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Machining of carbon and glass fibre reinforced composites

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Abstract

The combination of carbon and glass fibres in new reinforced composite components makes the machining of these promising materials challenging. The abrasive carbon and glass fibres cause tool wear and cutting edge rounding which results in higher process forces and insufficient workpiece quality. At the IWF, innovative process strategies for the machining of these materials have been developed, combining these with new cutting tool geometries. Furthermore, the classification of workpiece quality for reinforced plastic components has not been sufficiently addressed thus far and is also a focus of the work being undertaken. In order to adequately describe the workpiece quality, fibre pull-out and fibre protrusion must both be analysed. Using the example of a carbon and glass fibre composite material, the dependency of these characteristic quality parameters on process and tool parameters shall be analysed. The work described here compares an axial drilling with an helical milling process from both a technological (workpiece quality) and an economical (processing time) point of view.

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Keywords: composites; process strategy; drilling; milling

1. Introduction

The use of lightweight materials continues to grow in importance in the aeronautical and automotive industries, with more stringent guidelines on fuel consumption and emissions coming into place in the next years. The demand for economical machining strategies for fibre reinforced composites is therefore high, as these materials possess a high potential for the substitution of, for example, heavier aluminium alloys. Various research works have studied the machining of fibre reinforced composites in recent years [1,2,3]. However, the focus lay mostly on carbon fibre reinforced composites in the aeronautical industry [1], with some work also being undertaken on glass fibre reinforced materials [4]. The development of machining strategies for automotive components and the combination of both carbon and glass fibres in a single workpiece has thus far been studied only in a limited capacity.

2. Aim and current state of the art

The aim of the presented work is to develop a machining strategy for high quality bore hole machining in a CFRP/GFRP combined workpiece material, as shown in Fig. 1. Currently, the fibre protrusion and fibre pull-out requires manual post-machining, which is costly and time-consuming in series production. In both the automotive and aeronautical industries, drilling is one of the most important operations, with up to 55,000 holes being drilled in the production of an Airbus A350 aircraft and over 200 bore holes per car in the BMW i Series cars [5,6]. The aim is therefore to make manual reworking obsolete by achieving the required quality with the machining process alone. This can be achieved by controlled buckling and fracturing of the carbon and glass fibres during machining [5,7].

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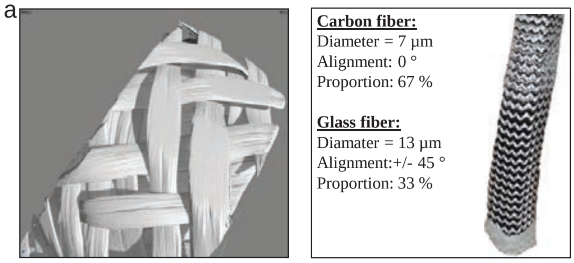

Fig.1. Carbon and glass fibre reinforced composite used in the investigations

Previous work by the authors has shown that the use of high speed cutting parameters has led to substantial improvements in the machining result [8,9]. This concept was thus transferred from peripheral milling to bore hole machining within the work described in this paper.

As also stated by [1], the conventional machining process outputs such as tool wear and surface quality are not sufficient for the classification of reinforced composite components. For the work undertaken here, quality criteria were therefore determined by the end-user, BMW AG. The quality criteria relate to fibre pull-out and fibre protrusion.

Nomenclature

v_c	Cutting speed
v_f	Feed rate
v_{fmill}	Milling feed rate
v_{fdrill}	Drilling feed rate
D	Diameter
I_F	Fibre protrusion
I_{PO}	Fibre pull-out
CFRP	Carbon fibre reinforced plastic
GFRP	Glass fibre reinforced plastic
CVD	Chemical vapour deposition
BMBF	Federal Ministry of Education and Research

3. Experimental set-up

The milling and drilling tests were undertaken on a 5-axis High Speed Cutting Machine from Roeders GmbH, Type RXP600DSH with a spindle speed up to n = 60000 rpm.

In order to allow an analysis of the machining processes for the CFRP/GFRP material, in a first step quality criteria had to be defined. Two criteria, fibre pull-out and fibre protrusion were chosen based on the requirements of the end-user, as shown in Fig.2. Fiber pull-out can reduce the workpiece thickness and therefore influence the strength and parallelism of parts for subsequent riveting and assembly processes. Fiber protrusion is less important for assembly activities, but becomes relevant in the varnishing of the workpieces. During this production step protruding fibers can break loose and fall into in the varnishing bath. This causes impurities in the paint layer and requires a high cleaning effort. The end-user defined the length of the fibers to be the most critical factor. The appearance of fiber pull-out and protrusion is due to an interplay of various influencing parameters. In addition to the location of the hole in the fiber braid and the resulting cutting angle, the condition of the cutting edge plays a major role. The cutting speed and feed rates are also important influencing process parameters as these impact the fibre seperation mechanism [10].

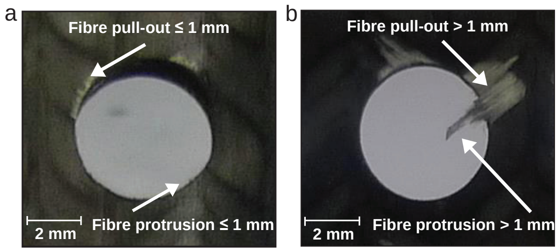

Fig. 2. Quality criteria for bore holes

The criteria were evaluated both at the hole entrance and exit, as shown in Fig 3. Additionally tool wear was also determined using scanning electron microscopy (SEM) images.

A study of process parameters was undertaken, as shown in Table 1. The two processes were compared from both technological as well as economical points of view, with an analysis of tool wear, drilled hole quality and time consumed.

Table 1. Process parameters for drilling and helical milling

Test/Parameter	Milling feed rate v_{fmill} (m/min)	Drilling feed rate v_{fdrill} (m/min)	Cutting speed v_c (m/min)
Helical Milling 1	7	0.75	678
Helical Milling 2	17	0.75	678
Drilling 1	-	0.6	700
Drilling 2	-	0.9	925

For all investigations, tools from Hufschmied Zerspanungssysteme GmbH were used. Fig. 3 shows the implemented process strategy for helical milling. As the first step, a hole with a depth of half the workpiece thickness is drilled. This is followed by the first milling process along a circular path. Subsequently, a further drilling step is carried out up to the full workpiece thickness before the tool moves at maximum feed to the depth of the second cutting stage. After a second milling process, the tool moves out of the hole.

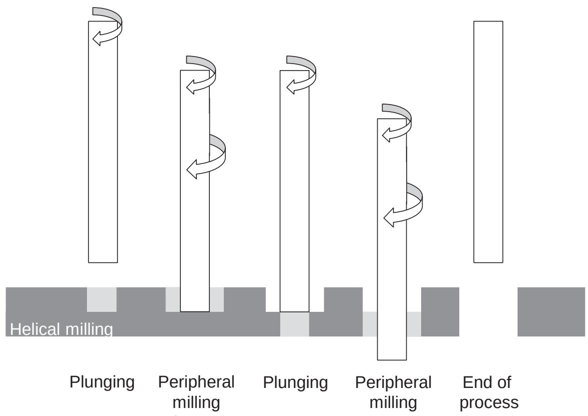

Fig. 3. Process strategy for helical milling

4. Results of the investigations

4.1 Drilling of CFRP/GFRP

The challenge in drilling of CFRPs is often the bore hole quality at the hole exit, as due to the anisotropy and inhomogeneity of the composite, fibre pull-out and protrusion occur [2,11]. Results of the parameter variations showed that the number of achievable holes within the set quality criteria is low, with some tendency to higher bore hole quality when implementing higher cutting speeds, see Fig. 4. It could be shown that the limiting factor is not tool wear, but rather the attainment of sufficient bore hole quality even with an unworn, new tool. During the process time, some cutting edge rounding could be observed.

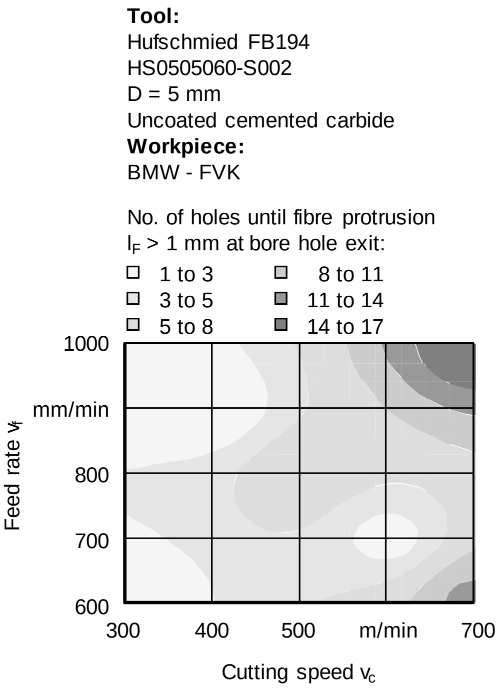

Fig. 4. No. of bore holes prior to reaching fibre protrusion of > 1mm

The use of CVD diamond coatings for the machining of CFRPs is reported by Iliescu et al. [12] to show a ten-fold improvement of tool life at higher cutting speeds compared to uncoated cemented carbide tools. This could not be shown in the drilling investigations here, in fact the CVD diamond coated tools did not show improvements of the bore hole quality, as shown in Fig. 5. This can be explained by the larger cutting edge radius of the coated tools, which may be compensated for when abrasive tool wear protection is required, however in this case the abrasive tool wear is not the limiting factor as the fibre pull-out and protrusions occur also at the beginning of the drilling tests with unused tools. Hintze et. al [13], Reimann et. al [14] and Faraz et. al [3] have also reported on poor workpiece quality with higher cutting edge rounding of the tools.

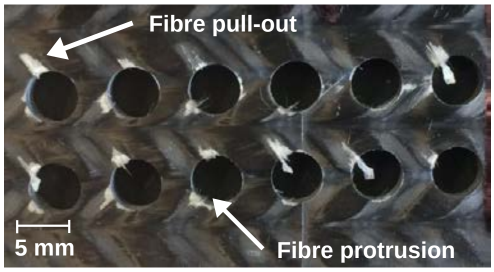

Fig. 5. Bore hole qualities after axial drilling with CVD diamond coated cutting tools, showing large fibre pull-outs

4.2 Helical milling of CFRP/GFRP

An alternative to drilling, which led to insufficient workpiece qualities as shown, is helical milling. The tool rotates on an orbit and moves in axial direction on a helical path. The advantage of this process is that it allows the production of bore holes with tools of a smaller diameter, which allows for easier chip evacuation and heat extraction as well as the production of differently sized holes with the same tool [1,15,16]. Further issues with conventional drilling can also be addressed, such as eliminating the stationary tool centre and compensation for the alteration of hole diameters due to tool wear. Sadek et al. [16] showed a reduction of 45 % in the axial force component and a 60 % reduction in tool temperature during helical milling compared with conventional drilling. Brinksmeier et al. [17] showed that significantly higher bore hole qualities could be achieved with helical milling compared with conventional drilling.

Within these investigations a helical milling process was used whereby the tool does not follow a helical path whilst moving in an axial direction but rather follows a step-wise trajectory. Results showed that the helical milling process could attain significant advantages over drilling, as shown in Fig. 6.

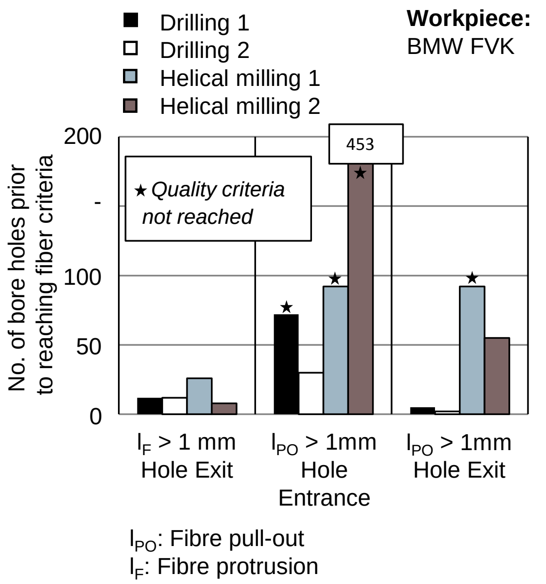

Fig. 6. Workpiece quality comparison for axial drilling and helical milling

Interestingly, the limiting criteria during drilling was fibre-pull out at the hole exit, with less than ten holes falling under the given criteria of $l_{PO} < 1$ mm. Using helical milling significant improvements could be made in this category, with almost 100 holes being reached. However, using helical milling, the fibre protrusion at the hole exit was the limiting criteria, with a significant variation in the number of bore holes falling within the cut-off point of $l_F < 1$ mm. The fibre protrusion at the bore hole entrance was not a limiting criteria in the drilling or milling tests and is thus not shown here.

As with the drilling process, the tool wear was not the limiting factor, although some cutting edge sharpening interestingly took place following implementation in the cutting process.

4.3 Component case study

Comparing the technologies drilling and milling using a case study of a real component allows an analysis from an economical point of view. Using the example of a BMW structural component with 10 bore holes of diameter D = 5 mm, 5 holes with D = 8 mm and 5 holes with D = 12 mm, a time calculation can be made, as shown in Table 2.

Table 2. Comparison of process times for axial drilling and helical milling

Bore hole/Process	Axial drilling	Helical milling
Bore hole 5 mm	0.8 s x 10	1.37 s x 10
Bore hole 8 mm	0.88 s x 5	1.6 s x 5
Bore hole 12 mm	0.93 s x 5	1.9 s x 5
Tool change	10 s x 2	-
Total	37.05 s	31.2 s

The time calculations show that the implemented helical milling process reduces the processing time for the component by 5.85s even though the helical milling processes are slower compared to drilling, due to the obsolete tool changes.

5. Conclusions

A number of conclusions can be drawn from the work:

- Drilling of CFRP/GFRP material leads to poor hole qualities with high level of pull-out, with the glass fibres most commonly causing more issues than the carbon fibres.
- Coating with CVD diamond did not bring any advantages for the drilling process due to the higher cutting edge rounding of the tools.
- Helical milling allows for higher bore hole qualities, with only one of the four quality criteria still requiring attention: the fibre protrusion at the bore hole exit.
- An evaluation of axial drilling and helical drilling using an example BMW component showed that the helical milling process results in aslightly increased processing time, however may allow manual reworking to be reduced or removed from the process chain due to the higher workpiece quality.

In further work it is planned to increase the cutting speeds and feed rates in order to achieve higher workpiece qualitites with reduced processing time.

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