1 the feed force is almost constant. The workpiece quality is mostly constant beside the required smoothing effects of the diamond coating during the first 10 bores. The duration depends on the tool design, the adhesion of the coating layer and the coating thickness. For optimal conditions and a coating thickness of 6^{+2} µm, Phase 1 has a maximum duration of 400 bores or 3.2 m total thickness of drilled CFRP material. These optimal conditions include a uniform coating wear without any premature coating flacking. During Phase 2 the inclination of the feed force increases, the phase lasts for a maximum of 50 bores. In Phase 3 the feed force shows a linear increase. The gradient of the feed force is strongly dependent on the tool design and the layer adhesion of the diamond coating. For tools, substrate material and coatings perfectly adjusted to the work piece material, the feed force remains as low as during Phase 1. The required tool, substrate and coating adjustment is most complex and subject of intensive research.
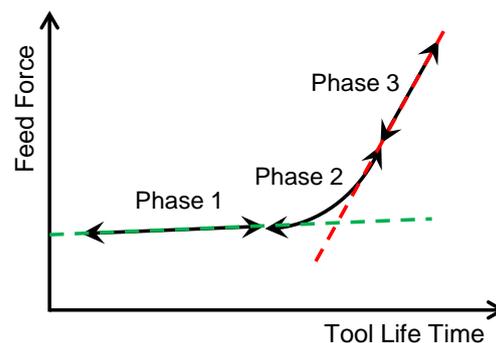

Fig. 4: Feed Force development during tool life time.

Fig. 5 shows the feed force development of all tools with parameter set 3 (vc = 90 m/min, f = 0.10 mm). The feed force has been measured in regular intervals for the bores 1, 150, 250, 400, 600, 800 and 1000. If the measured feed force exceeds the feed force of bore 1 by factor 5, the test series has been stopped. From the first to the 400th bore only a moderate increase of the feed force from F_f = 84 N to 107 N can be

recognized. The 1000th bore is being drilled with a feed force increase of 269% compared to bore 1 or F_f = 310 N. Model Ia shows a good layer adhesion of the diamond coating as the Phase 2 starts around the 400th bore. Nevertheless, the model is poorly adapted to the AS4C-CFRP as the feed force increases intensively in Phase 3. Model Ib shows very similar feed force values as Model Ia for the 1st and the 150th bore. Afterwards a more intense increase can be noticed resulting in a feed force of F_f = 152 N for Model Ib compared to 107 N for Model Ia at the 400th bore. The 1000th bore is being drilled with F_f = 480 N. The transition from Phase 1 to Phase 2 happens between the 150th and the 250th bore. Phase 3 wear starts about bore 400. Model II starts with a higher feed force of F_f = 105 N independent from the coating. Model IIa shows only a slight increase of the feed force of 14% to F_f = 120 N until the 250th bore. Between the 250th and the 400th the Phase 2 wear can be found. After 400 bores the tool shows intensive substrate wear. Model IIb displays a Phase 2 tool wear from the start, after bore 150 a transition to Phase 3 wear takes place. In total, the difference between the two coatings seems to be smaller for the Model I than for the Model II. The feed force correlates very well with delamination analyses in Fig. 3.
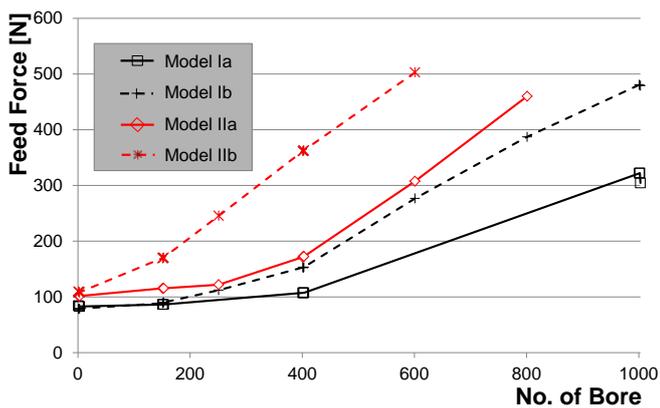
Fig. 5: Feed Force of parameter set 3 drilling tools, v_c = 90 m/min, f = 0.1 mm.

Fig. 6 shows the microscopic analysis of the worn cutting edges for process parameter set 3. All pictures show the clearance face of the drilling tools, as most wear occurs on the clearance face when machining CFRP. Model Ia has only been analysed after Bore 400 and 1000. At bore 400 the main cutting edge appears shiny. At bore 1000 a major flacking of the diamond coating can be observed for the full main cutting edge. Model Ib shows a major removal of the diamond coating at the cutting edge corner already for the 400th bore. The tool wear increases during the further machining operation until major parts of the clearance face miss diamond coating after the 1000th bore. Model IIa misses the protection of the diamond coating at the cutting edge corner for the 400th bore. The inhomogeneity of the coating removal alongside the clearance face, as well as heavily worn cutting edge corners usually result in a poor workpiece quality. The tool wear develops very similarly to Model Ib, increasing the coating removal towards the total length of the cutting edge. Nevertheless, Model IIa shows a more intensive tool wear at the cutting edge corner compared to Model Ib, but less wear

for the other parts of the cutting edge. The main cutting edge of Model IIb at the 150th bore appears shiny, comparable to the status of Model Ia at bore 400. At bore 250 and 400 a further propagation of the coating removal can be observed. At bore 400 the tool wear is similar to the tool wear of Model IIa at bore 800. These results correlate well with the measured feed forces. The feed force increases significantly when the diamond coating has been removed extensively. Model IIb shows the weakest wear resistance. Model Ib and IIa perform with a similar wear resistance.

The presented results show that the rake angle of γ = 5° of Model II is insufficient for both CFRP machining and wear resistance using diamond coatings. A higher rake angle would increase the machinability of CFRP resulting in less work piece damages. Additionally, low rake angles imply high normal forces onto the rake face. High normal forces result in an early failure of the diamond coating at the rake face due to the high hardness difference of coating and substrate in combination with the low toughness of the coating. The rake angle of γ = 25°, as used for geometry Model I shows better results.
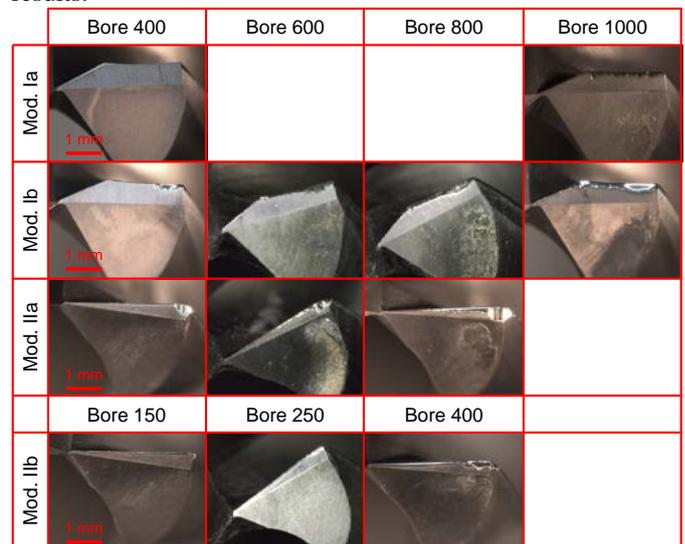
Fig. 6: Microscopic analyses of worn cutting edge for process parameter 3.

4. Influence of Cutting Strategies

The influence of different cutting parameters on the results is being discussed, analysing the feed force curves of the Models Ib and IIa, see Fig. 7. The results of the three different process parameter sets, as shown in Tab. 2, are analysed. The graphs of Model Ib are marked in black and the graphs of Model IIa are marked in red. The feed forces of the different parameter sets are very similar for each drill model. This indicates a small influence of the process parameter on the tool wear development.

For both models tool wear tends to transit from phase 1 to 2 faster when machining with parameter set 2 (v_c = 90 m/min; f = 0.06 mm). Parameter set 1 (v_c = 150 m/min; f = 0.06 mm) machines CFRP longest during wear phase 1, meanwhile during wear phase 3 the force inclination is most intense. This better wear resistance for the first 400-800 bores, when machining with higher cutting velocities is different to the knowledge in literature. Parameter set 3 (v_c = 90 m/min;

f = 0.10 mm) shows an average time till the transition from wear phase 1 to 2. The inclination angle during phase 3 is similar to parameter set 2 for both tools. In summary a high cutting velocity reduces the wear most as long as the cutting edge is protected by a diamond layer (Phase 1). The tungsten carbide wears faster with increasing cutting velocity (Phase 3). A higher feed rate and thus a shorter overall cutting length decreases the tool wear less than a high cutting velocity during phase 1. The feed has no effect on the feed force during phase 3.
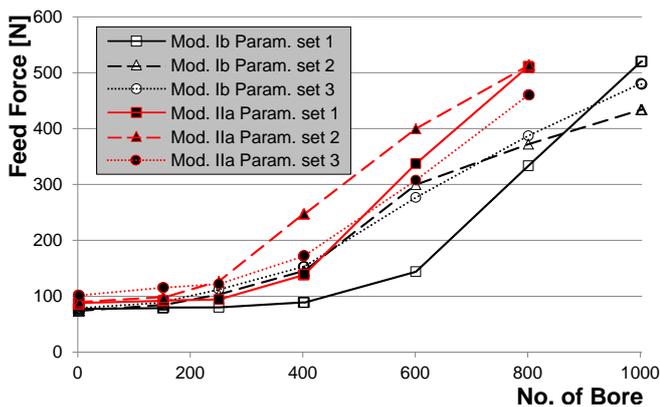

Fig. 7: Feed Force development of Models Ib and IIa.

5. Conclusion

The presented study shows a very good repeatability of the varied cutting velocities and feed rate effects on the different tools. Different tool geometries and coatings react very similarly to the different applied process parameters. The various analysing methods show a congruent picture of the diamond coating behaviour and resulting workpiece quality. Model II produces in general a worse bore quality and shows a weaker wear resistance than Model I. A rake angle of γ = 5° of Model II is insufficient for both CFRP machining and wear resistance using diamond coatings. A rake angle of γ = 25°, as used for geometry Model I shows better machining quality and lower feed forces. The influence of the substrate material can be neglected compared to the influence of the tool geometry. A proper evaluation of the substrate influence cannot be conducted within this study.

The applied diamond coatings increase the tool life time of the carbide tools substantially when machining CFRP. The best adapted tool Model Ia preserves the diamond coating and hence Phase 1 for about 400 bores. Afterwards a major removal of the diamond coating occurs. Models Ib and IIa show a Phase I duration of about 200 bores. For Model II the coating "version b" shows an insufficient wear resistance. The coating "version a" performs in general better than the "version b". The coating "version a" shows a better layer adhesion during Phase 1. The layer adhesion during Phase 3 is similar for the two coatings. The difference of wear protection between the two coating systems is smaller for the Model I tools than for the Model II tools. The resulting workpiece quality increases during the first 10 bores due to the roughness of the diamond coating after application. Model Ia and Ib produce good bore exit qualities for the bores 10-400.

The tools are competitive on the market of CFRP machining. The workpiece quality of Model II tools is in general insufficient for market participation. All tested models show an intensive increase of the feed force for the Phases 2 and 3. This shows an imperfect adaption of the tool to the requirements of machining CFRP and the diamond coating. The tools produce an insufficient workpiece quality during the Phases 2 and 3. A further development is required to enable low feed forces and high workpiece quality during Phase 2 and 3.

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