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Quality of drilled and milled rivet holes in carbon fiber reinforced plastics

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Abstract

In this paper, a conventional drilling process and a circular milling process are compared with respect to delamination and fiber protrusion when machining carbon fiber reinforced plastics (CFRP). The tool design (tool orthogonal clearance, drill-point angle) and the parameters (feed rate, cutting speed) are varied when drilling. The axial feed force and the spiral angles of the cutting edges can cause damages to the CFRP when circular milling. In this study, the possibilities to reduce those errors by the application of end mills with no spiral angle at the circumference cutter and no feed in axial direction are investigated. This milling process requires pre-drilled holes, and the final rivet hole dimension is then machined by circled movements without any motion in axial direction. For this special circular milling process, the tool design (rake angle of the circumference cutters) as well as the setting parameters (depth of cut, feed rate, cutting speed, up and down milling) are varied. The machining quality of both processes is compared. This is done by measuring the delaminations using an optical microscope. The fiber protrusion are visually identified with the help of an adapted imageprocessing algorithm. The diameters of the rivet holes are measured on two planes of the hole by a coordinate measuring machine. The cylindricity of the holes is determined using an instrument for roundness measurement.

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Keywords:drilling, milling, fiber reinforced plastics

1. Introduction

Due to its beneficial stiffness to mass ratio, carbon fiber reinforced plastics (CFRP) are increasingly used for aerospace applications and automotive, first of all for electronic vehicles [1]. Those materials are often linked with rivet hole connections. The machining of rivet holes in CFRP can result in damages like delamination or fiber protrusion. Those damages of the rivet holes strongly influence the strength of the connections, as they weaken the material structure [2-4]. Consequently, the machining strategy to avoid those damages is of great importance for the application of CFRP.

Laser machining of CFRP can result into thermal damage (micro-cracks, voids, delamination) due to the high process heat [5,6]. Although recent work successfully investigated possibilities of combined laser machining and drilling [7], material removal processes are commonly used to produce the holes in CFRP. In [8] it was shown that the quality of drilled holes is highly influences by the drill-point angle, while there is a conflict between lower delamination at the hole entrance and higher delamination at the holes exits with increasing point angles. Orbital milling, as described in [9], was shown to be a promising alternative to produce high quality holes in CFRP [10].

In this paper, a conventional drilling process and a circular milling process are compared with respect to dimensional accuracy, delamination and fiber protrusion when machining CFRP.

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2. Experimental Setup

The CFRP investigated in this paper consisted of 12 layers [0°, 90°, 0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°, 90°, 0°]. The individual layers were consolidated with epoxy (duroplastic matrix) in an autoclave, resulting in thicknesses of the CFRP-plates of 1.5 to 2 mm with fiber contents of 60 Vol.-%.

For both machining processes drilling and milling the CFRP plate was fixed in a fastening device, see Fig. 1(a). The device provided bores on the same location than the rivet holes but with diameter 12 mm to retain the plate against appearing axial forces, see Fig. 1(b). The fastening device was applied on the 5-axis machining centers table. Occurring dusts and chips were aspirated with a suction.

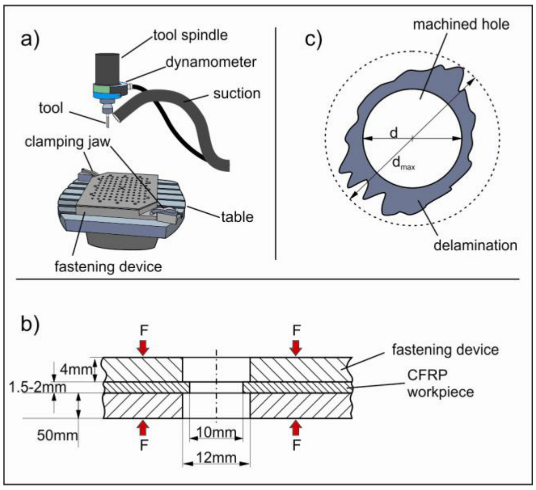

Fig. 1. (a) experimental setup; (b) cross section of fastening device; (c) measuring delamination factor.

For the drilling process, cemented carbide twist drills with a diameter of 10 mm were manufactured at the institute for manufacturing technologies and production systems (FBK). The geometry of the drills was varied with respect to drill-point angle (90°/130°/170°) and tool orthogonal clearance (6°/10°/14°), each with a helix angle of 30°, resulting in nine different tool geometries. The cutting edge radius' arithmetic average was 7,2 µm before the experiments. For all nine tools, a full factorial variation of cutting speed (50/150/250 m/min) and feed (0.02/0.10/0.18 mm/rev) was examined (Table 1). Every parameter combination was repeated three times. The hole pattern was randomly chosen to exclude the influence of tool wear.

Table 1. Drilling parameters.

Tool geometry parameters			
Tool diameter in mm	10		
Drill-point angle in degree	$\sigma_1 = 90$	$\sigma_2 = 130$	$\sigma_3 = 170$
Tool orthogonal clearance in degree	$\alpha_{o1} = 6$	$\alpha_{o2} = 10$	$\alpha_{o3} = 14$
Cutting parameters			
Feed in mm/rev.	$f_1 = 0.02$	$f_2 = 0.1$	$f_3 = 0.18$
Cutting speed in m/min	$v_{c1} = 50$	$v_{c2} = 150$	$v_{c3} = 250$

The triple tooth end mills with a diameter of 6 mm were also manufactured at Institute for Manufacturing Technology and Production Systems FBK. For the examined orbital milling process, targeting at a final diameter of 10 mm, the holes were pre-drilled to 8 mm diameter with parameters that assure damages smaller than the final diameter. The geometry was varied with respect to rake angle (0°/10°/20°) with a constant helix angle of 0°, to prevent forces in axial direction. The radial depth of cut, the feed and the cutting speed were varied according to a central composite statistical design CCD (Table 2). By using CCD, only the designs center point is repeated. For this reason there are no error bars for the lowest and highest values. Similar to the drilling experiments, the hole pattern was randomly chosen to exclude the influence of tool wear.

Table 2. Milling parameters.

Tool geometry parameters			
Tool diameter in mm	6		
No. of circumference cutter	3		
helix angle in degree	0		
Tool orthogonal rake angles in degree	$\gamma_{o1} = 0$	$\gamma_{o2} = 10$	$\gamma_{o3} = 20$
Cutting parameters			
Feed in mm/rev.	$f_1 = 0.03$	$f_2 = 0.13$	$f_3 = 0.23$
width of cut in mm	$a_{e1} = 0,1$	$a_{e2} = 0,3$	$a_{e3} = 0,5$
Cutting speed in m/min	$v_{c1} = 10$	$v_{c2} = 99$	$v_{c3} = 188$

The process was monitored by recording forces using a piezoeletronic dynamometer. The process result was evaluated by means of delamination factor and fiber protrusions. The delamination factor F_d at the surface (maximum diameter of delamination d_{max} devided by hole diameter d, see Fig. 1(c)) was determined optically using a light microscope. The same light microscopic images were used to determine the fiber protrusion, while this was done by a self-developed MATLAB-routine. The algorithm to detect the fiber projection is schematically shown in Fig. 2. After binarisation of the original image, a sobel operator is applied for edge detecting. The resulted edge image is used to find the drilling hole by using a circle hough-transformation. With this algorithm the center and the diameter of the hole can be detected [11]. The binary image and the detected drilling hole are logically combined to measure the fiber projection.

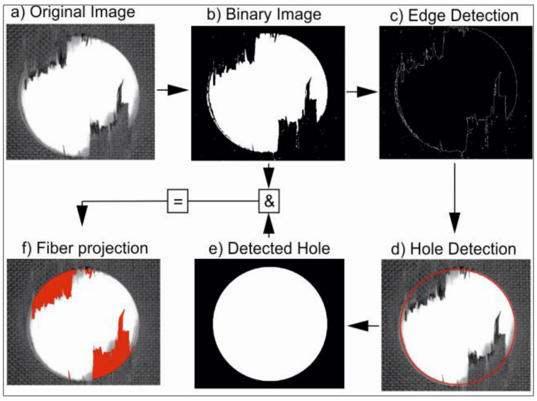

Fig. 2. Image processing algorithm.

3. Results and Discussion

3.1. Drilling

The axial feed force is shown in Fig. 3. It can be seen that the drill-point angle has a strong influence on the feed force. Increasing angles result into increasing forces. This could be led back to the fact that larger parts of the cutting edges are engaged in the workpiece, which means that there is a higher contact length. At a smaller drill-point angle, the drill point has already left the workpiece when the drills full width is in contact.

The cutting edge radius' arithmetic average was 13,1 µm after the experiments.

The tool orthogonal clearance has no clear influence on the axial feed force. On drill-point angle 90° and 130° the tool orthogonal clearance of 10° causes the lowest force. This changes for the drill-point angle of 170°. Here the tool orthogonal clearance of 14° leads to the lowest feed force.

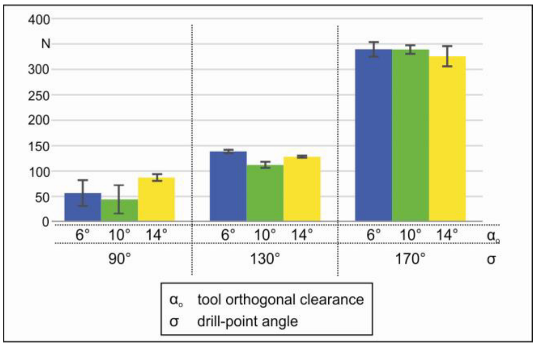

Fig. 3. axial feed force when drilling at $v_c = 150$ m/min and f = 0.1 mm.

The delamination in dependence of the three drill-point angles while changing the tool orthogonal clearances is shown in Figs. 4, 5 and 6. In Fig. 4 it is shown, that at a cutting speed of $v_c = 50$ m/min the delamination increases with the increase of the drill-point angle. This trend is less clear in Fig. 5 ($v_c = 150$ m/min) and Fig. 6 ($v_c = 250$ m/min), but here too the highest delamination occurs at the maximum drill-point angle of 170°. This can be led back to rising feed forces at large drill-point angles, compare Fig. 3. Higher axial forces lead to higher stresses at the CFRPs lower layers resulting in a higher delamination factor. Comparing the different cutting speeds, the delamination grows, but imperceptibly. The tool orthogonal clearance and the feed do not show any clear trend.

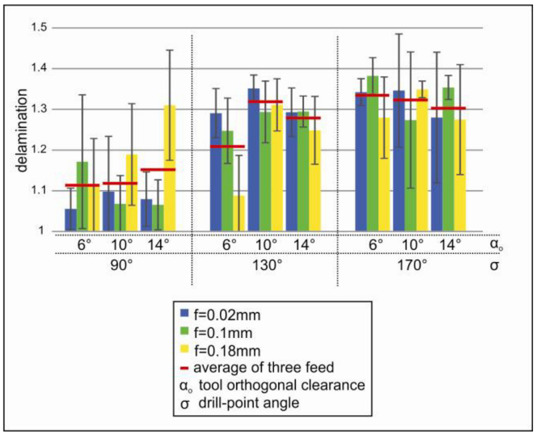

Fig. 4. delamination when drilling at $v_c = 50$ m/min.

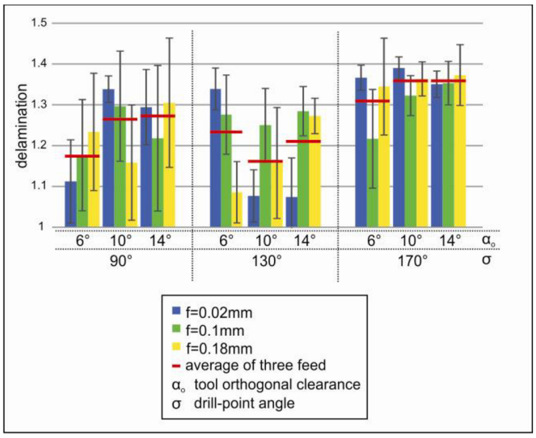

Fig. 5. delamination when drilling at $v_c = 150$ m/min.

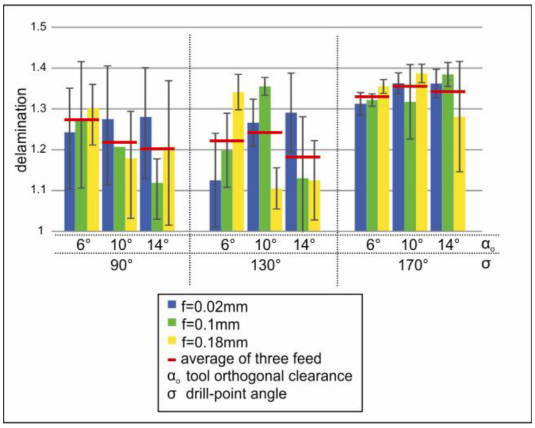

Fig. 6. delamination when drilling at vc = 250 m/min.

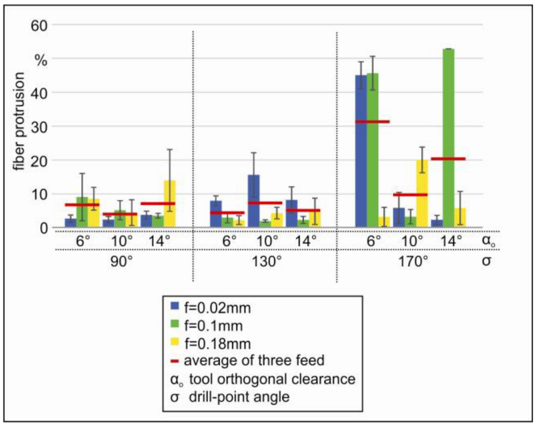

Fig. 7. fiber protrusion when drilling at v_c = 50 m/min.

The influence of the tool geometry (drill-point angle and the tool orthogonal clearance) as well as the influence of feed and cutting speed on the resulting fiber protrusion is shown in Figs. 7, 8 and 9.

It can be seen, similar to the delamination, that the fiber protrusion is highest for the largest drill-point angle. One reason could be the higher feed force. The drill pushes the fiber down instead of cutting it until the elasticity limit is exceeded, but at that time, fibers possibly already broke out of the matrix. In addition, the cutting edge is nearly parallel to the fiber when the angle is at 170° in contrast to the drill-point angle of 90°, hampering the already broke out fibers to be cut.

When machining with v_c = 150 m/min and 250 m/min, the 130° drill-point angle leads to the lowest fiber protrusion. It seems that this angle is a good balance between point contact (low angles) and line contact (large angles) with respect to fiber cutting conditions. More angles have to be examined to get more conclusive results.

For all cutting speeds the variation of the tool orthogonal clearance as well as the feed causes randomly an increase or decrease of the fiber protrusion and hence no clear trend can be concluded.

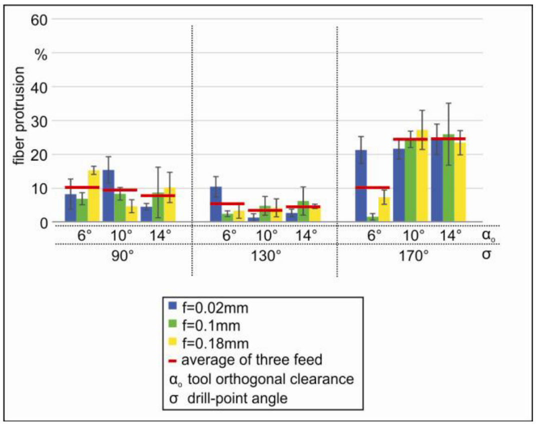

Fig. 8. fiber protrusion when drilling at v_c = 150 m/min.

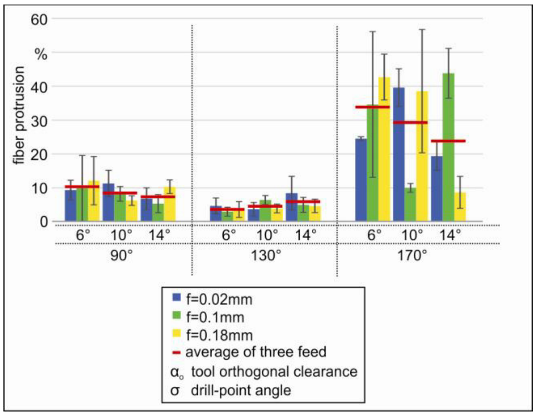

Fig. 9. fiber protrusion when drilling at v_c = 250 m/min.

3.2. Milling

The delamination while milling CFRP with different parameters is shown in Fig. 10-12. Fig. 10 demonstrates the influence of the width of cut a_e. For $a_e = 0.1$ mm no delamination appears (delamination factor = 1). Lower width of cuts result into lower loads affecting the CFRP and hence in reduced delamination.

In Fig. 11 the influence of cutting speed v_c on the delamination is shown. The lowest factor appears at the highest cutting speed. In contrast to the drilling process, the end mill is in full contact all time (depth of cut is the plate thickness), as pre-drilled holes were milled. In combination with the applied helix angle of 0° (negligible axial force), higher cutting speeds result into better cutting conditions and less deformations.

Fig. 12 shows the influence of the feed on delamination. A smaller feed leads to less delamination. Higher feeds result into more material removed per rotation and hence higher loads, highly influencing delamination.

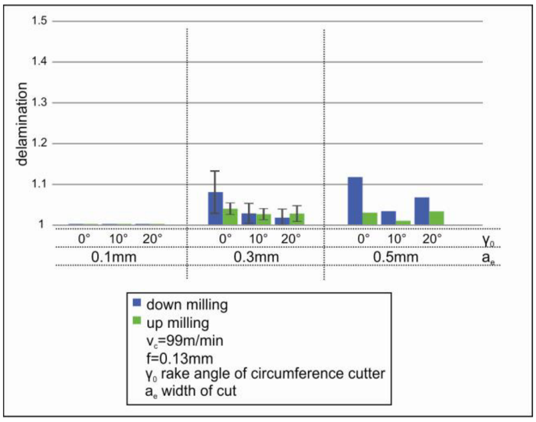

Fig. 10. influence of width of cut a_e with constant v_c and f while milling.

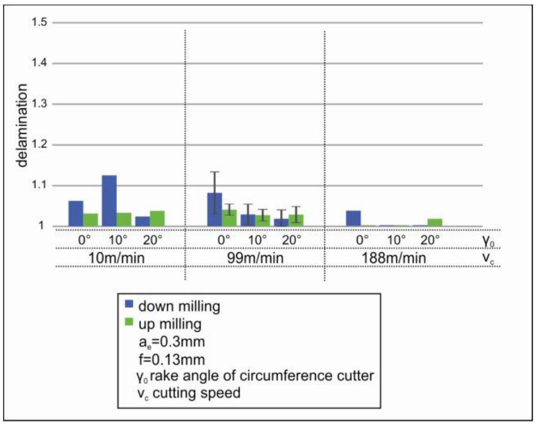

Fig. 11. influence of cutting speed v_c with constant a_e and f while milling.

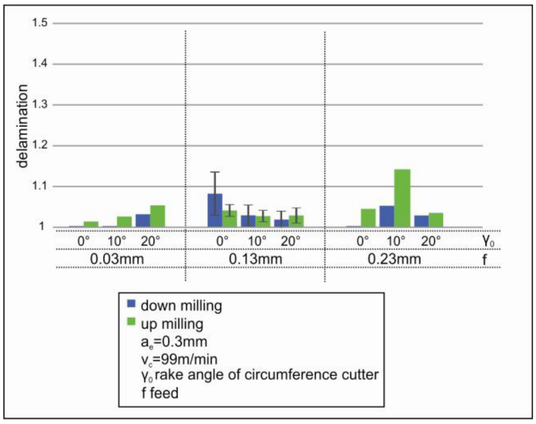

Fig. 12. influence of feed f with constant a_e and v_c while milling.

The results depicted in Figures 10-12 do not allow to make a clear statement on the influence of up and down milling or the variation of the rake angle of the circumference cutter.

The fiber protrusion is shown in Figure 13-15. The lowest protrusion appears at the least width of cut a_e and the highest cutting speed. The variation of feed has a weak influence on the fiber protrusion, however the highest value appears at the highest feed.

Those results correspond to the delamination results. Lower depths of cut result into lower deformations and hence lower fiber deflections in the preliminary deformation zone. Higher cutting speeds result into less deformation and better cutting conditions. Higher feeds result into higher loads and hence cause a "push away" or deflection of the fibers instead of cutting them.

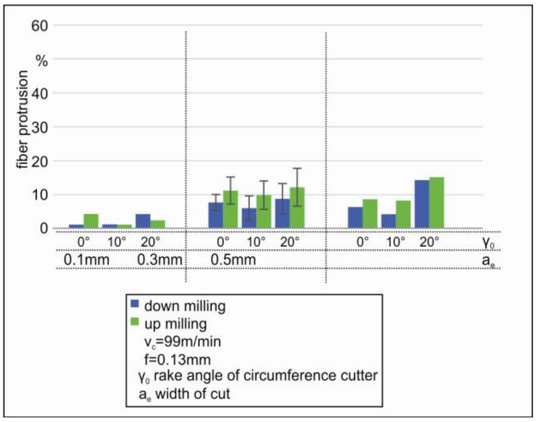

Fig. 13. influence of width of cut a_e with constant v_c and f while milling.

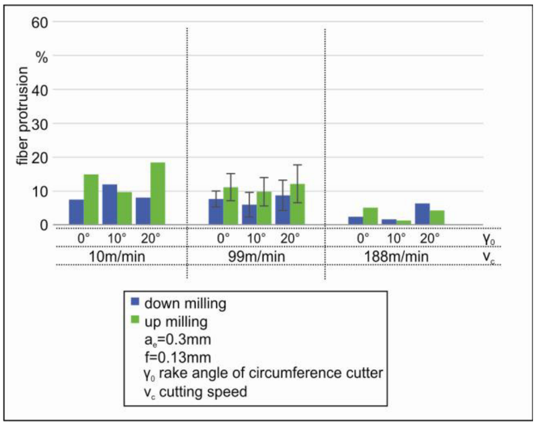

Fig. 14. influence of cutting speed v_c with constant a_e and f while milling.

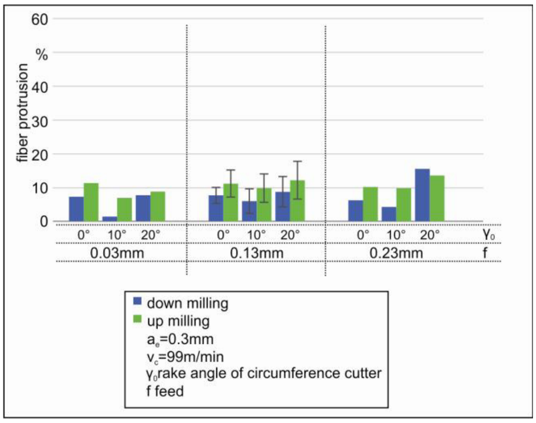

Fig. 15. influence of feed f with constant a_e and v_c while milling.

4. Conclusion and Outlook

In this paper, drilling and orbital milling of CFRP was examined, applying different tool geometries. The quality of the holes were evaluated by means of delamination and fiber protrusion, where a self-developed MATLAB routine was used.

For the drilling process, the drill-point angle was identified to have the highest influence on the quality. A high angle is unfavorable as a result of higher axial forces and cutting edge contact.

The orbital milling was executed in pre-drilled holes to achieve a full contact in axial direction. In combination with helix angles of 0°, this resulted in comparably good cutting conditions, achieving considerably better qualities than the drilling process. The rake angle as well as up and down milling mode did not show a clear influence, while high cutting speeds at low widths of cut were favorable.

In future investigations the influence of the hole quality on the crash behavior of rivet joints will be investigated.

Acknowledgements

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