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Procedia CIRP 1 (2012) 471 – 476
www.elsevier.com/locate/procedia

5th CIRP Conference on High Performance Cutting 2012

Influence of Point Angle on Drill Hole Quality and Machining Forces when Drilling CFRP

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Abstract

This paper presents the results of investigations concerning the influence of the point angle of a drill tool and increased cutting speeds on machining forces and drill hole quality (delamination, fraying, burr formation). Elevated point angles result in increased feed force F_f while the drilling torque T_d stays almost constant. The assessment of characteristics concerning drill holes show that the quality at the entrance is best when using point angles > 180°, while it is poor at the exit. The increase in cutting speed leads to almost no differences in drill hole quality but does lead to rising feed forces and decreasing drilling torques.

Keywords: Drilling; Composite; Quality; Tool design; CFRP

1. Introduction

With the increasing need for lightweight design, carbon fiber reinforced plastic (CFRP) has entered several new markets. In the past CFRP was used mainly in the aerospace industry and the leisure industry, whereas nowadays it is also used in the automotive and the wind energy industry [1].

Despite its numerous advantages like high specific strength and stiffness there are various problems, e. g., in machining. One of the most common machining processes is the drilling of holes for the jointing of CFRP components [2]. The disadvantages when drilling CFRP are tool wear and material-specific degradations. The most common damage of the drill hole is delamination, which can be evaluated with the delamination factor [3]. But there are several other degradations like burr formation, fiber and fiber bundle pull-outs, thermal damaging, fiber fracture, failure in surface integrity and fraying [4, 5, 6, 7, 8, 9]. Figure 1 shows three typical material-specific damages.

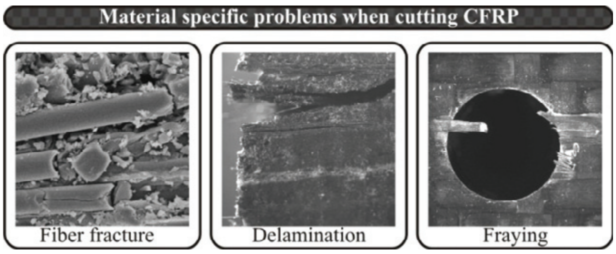

Fig. 1. Material specific damages [9]

Several researchers conducted experiments to prove the influence of tool design on machining CFRP. Abrao et al. arrived at the conclusion that the “Brad & Spur“ drills obtained the best results concerning mechanical loads and drill hole quality because of the initial cutting at the drill hole wall [10]. Hocheng and Tsao analyzed in their works done in 2003, 2005 and 2006 the critical thrust force at the beginning of delamination. They compared five different drill types: a twist drill, a candle stick drill, a saw drill, a core drill and a step drill. For these types of drilling tools an analytical model was developed to predict the critical thrust force. To prove this theoretical model, further experimental

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investigations were conducted. The results show that the type of drilling tool has a significant influence at the onset of delamination. The best results concerning delamination were achieved with the core drill while the twist drill achieved the poorest results [11, 12, 13]. Also Faraz et al. and Marques et al. examined the influence of various drill types on mechanical loads, drill hole quality or the tool wear [14, 15]. Shyha et al. analyzed in 2009 the effects in drilling CFRP with small drilling diameters (1.5 mm). They used cemented carbide twist drills and step drills with varying point angles (118° and 140°) and helix angles (24° and 30°) at different process parameters. The results showed that uncoated step drills at high feed rates produced the best results concerning tool life but result in maximum delamination. The influence of the point angle concerning tool life, thrust force and delamination is not significant [16].

Concerning the drilling of CFRP with higher cutting speeds, Lin and Chen did some investigations in 1996. They analyzed the influence of cutting speed (210 m/min, 530 m/min and 850 m/min) on thrust force, drilling torque and tool wear. The results show that with increasing cutting speeds v_c at constant feed rates f thrust force and tool wear are increasing, while moment stays almost constant [17]. Campos et al. analyzed the influence of different tool types on delamination at cutting speeds up to 628 m/min. They draw the conclusion that the influence of feed rate f on delamination is reduced at elevated cutting speeds [18].

To reduce the disadvantages when drilling CFRP the drilling parameters and the tool design have to be adjusted to the challenges of this material [19]. The aim of this paper is to present the results of the investigations into the influence of point angle and drilling parameters on drill hole quality and drilling forces.

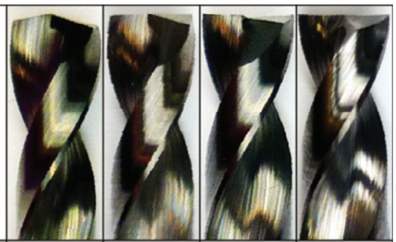
2. Experimental Setup

2.1. Work Piece Material

The material used in the tests is CFRP, consisting of an epoxy matrix system reinforced by HT (high tenacity) carbon fibers. The laminate has a fiber volume content of about 55%, a thickness of 9 mm, a tensile strength (0°/90°) of 800 MPa and a Young´s modulus of 67 GPa in the same direction. The weave type, the carbon fibers are placed into the matrix, is a 4H Satin.

2.2. Drilling Tools

The applied tools are made of cemented carbide with a hardness HV30 of about 1600 N/mm² and the same tool geometry except for the angles at the main cutting edge and the point angle, which can be seen in Figure 2. The angles at the cutting edge are measured in the cutting edge normal plane.



Name of tool	T1	T2	T3	T4
Point angle [°]	155	175	185	185/178
Rake angle [°]	31	31	31	31
Clearance angle [°]	7	8	7	6
Wedge angle [°]	52	51	52	53
Cutting material	Cemented Carbide			

Fig. 2. Characteristics of used drilling tools

The point angles are 155° for tool T1, 175° for tool T2, 185° for tool T3 and 185° with a center tip of 178° for tool T4. The differences in the angles on the main cutting edge are a result of the variation of the point angles and differ only in a small range. The shown angles are measured on the tool nose. All the used drilling tools have a diameter of $D = 6.8$ mm. As the wear progress is 5th CIRP Conference on High Performance Cutting 2012in a small range (cutting edge rounding up to 10 µm at the end of the test series), the same tools were used for one test series.

2.3. Machining Tests

The cutting tests were performed on a machining center of the type Ex-Cell-O XHC 241. Figure 3 shows the machining center and its technical details.

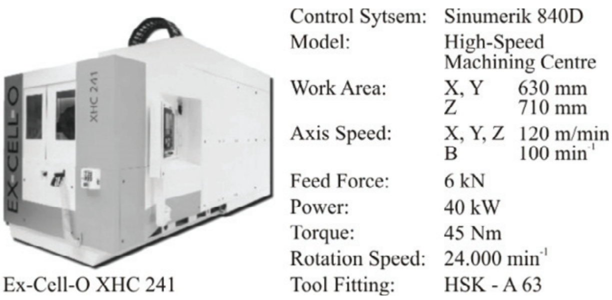


Fig. 3. Test machine Ex-Cell-O XHC 241

The feed forces and the drilling torques were measured with a rotating dynamometer of Kistler company. The images to calculate the delamination factor F_d and the fraying were taken with a stereomicroscope (Leica MZ6). The burr height was measured with a Keyence laser triangulation sensor and evaluated with a self-designed software tool. Fig. 4 illustrates the delamination factor F_d and the measurement of the burr height h_0.

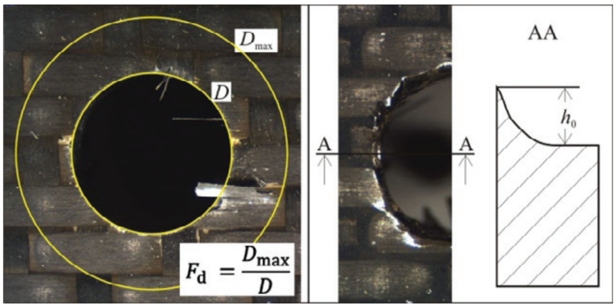


Fig. 4. Delamination factor F_d and burr height h_0

The experiments concerning the variation in point angle were conducted with the following parameters, which can be seen in table 1. As the feed is the critical parameter in drilling CFRP, only the feed was varied. Due to former tests, the cutting speed was remained constant at a low level to achieve clear signals while drilling.

Table 1. Parameters for the investigation into point angles

Parameter	Range					
f [mm]	0.05	0.10	0.15	0.20	0.30	0.40
v_c [m/min]			42.7			

The investigations concerning the variation in the process parameters, mainly the cutting speed v_c, were conducted with the following parameters (see Table 2).

Table 2. Parameters for the investigation into cutting speeds

Parameter	Range						
f [mm]	0.10		0.15		0.20		
v_c [m/min]	21	43	64	85	128	171	214
	256	299	342	385	427	470	513

All experiments were conducted without coolant.

3. Results and Discussion

At the beginning the influence of the point angle σ on drilling forces as well as on delamination, fraying and burr height is presented. Afterwards the influence of elevated cutting speeds v_c and feed rates f are analyzed. The intention in applying a tool geometry like T4 (point angle $\sigma > 180°$) is to cut the material at first with the outer area of the cutting tool. Hence the primary cutting of the CFRP, especially the carbon fibers, takes place at the drill hole wall. At this time the fibers are still embedded in the matrix material and thus the prestress of the fibers is maximal. This should lead to a definite cut of the fiber at the drill hole wall and thus to an improved quality in the peripheral zone of the drill hole.

Figure 5 depicts the feed forces F_f obtained when drilling with the four tools.

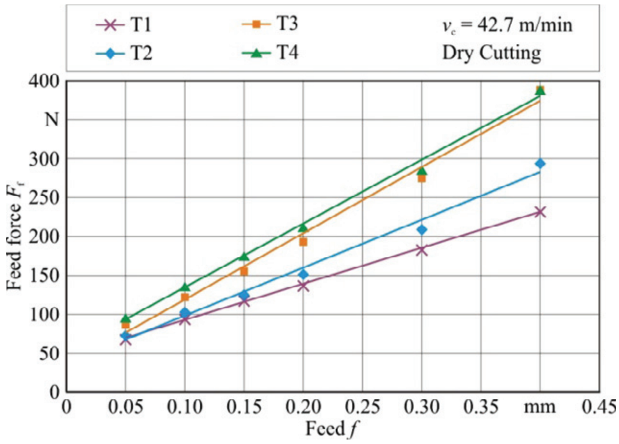


Fig. 5. Feed force F_f at varying point angles

The comparison of the four tools in fig. 5 show that T1 and T2 possess almost the same trend and produce the smallest feed force F_f. Higher feed forces F_f are achieved when using tools T3 and T4, which also have quite the same trend. Hence the conclusion can be drawn that with the rise of the point angle also the feed forces F_f increase. The drilling torque T_d shown in Figure 6 displays the same trend.

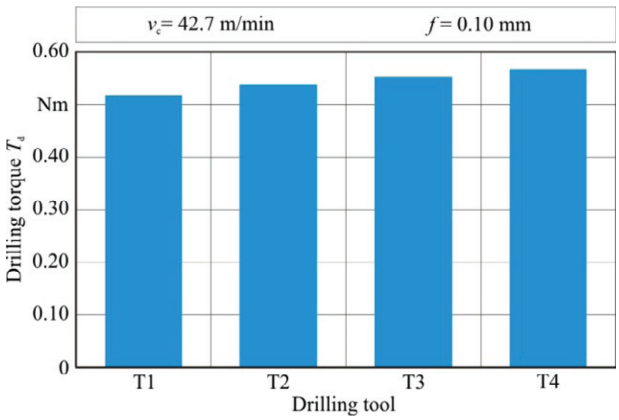


Fig. 6. Drilling torque T_d for tools of different point angles

As shown in Fig. 6, the difference in the amount of drilling torque T_d of the tools T1 to T4 is only marginal. The same can be seen at the range of parameters analyzed. In contrast to the drilling torque, delamination is strongly affected by the point angle. Fig. 7 depicts the delamination factor F_d at the drill hole entrance and exit of the drilling tool when using T1 to T4. The selected parameters are a feed rate of $f = 0.05$ mm and a cutting speed of $v_c = 42.7$ m/min. The bold line at value 1.00 of Fig. 7 is the minimal value which can be achieved when using the delamination factor F_d according to Chen.

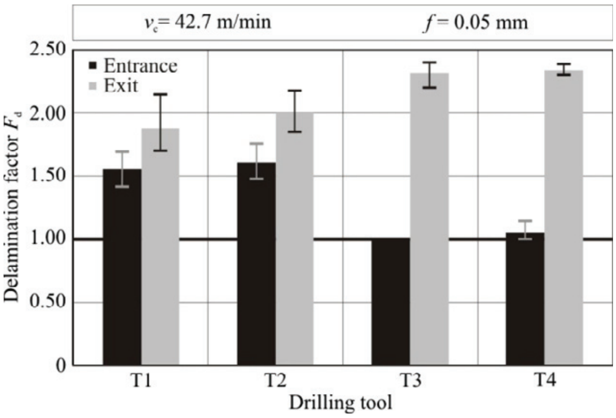


Fig. 7. Delamination factor F_d at the drill hole entrance and exit

It can be seen that the point angle has great influence on the delamination factor F_d. At the entrance T3 and T4 attain the best results due to their point angle $\sigma > 180°$. This point angle cuts at first the fibers and the matrix at the drill hole wall and therefore leads to best results regarding delamination at the entrance. Due to the greater chip thickness and the higher forces at the outer area of the tools T3 and T4, the results at the exit are poor. Quite the opposite can be detected when looking at the tools T1 and T2. These tools achieve better values at the exit but lead to increasing delamination factors F_d at the entrance.

The images of the drill holes and the peripheral zone (Fig. 8, 9) show the fraying and the delamination. Figure 8 shows the drill hole quality at the entrance.

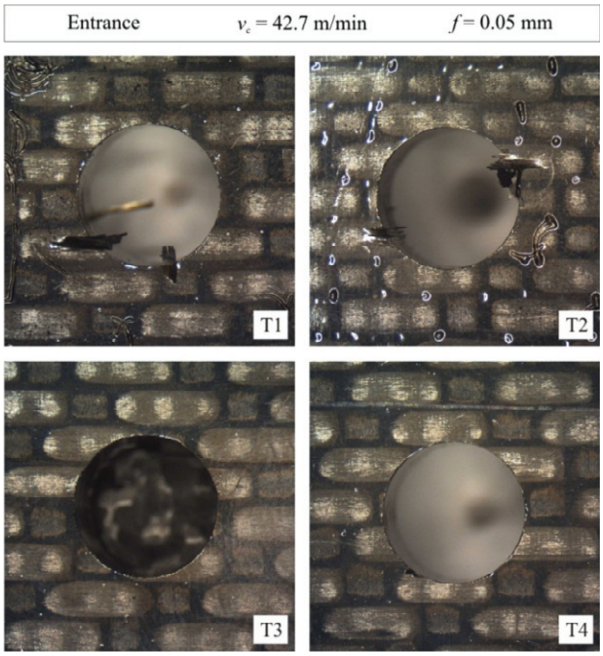


Fig. 8. Drill hole quality at the entrance of the drill (D = 6.8 mm)

The images of the drill hole entrance manufactured with the tools T1 to T4 with a cutting speed of $v_c = 42.7$ m/min and a feed rate of $f = 0.05$ mm show visible differences. While the tools T1 and T2 generate fraying at the drill holes, the tools T3 and T4 lead to no fraying and delamination because of the initial cutting at the drill hole wall. The drill hole quality at the exit with the same parameters is different (see Figure 9).

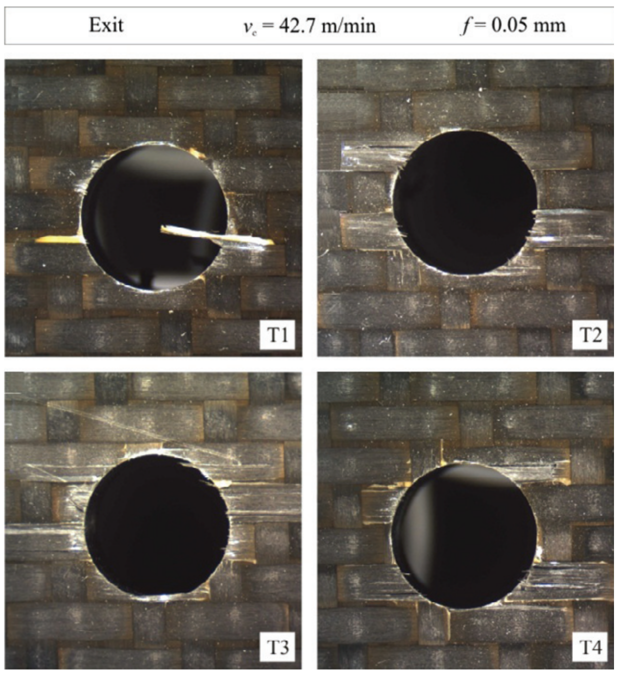


Fig. 9. Drill hole quality at the exit of the drill (D = 6.8 mm)

Concerning fraying, the result at the exit is almost the same. While T1 produces an apparent amount of fraying, this amount is clearly reduced when using T2 to T4. However, there are disadvantages as well when using the tools with elevated point angles (T2 to T4). These types of drilling tools lead to a drastic increase in delamination at the exit, which can also be seen in figure 7. Another problem when applying tools with point angles $\sigma \approx 180°$ is the tendency to form a lid or cap. In the presented results, T1 produced no lid while T2 produced a lid in 16.7% of the produced holes. The amount of lids rose with T3 to a maximum of 30%. To reduce this effect, tool T3 (point angle $\sigma = 185°$) was applied with a center tip (178°) to cut the material at the inner area as well. The applied center tip (tool T4) leads to a reduction down to 23.33%.

Another problem is burr formation, which seems to be linked to delamination and fraying. Moreover it is sometimes difficult to differ between these criterions. Figure 10 shows the measured values of the burr height h_0 and the best-fit curves at the entrance at varying feed rates f generated with the four drilling tools.

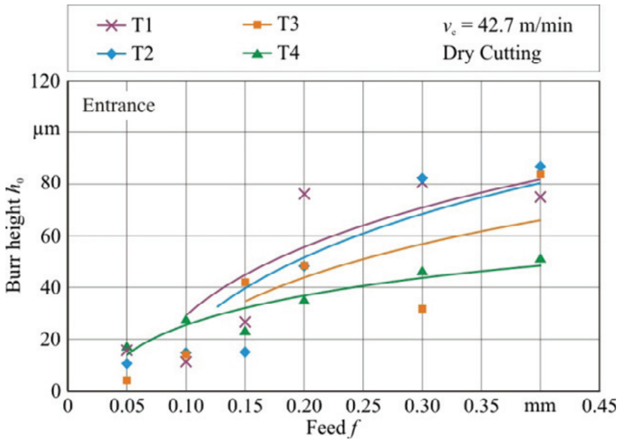


Fig. 10. Burr height h_0 at the entrance

To find a clear trend when analyzing the burr height h_0 is quite hard because of problems at the measurement and the irregular burr formation due to the connection to fraying and delamination. At low feed rates the burr height produced with the four tools is quite similar and the amounts are rising with increasing feed rates due to the greater displacement of the material. Only at elevated feed rates, tool T4 has an advantage over the others. At the exit, the results are different (cf. Fig. 11).

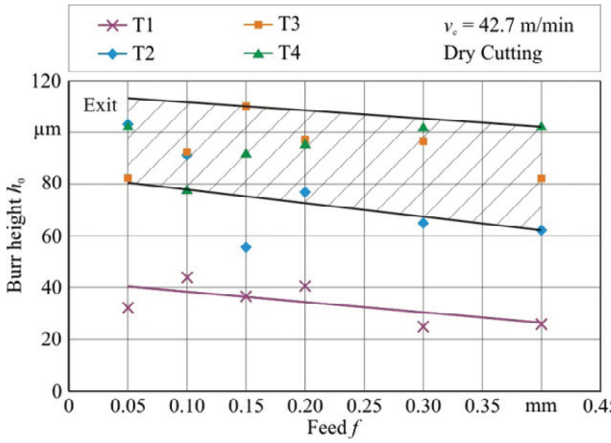


Fig. 11. Burr height h_0 at the exit

According to the scatter of results at the exit, no clear trend for tools T2, T3 and T4 is visible. Only tool T1 shows a clear trend and achieves the best results while the tools T2, T3 and T4 attain greater amounts of burr height. One possible reason for the elevated burr height with tool T3 and T4 could be the higher axial force compared to T1 where the forces are also axial deflected. The progress of burr height h_0 with the feed rate f is slightly decreasing. The trend in burr height at the exit with the four tools corresponds to a great extent with the delamination illustrated in fig. 9.

Besides the influence of the point angle of the drilling tools on drilling forces and drill hole quality, the effects of cutting speed v_c are investigated in this paper using tool T1. Figure 12 shows the connection between feed force F_f and cutting parameters.

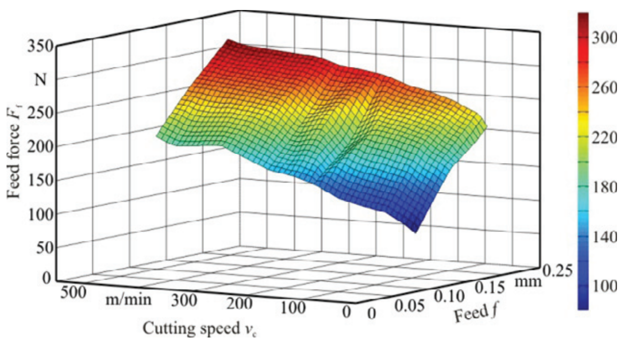


Fig. 12. Feed force F_f at varying cutting parameters (tool T1)

Figure 12 shows that feed force F_f not only rises with elevated feed rates but also increases with elevated cutting speeds. This gain of feed forces F_f is partly due to tool wear but also due to dynamic effects. The development of drilling torque T_d is different (see Fig. 13).

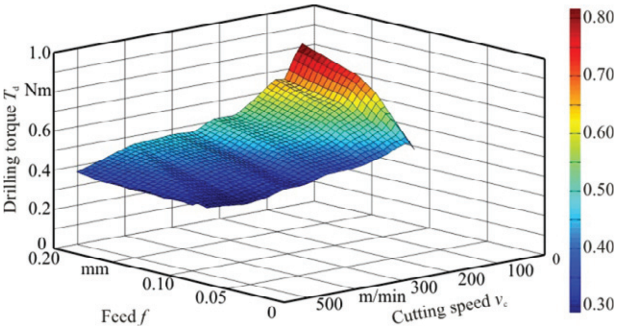


Fig. 13. Drilling torque T_d at varying cutting parameters (tool T1)

It can be seen that the drilling torque decreases with the increase in cutting speed but rises with elevated feed. One reason can be that at elevated cutting speeds no material (especially matrix material) adheres at the tool, therefore less friction is generated and thus the drilling torque shrinks. Further investigations need to be conducted to prove other possible reasons for the decrease of drilling torque at higher cutting speeds. Looking at the drilling forces the attendance of a HSC-effect may be assumed. However the resulting delamination factors at the produced drill holes are not significantly affected by elevated cutting speeds.

4. Conclusion

The conclusion can be drawn that increasing point angles result in:

- Increasing feed forces F_f but almost similar drilling torques T_d
- Improved drill hole qualities at the entrance especially concerning fraying and delamination
- Poorer drill hole qualities at the exit (mainly delamination).

Increasing cutting speeds (using tool T1) result in elevated feed forces and decreasing drilling torques while the drill hole quality stays almost unaffected.

Acknowledgements

The presented investigations are kindly supported by the German Research Foundation DFG in the context of the Graduate School of Excellence advanced Manufacturing Engineering (GSaME), funded under the Excellence Initiative.

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