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Influence of the quality of rivet holes in carbon-fiber-reinforced-polymer (CFRP) on the connection stability

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Abstract

Components made of carbon-fiber-reinforced-polymer (CFRP) are frequently linked together via rivet connections. The machining of the holes of the rivet connections can cause damages such as delamination (layer separation) or fiber protrusion (non-cut fibers). Those damages affect the strength of the connections, since they weaken the structure and thus reduce the quality of the connection. In this paper three manufacturing strategies – conventional drilling, industrial state-of-the-art drilling , and circular milling – are compared with respect to the machining quality and the resulting connection strength with respect to trigger force (to initiate the rivet connection failure case) achieved.

The study revealed a direct relationship between the hole quality and the trigger force. The hole manufactured via circular milling resulted in the smallest variation in the cylindricity and the lowest delamination and fiber protrusion. The trigger force required to initiate failure was highest for the rivet connections manufactured via circular milling.

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Keywords: drilling; milling; carbon-fiber-reinforced-polymers

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1. Introduction

Carbon-fiber-reinforced-polymers (CFRP) are composite materials with inhomogeneous and anisotropic properties with respect to the fiber orientation [1]. Because of its good mass-stiffness-ratio, CFRP is becoming increasingly popular in aerospace and automotive applications [2]. Thus, the Boing 787 or the Airbus A 350 already consist of 50 % CFRP [3]. The structures used are assembled of several CFRP components. The assembly is often implemented by means of rivet connections. A high-quality structure is (beside other criteria) characterized by a high strength to mass ratio, which implies a high quality for the riveted connections as they are load bearing elements in the structure. Occurring imperfections while machining rivet holes in CFRP are inter alia fiber protrusion and delamination. These imperfections at the rivet hole have a strong influence on the rivet hole connections as they weaken the material [4]. Compared to a hole without imperfections, holes with lower quality can lead to significantly lower strengths (about 11%) [16]. If the CFRP structure fails through external energy, the CFRP has excellent energy absorption properties especially when continuous fiber-reinforced [5]. Therefore CFRP is superior to metals at crushing [6] and thus, CFRP is used in energy absorbing structures.

Different machining strategies influence the quality of the rivet hole. Laser machining of CFRP can cause high thermal damage (micro-cracks, voids, and delamination) due to the high process heat [7]. Although recent work successfully investigated possibilities of combined laser machining and drilling [8], chip forming processes are commonly used to produce the holes in CFRP.

In [9] is shown, that the quality of the drilled rivet hole strongly depends on the drill-point angle. A larger drill-point angle leads to lower delamination around the hole entrance but higher delamination at the hole exit. When drilling the rivet hole, the damage can also be reduced by the choice of a suitable clamping [10].

Orbital milling (as shown in [11]) is a promising alternative for machining rivet holes of high quality in CFRP [12]. Also the circular milling (the end mill does not move in the direction of the tool axis) results in a reduction of delamination and fiber protrusion as compared with a drilling process [13].

To evaluate the CFRP's material strength after a drilling operation, different tests can be made as described in [17]. Combinations of these different test setups enable an efficient evaluation of the material strength [17].

In the present paper, the influence of the rivet hole's quality on the strength of the rivet connection is investigated by comparing three different manufacturing strategies: conventional drilling with a twist drill, drilling with a state of the art CFRP-drill and circular milling. The quality, described by the delamination and the fiber protrusion, is compared. Finally, the influence of the quality on the trigger force is compared. The trigger force is the force that is necessary to initiate a progressive hole bearing failure (a measure for the connection strength).

2. Experimental setup

For the experimental characterization bidirectional CFRP plates as tensile specimen with 12 layers [0°,90°,0°,90°,0°,90°,90°,0°,90°,0°,90°,0°] were manufactured from the unidirectional prepreg C100715038 supplied by SGL. The plates were cured for 1 h at 130 °C and 24 bar in an autoclave. Subjected to manufacturing tolerances, the tested plates had a thickness of 1.5-1.85 mm with fiber contents of 60 Vol.-%.

7 rivet holes for each of the three manufacturing strategies were made. 2 of them were cut to investigate the inner damage. 5 of them were used to analyze the influence of the rivet hole quality on the trigger force. The cutting edge radius and the cutting edge form factor of the tools were measured using an optical device based on the phase measuring fringe projection.

2.1. Manufacturing processes

For all three machining strategies, conventional drilling with a twist drill, drilling with a state of the art CFRP-drill, and circular milling (see Fig. 1. c), the CFRP plates were fixed in a fastening device, see Fig. 1. a). The fastening device consisted of a bottom and an upper part. The fastening device was attached on a 5-axis machining centers table, see Fig. 1. b). Dust, produced during the machining processes, was removed by a suction. A 3d-printed suction adapter guaranteed a complete elimination of the dust.

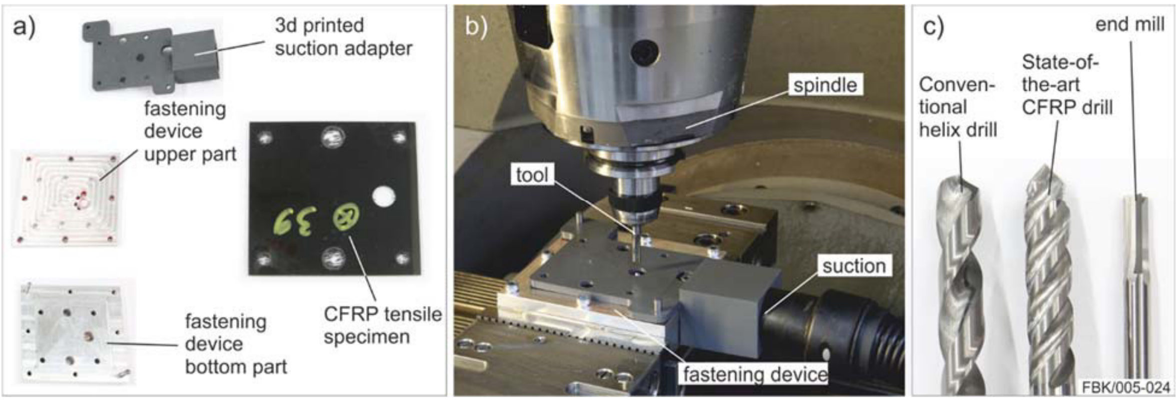

Fig. 1. a) Details fastening device; b) fastening device attached on 5-axis machining center; c) applied tools.

The conventional drilling process was representative for a non-optimized drilling process as a worst-case reference. The uncoated cemented carbide twist drills with a tool orthogonal rake angle $\gamma_0 = 30°$ had a diameter of 10 mm and drill point angle of $\sigma = 118°$. For the cutting edge radius each cutting edge of every tool was measured three times. Each measurement included 100 cross-sections. The average measured cutting edge radius was $r_\beta = 2$ µm (standard deviation was $\sigma_{r\beta} = 0.4$ µm) with a cutting edge form factor $K = 1$ before the machining [14]. The cutting parameters were $f = 0.03$ mm/rev and $v_c = 47$ m/min. The process conditions are listed in table 1.

Table 1. Drilling parameters (conventional drilling with twist drill)

Tool geometry parameters		Cutting parameters	
Tool diameter in mm	10	Feed in mm/rev.	$f = 0.03$
No. of major cutting edges	2	Cutting speed in m/min	$v_c = 47$
tool orthogonal rake angle in degree	$\gamma_0 = 30$		
drill point angle in degree	$\sigma = 118$		
Cutting edge radius in µm	$r_\beta = 2$		
Cutting edge form factor	$K = 1.0$		

For the state of the art drilling process uncoated cemented carbide step drills with a diameter of 10 mm were used. Those kinds of step drills are used for operation in industrial application and thus represent the prevailing quality of rivet holes. The steps allow the gradual increase of the hole diameter while the drill passes the CFRP. Thus, the load on the CFRP is reduced and hence the hole's damages. The tool orthogonal rake angle was $\gamma_0 = 30°$, the drill point angle $\sigma = 90°$. The radius of the cutting edge was $r_\beta = 3.4$ µm (standard deviation was $\sigma_{r\beta} = 1.0$ µm) and the cutting edge form factor was $K = 1$. The optimal process parameters $f = 0.08$ mm/rev and $v_c = 283$ m/min were specified by the drill manufacturer and are shown in table 2.

Table 2. Drilling parameters (CFRP-step drill)

Tool geometry parameters		Cutting parameters	
Tool diameter in mm	10	Feed in mm/rev.	$f = 0.08$
No. of major cutting edge	2	Cutting speed in m/min	$v_c = 283$
tool orthogonal rake angle in degree	$\gamma_0 = 30$		
drill point angle in degree	$\sigma = 90$		
Cutting edge radius in µm	$r_\beta = 3.4$		
Cutting edge form factor	$K = 1.0$		

The circular milling process was done in two steps. First step was machining a pre-drilled hole to 7 mm diameter with parameters assuring that resulting damages are smaller in diameter than the final diameter of 10 mm. The second step was the actual milling process, done by triple tooth end mills with a diameter of 6 mm. The end mills consisted of uncoated cemented carbide (WC + Cr_3Cr_2 + VC: 90 %; Co: 10 %; grain size: 0.6 µm) and were manufactured at the *Institute for Manufacturing Technology and Production Systems- FBK*. The milling tool's rake angle γ_0 is 10°. A constant helix angle of 0° in combination with the circular movement of the end mill in plate plane prevented forces in axial direction. Before the machining, the average cutting edge radius was $r_\beta = 2.7$ µm (standard deviation was $\sigma_{r\beta} = 0.5$ µm) with a cutting edge form factor $K = 1$ before the machining. The parameters of the milling process are summarized in table 3.

Table 3. Milling parameters.

Tool geometry parameters		Cutting parameters	
Tool diameter in mm	6	Feed in mm/rev.	$f = 0.03$
No. of circumference cutter	3	Width of cut in mm	$a_e = 0.1$
Helix angle in degree	0	Cutting speed in m/min	$v_c = 188$
tool orthogonal rake angle in degree	$\gamma_0 = 10$		
Cutting edge radius in µm	$r_\beta = 2.7$		
Cutting edge form factor	$K = 1.0$		

2.2. Investigation of hole quality / Analyses of hole quality

The investigation of the hole quality was done by analyzing the delamination, the fiber protrusion and the inner damages in the CFRP plates near the rivet hole.

The delamination was determined by the delamination factor $F_{d,}$ maximum diameter of delamination divided by hole diameter. F_d was measured optically using a light microscope. This light microscope was also used to determine the fiber protrusion, percentage coverage of the circular area of uncut fibers, while this was done by a self-developed MATLAB-routine [13]. F_d and the fiber protrusion were measured on 5 holes per machining strategy. The values shown in the results are the mean values over the 5 holes.

For the analysis of inner damages of the rivet holes a laboratory X-ray micro computed tomography (XCT) device with a 180 kV nano focus tube, a 2300 x 2300 pixel detector and a wolfram target was used. For all scans the pixel distance was 7.5 µm, the tube voltage was 100 kV and the measurement current was 80 µA. 1,800 pictures, each averaged from 5 frames, were taken with a recording time of 500 ms per frame for each scan. Commercial software was used for the reconstruction and analysis of the 3D volume.

2.3. Experimental characterization

The energy absorption during tensile failure of the riveted joint is highly influenced by the laminate layup and the drilling hole quality. The chosen layup is responsible for the occurring failure mechanism. Therefore a layup has been chosen to prevent shear, cleavage or flank-tension fracture in order to achieve bearing load failure with constant repeat accuracy [15]. To prove the correlation between of the drilling hole quality and the energy absorption capabilities experimental tests have been carried out with a tension testing machine by IVW GmbH. A constant testing speed was used to reduce the influence on the tensile strength of the material through strain rate effects [15]. Therefore, a test jig has been designed and manufactured (see Fig. 2). The CFRP plate with the machined rivet hole was attached between clamping jaws to prevent relative motion during the experiment. This is realized by applying equivalent calming pressure around the pin hole. Furthermore it is necessary to meet a minimum distance between the claming and the measuring region to not influence the test results. FEA tools helped to find a suitable design to solve this problem. A CFRP slipknot was used to pull a steel bolt through the laminate which represents the desired load case. The slipknot allowed an unhindered view on the failure region around the bolt when damage occurred. The longitudinal tension forces were recorded by using a strain-gauge-load cell on the lower mounting point. The movement of the bolt through the laminate was evaluated by using an image based tracking algorithm. For each variation of the drilling hole quality 3 samples have been tested. The amount of the trigger force provided information on the strength of the rivet connection.

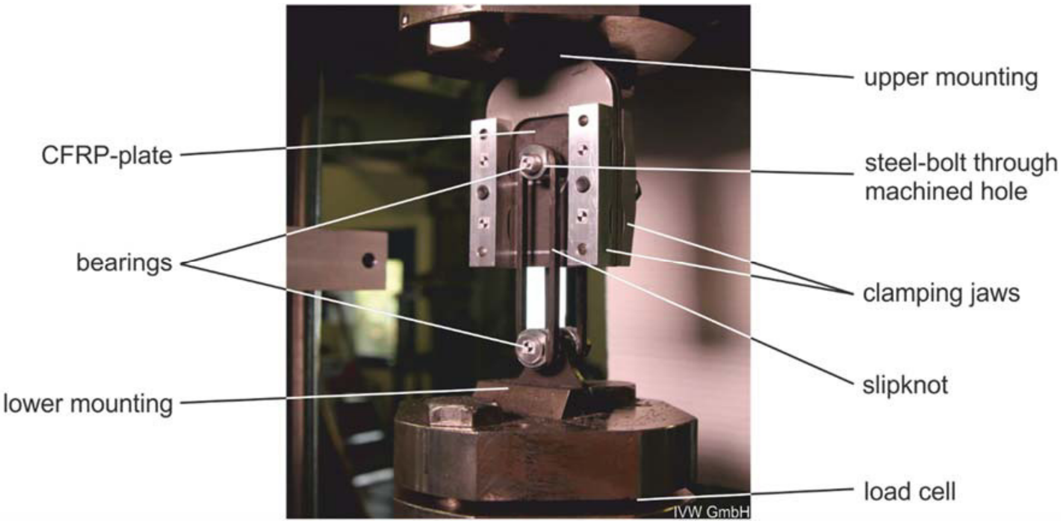

Fig. 2. Tension testing machine with attached test jig.

3. Results

It has been found that the different machining processes - conventional drilling with a twist drill, drilling with a state-of-the-art CFRP-drill, and circular milling - have resulted in different qualities (see Fig. 3) and trigger forces, representing different connection strengths.

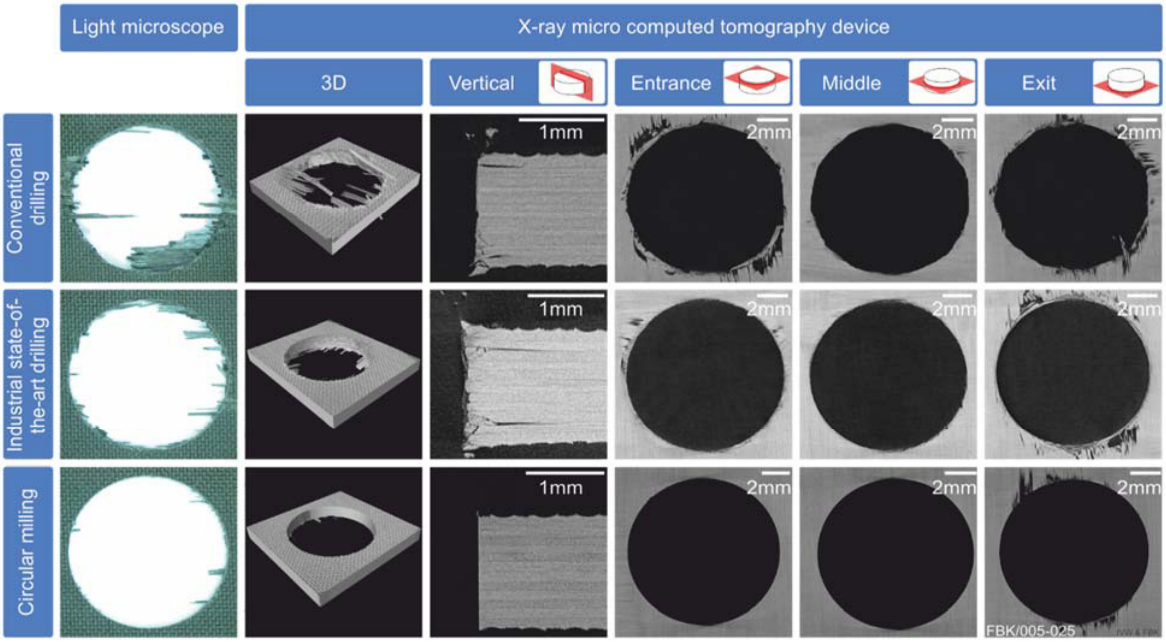

Fig. 3. Overview of the rivet hole qualities machined by different processes.

Drilling with conventional helix drills produced rivet holes which have the highest delamination factor F_d and fiber protrusion (see Fig 4 b). Because of the unfavorable geometry like the tool orthogonal rake angle γ_0, the fibers were pulled up contrary to the feed direction. This caused a flaking of the CFRP plate's uppermost layers → peel-up delamination. When the drill point exited the CFRP plate, the feed forces effected a flanking of the lower layers of the CFRP plate → push-out delamination. Both effects, peel-up and push-out delamination led to a higher delamination factor F_d compared to the other machining processes investigated in this paper, see Fig. 4 b). The relatively large drill point angle $\sigma = 118$ ° resulted in an unfavorable position from the cutting edge to the fiber. That means the angle between carbon fiber and cutting edge was large and thereby nearly parallel when the drill point angle is large. This fact led to a larger contact length between fiber and cutting edge, which reduced the ability to cut the fiber. Therefore, the fiber protrusion was higher than for the other machining processes.

The rivet holes, machined by a state-of-the-art CFRP-drill, exhibited a lower delamination factor F_d and less fiber protrusion than the rivet holes machined by a conventional helix drill. The smaller drill point angle, the steps and other optimizations (see Fig. 4. b) led to favorable cutting behavior. Moreover, this process was the fastest and thus the most cost-effective process.

The circular milling process needed pre-drilling, whereby it had to be ensured, that the delamination diameter was smaller than the final diameter of the rivet hole. The end mill's constant helix angle of 0° prevented forces in axial direction, thus a delamination could be largely prohibited [13]. Also, the beneficial angle between cutting edge and fiber led to low fiber protrusions, see Fig. 4 b).

The results for the delamination factor measured by light microscope were confirmed by XCT analysis. Fig. 3 shows clearly the peel-up and push-out delamination for the drilled holes. The results of [10] showed that F_d measured by light microscope is sufficient for the evaluation of bore hole quality. But it is clearly visible in the vertical view of Fig. 3 that the bore hole walls of the drilled holes had a poor quality compared to the milled hole.

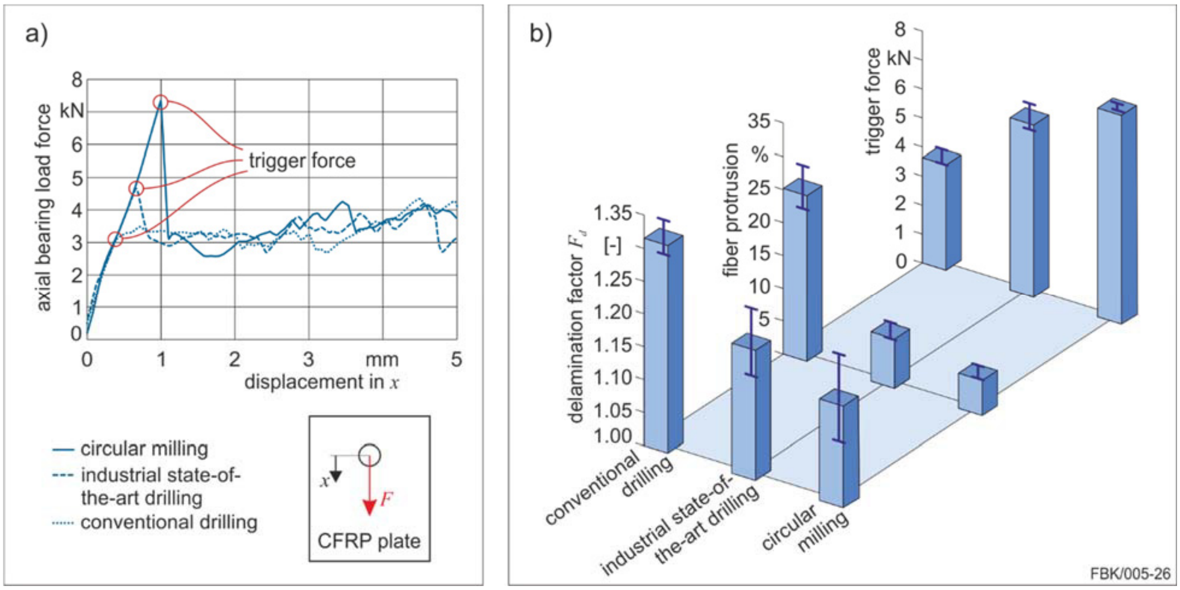

Fig. 4. a) Influence of the machining process on the trigger force (one measurement); b) Delamination factor, fiber protrusion and trigger force based on the machining processes (mean value).

The experimental results show a clear dependence of the drilling hole quality to the trigger force. The shearing and the hole bearing's measured trigger force were influenced by any kind of triggering mechanism. Delamination within the CFRP plate, induced by the drilling process, lowered the axial tensile strength of the hole and implanted an initial crack at the bore edge. This kind of localized damage behaved like a trigger under high bearing stresses.

4. Conclusion and Outlook

In this paper, the influence of three machining strategies on the rivet hole quality and ultimately on the corresponding strength of the rivet connections was examined. The quality of the rivet holes was investigated by means of delamination and fiber protrusion. The strengths of the connections were compared by the trigger force in a tensile test.

For the drilling processes, the delamination factor was high, because of the movement of the drill tools in spindle axis direction which causes feed forces. In addition, the helix angle leads to an up pealing of the fibers. The unfavorable angle between the cutting edge and the fibers resulted in uncut fibers and thus in a higher fiber protrusion. In the milling process there was no movement in spindle axis direction and hence no force in the same. Also the helix angle of 0 ° prevented any force in spindle axis direction. The tensile tests proved that the strength of the rivet connection correlated directly with the rivet hole quality. The trigger force was influenced by the delamination within the CFRP plate, which acted as a triggering mechanism whilst the damages on the hole implanted initial cracks at the rivet hole edge.

In future investigations the influence of different weakening geometries near the rivet hole on the crash behavior will be investigated.

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