INNOVATIVE TOOL AND PROCESS CONCEPT FOR DRILLING CFRP/TITANIUM STACK MATERIAL

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Keywords: stack drilling, CFRP, titanium, counter drilling

Abstract
An innovative tooling concept for the purpose of cutting stacks of aerospace materials is presented. The concept addresses specific process requirements and is characterized by a counter drilling process step in order to achieve a quality free of delamination and fiber fuzzing. A study is carried out and the concept is compared to a state-of-the-art one-shot drilling tool. The new tool is able to extend tool life and reduce material damage.

1. Introduction

Reducing carbon dioxide emissions has been announced by the transportation industry to be the prioritized goal in order to contribute to the fulfilment of the political efforts in restricting climate change effects on a global perspective. Due to this strategy, transportation units have to become lighter to safe up energy while in use. In order to meet these requirements, the transportation industry applies highly innovative lightweight materials for example carbon fiber reinforced plastics (CFRP) and lightweight metal alloys. As the demand for material specifications regarding structural weight and mechanical load capabilities rises, challenges in processing these materials are shifting towards new demands also. High material costs have to be compensated by highly productive machining processes on the one hand, on the other, the material specifications require new working processes and tooling solutions. [1]

Against this background, Fraunhofer IPA has developed and patented an innovative drilling tool and process, focusing on combined laminates of CFRP and metal alloys (stacks), which are primarily used in aerospace industry and most difficult to machine. Drilling CFRP / metal alloy stacks induces high tool wear which limits the achievable amount of drill holes while meeting the required quality specifications. The innovative tool and process both extend~~s~~ tool life and increase~~s~~ the process stability and quality by a material specific tool layout addressing the specific material cutting conditions, which vary~~y~~ strongly between metal alloys like titanium and CFRP.

2. State of the Art

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In modern airplanes, up to 1, 000, 000 rivets are applied, most commonly in ¼" dimension. [2] The percentage distribution of mixed material processed for rivet connections is given in the graphic below. As can be seen, 45% allocate on CFRP/metal alloys combinations.

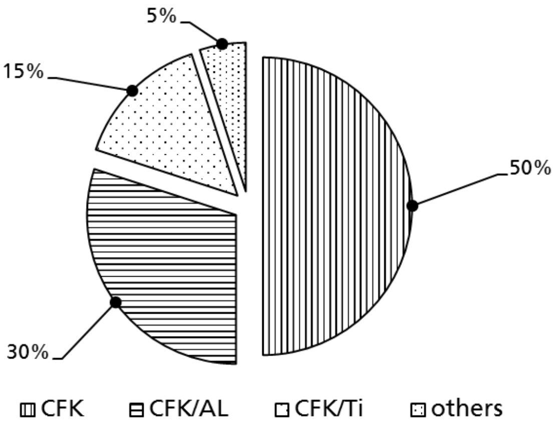

Figure 1: Frequency of material used in aerospace [3]

In order to create these drill holes, so called one-shot drilling tools and processes are being used. These tools are characterized by a geometrical tool layout which enables cutting performance in both CFRP and metal alloy materials. On the downside, this layout represents a compromise and thus, tool life performance is limited. Depending on the material layer structure and given drilling direction, the tool is specifically designed. [4] Quality requirements refer to burr formation on the entry side with less than 0.05 mm and on the exit side with less than 0.1 mm. No CFRP fuzzing and delamination is allowed. The borehole dimension for rivet connection is commonly tolerated with IT 8. [5]

3. Methodical Approach

For deriving an improvement approach, the physical and technical drawbacks of the state of the art technology has been analyzed. Considering the material's structural integrity of CFRP, drilling operations induce force loads with impact direction orthogonal to the main loading axis of the material. Thus, acting forces can cause severe damage of the laminated structures, called delamination. The most critical points of drilling CFRP is at the entry and exit side. The damage phenomena are defined as peel-up and push-out delamination. [6,7] further, fiber fuzzing can occur on both sides due to advanced tool wear. Both defects, delamination and fiber fuzzing, strongly increase by high drilling tool temperature caused by cutting the metal alloy in the top layer of the stack, especially for thermoplastic CFRP materials. If the stack is built up with CFRP as top layer and the metal alloy as bottom layer, hot metal chips damage the whole face when they are ejected by the turning tool. Abrasive chips grind alongside the whole face and damage the open-pored surface of CFRP. [8]
Another process disadvantages regarding high precision drilling can be seen in the non-productive retraction operation of the tool from the drilling hole. The tool still remains turning and by retracting the drill from the hole, the lateral cutting edges ream the whole face causing diameter deviation.
Further limitations can be seen in the one-shot tool design which reflects the geometrical cutting requirements as a compromise for two types of material. Metal alloys require higher cutting wedge angles for stability compared with fiber reinforced plastics with low cutting forces. On the other hand, CFRP demands sharp edges and a lower point. Chip formation and morphology also is portrayed on different twist angle and flute volume. In order to machine stack material, one-shot tools are designed with a compromised layout, as illustrated below. [6,9]

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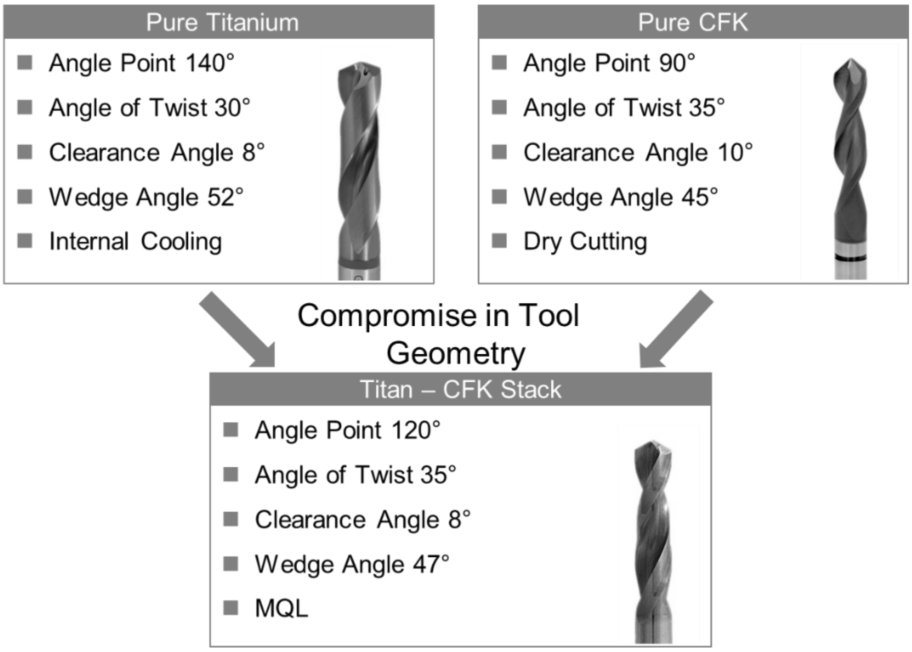

Figure 2: Development of stack drilling tools

The innovative tool concept described in this study, addresses these issues and meets the different requirements for material specific cutting. The concept has been derived from the process demands and first evaluation results are given in the following chapters.

4. Results

In the following passages the achieved solution is closely delineated. Starting with the description of the clamping system and the innovative tooling concept, first results of a prototype study are outlined.

4.1. Counter Drilling Tool Concept

The innovative counter drilling concept addresses the aforementioned issues of one-shot drilling and solves the conflicting requirements of drilling two distinct materials in sequence and with only one tool. The new process is differentiated and now involves 4 distinct process steps. The material specific cutting requirements are met with a tool containing 3 different diameter segments and 5 cutting edges. Four out of them are working pairwise and one as a single cutter.

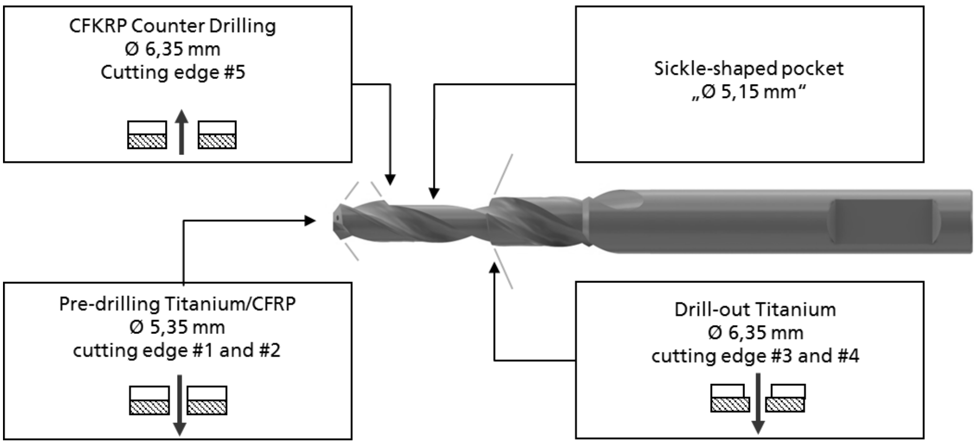

Figure 3: Innovative Tooling Concept

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The process-layout distinguishes four steps. In the first step, a smaller diameter pre-drilling hole of 5.35 mm is performed in one-shot style. A second step involves drilling the upper layer of the stack material up to the nominal diameter of 6.35 mm. Then, the tool is retracted so far that the axial omitted second diameter segment is oriented centrically to the workpiece thickness. By changing the revolting direction, the tool is tilted radially by 0.50 mm. By this radial extension, the single cutting edge which faces the rear direction of the tool now describes a machining orbit of 6.35 mm. The tool axis has an offset of 0.50 mm with reference to the centrically spindle revolting axis.
With further retracting the tool, the lower layer is being processed by the single cutting edge. After machining the lower CFRP layer up to 6.35 mm, the tool again changes revolting direction. In consequence, the tool rotation axis and the spindle turning axis are again co-central as in step 1 and 2. The last step includes removing the tool without any touching of the tool and the drilling hole. This results in an improved wear behavior and better drilling quality.

Table 1: Process definition

		Cutting Speed [m/min]	Feed Rate [mm]	Turning direction of Tool	Engaged Cutting Edge
IPA Tool	*Titanium drilling*	24	0,080	Clockwise	1+2
	Titanium drilling-out	24	0,175	Clockwise	3+4
	CFRP drilling	100	0,200	Clockwise	1+2
	CFRP drilling-out	70	0,100	Anti-clockwise	5
Reference Tool	*Titanium drilling*	24	0,080	Clockwise	1+2
	CFRP drilling	100	0,200	clockwise	1+2

In order to describe the process closely, the table below defines the process steps with the applied process parameters for both, the standard one-shot and the new counter drilling process. To provoke chip breaking, both processes make use of pecking. Minimum quantity lubrication was applied with 30ml/h equally for both tools. In order to ensure comparability, both tools have been coated with the identical TiXCo coating. The effect on quality output can therefore be repatriated mainly on tool geometry with minimizing the effect of other factors. TiXCo coatings are based on three coating layers applied with PVD technology. TiN functions as basic bonding layer. Core layer is TiALN which provides high toughness. TiSIN as toplayer is characterized by a hardness of 40 GPa.

4.2. Clamping System

The tool clamping system is a basic component of this system and allows the necessary eccentrically movement of the tool in reverse turning direction. The system in charge was developed by Walter Bauer Tools and works in a purely passive way. The change of turning direction and angular acceleration gives the impulse and centrifugal power to move the front part of the 2-part-clamping system including the tool eccentrically. The systems specifications are listed below. For performing the counter drilling process, several market solutions can be applied, too.

Table 2: Technical data of clamping system

Maximum allowed torque [Nm]	*Maximum allowed torque in reverse direction [Nm]*	*Maximum allowed radial deviation for 1 kg in [mm]*			
		6000 Rev./min	4200 Rev./min	3500 Rev./min	3000 Rev./min

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180	90	0,2	0,4	0,6	0,8

The system's primary purpose to perform rear wise deburring has been successfully extended and its capability to machine pre-drilled holes has been proofed. The development is able to drill and counter-drill full material. The scope of investigation is valid for drilling diameters of 6.35 mm and material thickness up to 10 mm with the built-up prototype. Application can be extended with diameters ranging from 4.00 mm to full 1 inch holes.

4.3. Results of the Quality Investigation

Investigations have been performed using a 2 layer stack material with 5mm layer thickness each. Titanium represents the upper layer and CFRP is located on the downside. Quality was evaluated with respect to delamination and fuzzing. The innovative counter drilling tool has been benchmarked against a state-of-the-art one-shot drilling tool.

The delamination index represents the largest detectable material damage on each drilling hole. The index can be calculated as shown in equation (1). The fuzzing index shows the overlapping surface of the borehole by uncut fibers relative to the area of the nominal diameter. The index is given in equation (2).

$$Delamination\ Index\ = \frac{\emptyset\ maximum\ damage\ -\ \emptyset\ nominal}{2}\ in\ [\mu m] \qquad eqa.\ (1)$$

$$Fuzzing\ Index = \frac{Area_{Fibres}}{Area_{borehole}}\ in\ [\%] \qquad eqa.\ (2)$$

The reference tool (one-Shot driller) performed 119 borehole. Tool life limit was indicated with sparkling, while drilling titanium.

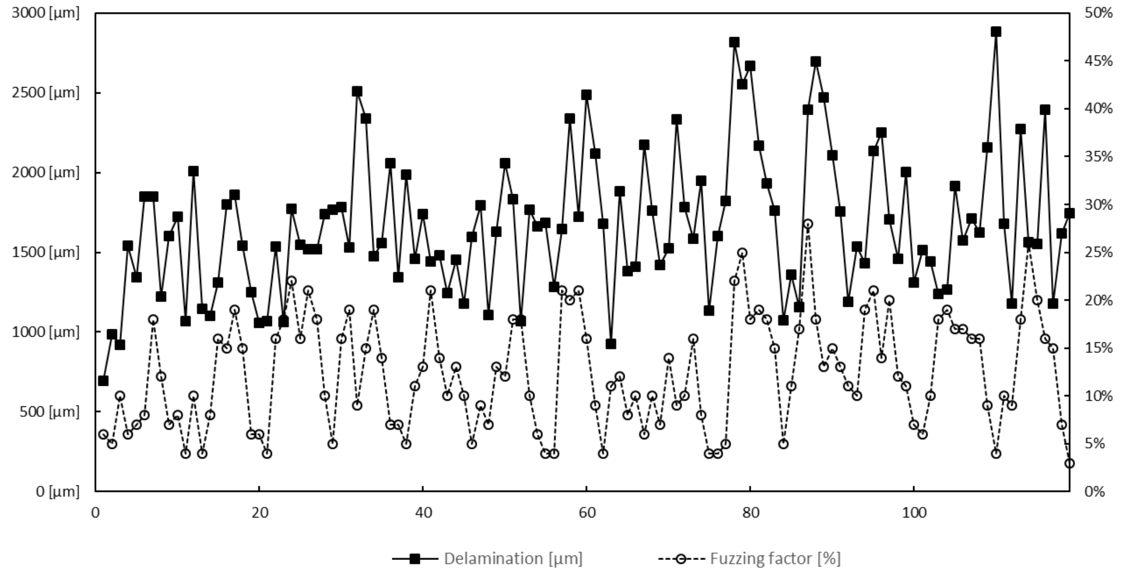

Figure 4: One-Shot Reference Tool - Quality Results

The counter drilling tool achieved 253 boreholes. Until borehole 200, the delamination level is stable and does not exceed an degree of 2000 µm.

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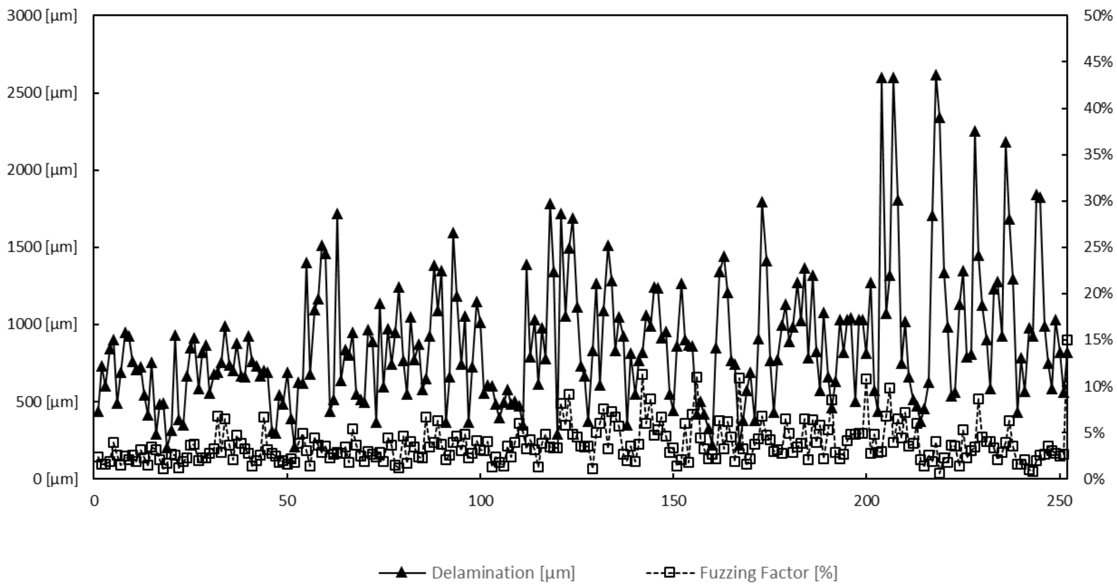

Figure 5: Counter Drilling Tool - Quality Results

Weighting each factor with its mean value, the comparison of both tools can be conducted. Delamination phenomena can be reduced by almost half and fiber fuzzing is decreased by 8 percentage points.

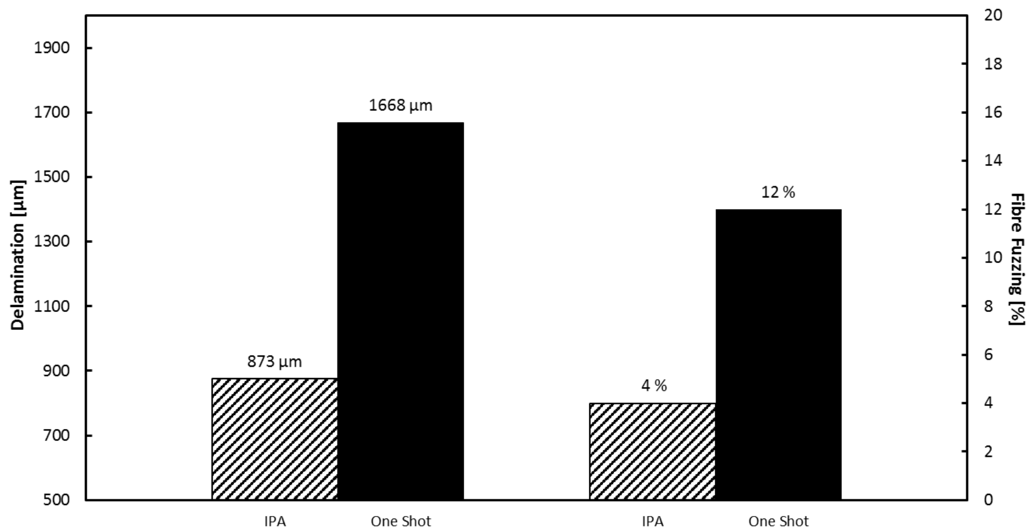

Figure 6: *Quality results in comparison*

4.4. Evaluation of the total tooling concept

The investigated tooling concept was able to perform counter drilling boreholes with diameter of 6.35 mm and 10 mm combined material thickness. The stack layout was chosen to be titanium on the upper side and CFRP on the lower side. This structural order has some severe challenges, since the tool is being heated up while drilling titanium and hence, a hot tool is entering a heat sensitive material. Moreover, CFRP on the lower side has no support at the drilling tool exit compared with being on the upper side. Therefore, CFRP is inclined to develop push-out delamination more easily.

Applying the innovative drilling concept, these issues could be solved. By separating the final machining process steps in terms of space and time, the effect of heat could be minimized. The quality producing steps are being performed with material specific cutting edges. These cutting edges are only meshing for reaming or drilling out the nominal diameter from 5.35 to 6.35 mm in this case. With

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respect to CFRP being the lower layer, push-out delamination is inevitable when performing the pre-drilling hole. By performing the drill-out step with flow of forces directed inside the material, possible delamination defects are removed.

5. Discussion

As can be seen in the graphics from above, the counter drilling tool achieves better quality output with respect to delamination and fiber fuzzing. Moreover, the counter drilling tool attained higher tool life. In comparison, the one-shot drilling tool achieved 119 boreholes. Tool life end was indicated by sparkling while drilling the titanium layer. The counter drilling tool performed 253 boreholes showing no sparkling at all. Tool life end for counter drilling process is not yet reached. Even when performing 200+ boreholes, the quality output is better compared to the one-shot tool showing less delamination and fiber fuzzing. However, increasing volatility of delamination starting from around drilling whole number 200 can detect a possible process limit.

Table 3: Quality Study and Comparison

	Drilling Level	*Average Delamination*	*Standard Deviation for Delamination*	*Average Fiber Fuzzing*	*Standard Deviation for Fiber Fuzzing*
	[# boreholes]	[µm]	[µm]	[%]	[% Points]
One-Shot	119	1668	± 438	12	± 5,75
IPA Tool	119	756	± 317	3	± 1,25
IPA Tool	253	873	± 429	4	± 2,06

The increased performance can be explained by an optimized process design. As described earlier, the innovative tooling concept addresses the specific material demands for cutting. Each material is machined with specific cutting edges. Moreover, recorded force level is decreased comparing both tooling concepts.

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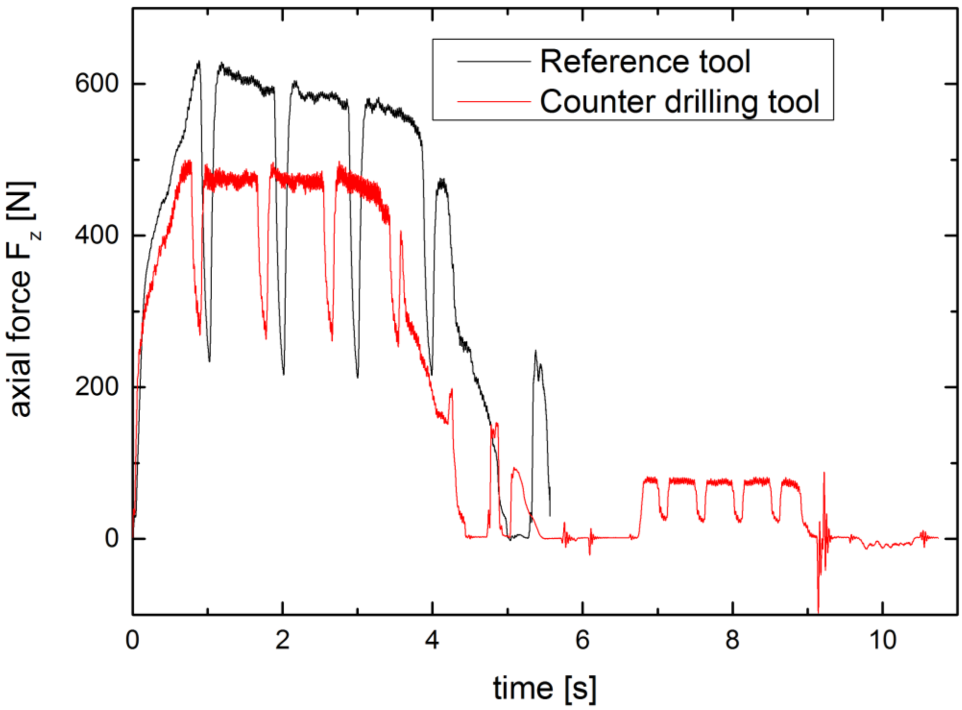

Figure 7: Force Level in comparison

The axial force level in drilling titanium is lowered by around 100 N, mainly because of a reduction in diameter for the pre-drilling borehole compared to the one-shot process. In CFRP layer, the feed force is reduced from around 210 N (black line) to 140 N (red line) between processstep 4.5 sec and 6 sec. By this, the force sensitive CFRP is spared against a high level of forces acting against the main loading axis causing delamination and fibre fraying. The following peaks (processstep of 6.8 sec to 9 sec) indicate the drilling out of the upper titanium level to nominal diameter of 6.35 mm. Next, the tool is being retracted and tool revolving direction is changed to anti-clockwise. This process is marked by a short force amplitude. Afterwards, CRFP is drilled out in reverse feed direction. As can be seen, the force level in this process step is very low and acting force direction is orientated into the workpiece. With this process step, existing material damages are removed and a material specific mechaning is performed with a low level of delamination and fibre fraying in consequence. Applying a single cutting edge for CFRP with tall pointing and wedge angle as well as a fore leading outstanding edge point, further damage is suppressed.

6. Conclusion

The new tooling concept reveals obvious advantages above the state of the art tools. Quality and process stability could be improved. The compromise tool geometry which negates optimized cutting conditions was transferred into a material specific tool layout with 5 distinct cutting edges. By addressing material specific tool design not only quality output could be improved but also tool life performance using the right cutting edge geometry needed to machine each material layer.
Since this concept reflects a prototype state of development, issues have to be addressed concerning tool deflection caused by cutting forces and supporting phases on the circumferential surface. Fine-adjustments have to be realized to bring out full potential. With respect to this prototyping state of development, the concept reveals high potential for cutting stack material providing high process stability and damage-reduced quality.

The concept can be extended for the purpose of machining a wide range of material combinations but also to machine pure materials, too. Especially concerning drilling CFRP, the separation of machining the upper and lower side provides advantages concerning delamination and fiber fuzzing. The specific cutting edges can be designed in accordance with the material properties and machining behavior. The force flow direction can be deliberately directed with the aim of quality output increase. Also, there is a purpose built tool derivation possible for machining hard-to-machine materials like titanium. Burr formation on both the entry and exit side can be removed.

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