Experimental Investigation of Machinability of the Hybrid Fibre Reinforced Epoxy/Polymer Composite

Martina Ryvolová[1]

[1] Institute for Nanomaterials, Technologies and Innovation, Technical University of Liberec, Czech Republic
martina.ryvolova@tul.cz

Abstract. The use of FRP in technical applications - aerospace, automotive and industrial components - demands their high-quality processing. Namely process drilling, cutting, and machining. Tools properties (material, geometry), process parameters (speed, RPM, feed), and hole/cutting edge quality are typically evaluated. The topic of this paper is a practical evaluation of the machinability of a composite material - fiber-reinforced plastic (FRP). Composite test plates were fabricated with hybrid reinforcement and three types of epoxy matrices. The drilling process had two variables: tool diameter and tool feed rate. Considering the quality of the drilled hole, one of the material combinations was selected to produce the reinforcement part of the battery box. The design and production are part of the Technical University of Liberec Modular Platform for Autonomous Chassis of Specialized Electric Vehicles for Cargo and Equipment Transportation project.

Keywords: glass fiber noncrimp fabric, carbon fiber woven fabric, reinforced plastic, machinability, drilling

1 Introduction

The production of battery boxes for electric vehicles is determined by two basic requirements: weight reduction and sufficient strength and rigidity. These properties clearly define the use of fiber-reinforced plastics (FRP) as the most suitable material for box production. In the modular platform project of the TUL project for the autonomous chassis of specialized electric vehicles for transporting cargo and equipment, a battery box with composite reinforcement was designed and manufactured. The selection of a suitable combination was part of the process. Evaluation parameters included the mechanical performance of the composite, its chemical resistance, and machinability using standard procedures such as drilling, cutting, and machining.

Fiber-reinforced composites are used as a structural material in aerospace, automotive, mechanical, and electrical engineering and a wide range of technical applications. For these applications, the need to drill or machine FRP arises. The operations are considered critical due to the possibility of damage to the composite structure by delamination. The disadvantages are associated with three main factors: tool parameters, process parameters, and maintaining the quality and performance of the composite. [1–3]

M. Petr et al. (eds.), *62nd International Conference of Machine Design Departments (ICMD 2022)*,
Atlantis Highlights in Engineering 28,
https://doi.org/10.2991/978-94-6463-423-5_44

High-speed steel (HSS) or tungsten carbide (WC) drilling bits are usually used to drill polymer composites [1]. Studies [3–10] present the relationships between tool geometry and cutting parameters when drilling in different types of FRP. Authors [10] described the influence of the drill tip on the delamination using a mathematical model [11-13].

Achieving strict dimensional and geometric tolerances is a complex process due to the nature of polymer composites. The authors [14–17] investigated the correlation between process parameters and delamination/performance in composite performance, including undesirable temperature rise. The classification of drilling damage in polymer composite materials [18] is summarized into four categories: geometric defects, temperature-induced damage, drilling-induced damage, and delamination on the entrance and exit sides of the drilled composite. [10, 19, 20]

Delamination is a severe problem associated with drilling fiber-reinforced composite materials. It reduces the material's structural integrity, resulting in poor assembly tolerance and causes long-term deterioration of properties. Reference [6] describes two basic delamination mechanisms associated with drilling composites; peel-up at the entrance and a drill push-out effect at the exit of the composite. Peel-up occurs when the drill bit enters the laminate (Fig. 1a). The cutting force applied in the circumferential direction is the cause of delamination. The push-out effect is a function of the tool geometry and the friction between the tool and the workpiece. It occurs as the drill bit exits the composite, when the layer thickness thins, and delamination occurs when the load exceeds the interlaminar bond strength (Fig. 1b).

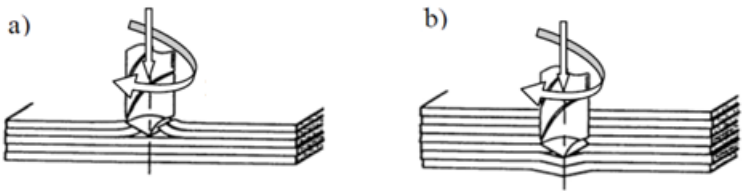

Fig. 1. Drilling delamination; a) peel-up delamination on the entrance side of FRP, b) push-up delamination at the exit side of FRP [6]

Delamination factor F_d describes the deterioration degree using geometrical parameters of a drilled hole at the entrance/exit side according to equation (1) [2, 9, 14, 15]:

$$F_d = \frac{D_{max}}{D} \tag{1}$$

Where: F_d – factor of delamination [-]; D – drill diameter [mm]; D_{max} - diameter of the delamination area [mm].

The analysis of the cited sources confirmed that the significant influence on the delamination factor is due to the feed rate, rotational speed, and differences in the shapes of the cutting edges of the drill bits used. [3–10, 14 - 20]

2 Materials and Methods

2.1 Specimen preparation

For the fabrication of the composite reinforcement of the battery box, woven and multiaxial carbon and glass fiber knitted fabrics were available as reinforcement. The mechanical properties, chemical resistance, and machinability were considered when selecting the material combination. The composite plates consist of a layer of carbon fabric (200 g m^{-2}), three layers of quadriaxial glass fiber NCF (800 g m^{-2}), and a layer of carbon fabric (200 g m^{-2}). The description and characteristics of the epoxy matrices are given in Table 1. Reinforcement and matrix were used to fabricate composite plates with a size of 200 x 150 mm and a thickness of 3.3 mm.

The hardness of the matrix was measured with a DURAMIN 40 (Struers) Brinell hardness at a 10 N load. Flexural strength measurements were made on ten specimens for each matrix type according to standard ISO 178.

Table 1. Parameters of Epoxy Resin Systems

Resin	Hardener	Hardness [HB1/10]	Flexural strength [MPa]
CHS 531	Telalit	16.24 ±1.63	36.23 ± 6.65
LG 285	HG 285	17.19 ± 1.38	91.67 ± 19.25
LG 120	HG 350	21.10 ±0.51	8.17 ± 2.13

2.2 The drilling process

The experiment was carried out on a stand drilling machine with a table to clamp the specimens with standard HSS double threaded drill bits with diameters of 3.0, 5.5, and 9.5 mm. A general rule of thumb for drilling metallic and non-metallic materials is that the speed decreases with increasing drill diameter and decreases with increasing material hardness. The purpose of the experiment was to evaluate the effect of spindle speeds at a constant feed rate of 0.1 mm/rev on the quality of the drilled hole edge, damage at the entrance (peel-up) and exit (push-out) of the drill bit from FRP and possible delamination of the FRP for composite specimens from three epoxy systems.

3 Results

The drilled holes took photos from the entrance and exit sides. The image processing software converted the images to grayscale. Figures are arranged according to the matrix type; the top image shows the entrance of the drill bit into the composite, and the bottom figure shows the exit of the drill bit from the composite. The evaluation parameters include hole shape, pulled-out fibers, peeled-off matrix flakes, and delamination layers. Figures present the degree and size of delamination depending on spindle speed and constant feed rate. [5, 9] Composite composition is the same for all three specimens. [14]

Figs. 2 and 3 compare the holes damage at two different spindle speeds by the drilling bit diameter of 3 mm; Fig. 2 at 265 rpm, Fig. 3 at 850 rpm. The low speed caused the delamination of the composite layers in the LG 120 specimen (Fig. 2), fiber pull out, and matrix peeling in the LG 285 and CHS 531 specimens (Fig. 2). The damages difference is due to the different hardness of the matrices probably.

Drilling the holes at a higher spindle speed (850 rpm) is done in LG 285, and CHS 531 without delamination and fibers pulled out (Fig. 3). In the LG 120 specimen, fibers are pulled out on the exit side of the hole (Fig. 3)

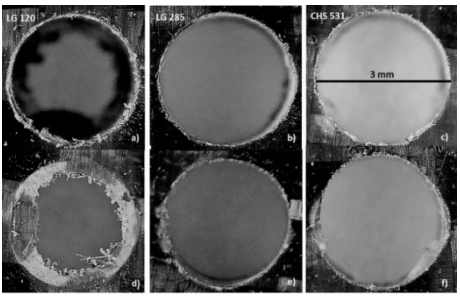

Fig. 2. Comparison of drilled holes; drill bit diameter 3 mm; 265 rpm; a), b), c) entrance side d), e), f) exit side.

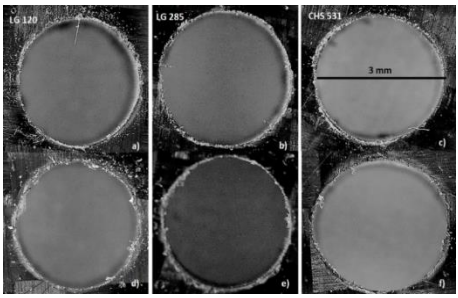

Fig. 3. Comparison of drilled holes; drill bit diameter 3 mm, 850 rpm; a), b), c) entrance side; d), e), f) exit side.

Figures 4-6 show the effect of spindle speed on the quality of the drilled hole with a drill diameter of 5.5 mm at 265 rpm (Fig. 4), 475 rpm (Fig. 5), and 850 rpm (Fig. 6). The 265 rpm is suitable for the more hardness matrix type, LG 120 specimen. For other specimens, LG 285 and CHS 531, the matrix scales are peeled off from the edges of the holes (Fig. 4). The soft matrix of specimen CHS 531 requires a higher drilling speed.

At 475 rpm, all specimens experienced a different degree of composite delamination on the exit side. The 475 rpm is inappropriate in combination with the drill diameter of 5.5 mm for composite drilling (Fig. 5).

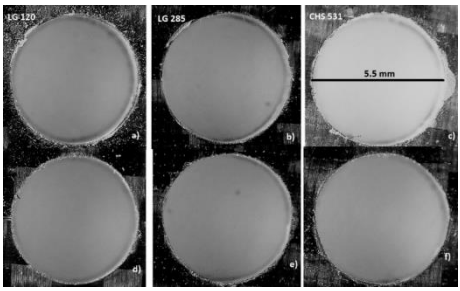

Fig. 4. Comparison of the holes; drill bit diameter 5.5 mm, 265 rpm; a), b), c) entrance side; d), e), f) exit side.

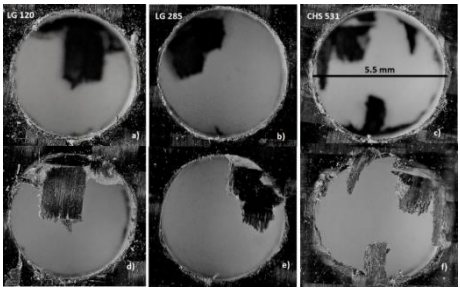

Fig. 5. Comparison of the holes; drill bit diameter 5.5 mm, 475 rpm; a), b), c) entrance side; d), e), f) exit side.

At 850 rpm, matrix flaking occurred in specimens LG 120 and CHS 531. Fig. 6 shows the delamination of the bottom layer of the CHS 531 specimen. Specimen LG 285 presents a similar excellent result for spindle speed 265 and 850 rpm based on visual assessment.

Figs. 7-9 show the effect of the drill bit with a diameter of 9.5 mm at the spindle speed of 150 rpm (Fig. 7), 265 rpm (Fig. 8) and 450 rpm (Fig. 9).
The holes drilled at 150 rpm are free from delamination and fiber to pull out on both sides for all composite specimens; see Fig. 7.

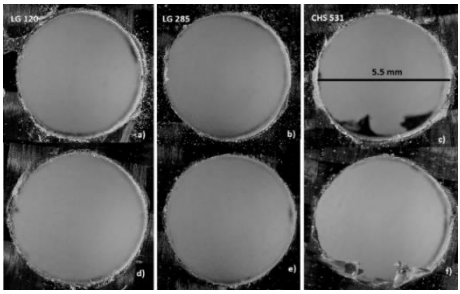

Fig. 6. Comparison of drilled holes; drill bit diameter 5.5 mm, 850 rpm; a), b), c) entrance side; d), e), f) exit side.

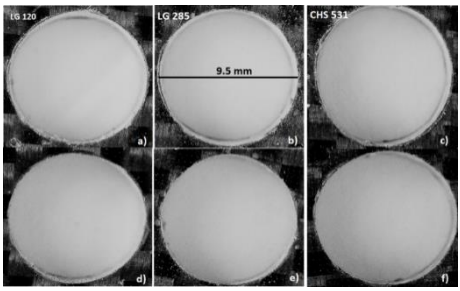

Fig. 7. Comparison of drilled holes; drill bit diameter 9.5 mm, 150 rpm; a), b), c) entrance side; d), e), f) exit side.

The holes in the LG 120 and CHS 531 specimens show the shape deviations at 265 rpm, Fig. 8. The drilling caused delamination on the exit side of LG 285 specimen, Fig. 8. The process was carried out directly; without pre-drilling with a minor diameter drill bit in all cases.

The thin flakes of the matrix peeled off at the edges of holes at 450 rpm for LG 285 and CHS 531 specimens, Fig. 9. The hole shape of the CHS 531 specimen is significantly uncircular. The LG 285 specimen presents a less deviation of the shape. The entrance and exit of the LG 120 specimen are without pull-out fibers, peeled-off matrix flakes, and delamination; the hole shape is round. The drilling was carried out directly; without pre-drilling.

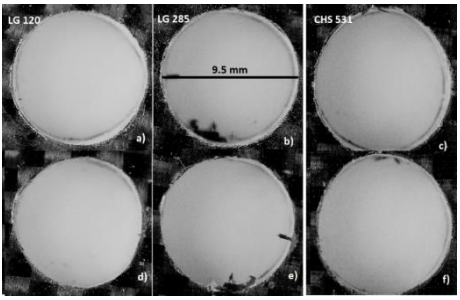

Fig. 8. Comparison of drilled holes; drill bit diameter 9.5 mm, 265 rpm; a), b), c) entrance side; d), e), f) exit side.

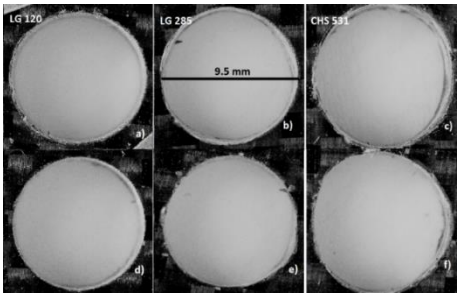

Fig. 9. Comparison of drilled holes; drill bit diameter 9.5 mm, 450 rpm; a), b), c) entrance side; d), e), f) exit side.

4 Conclusions

The experimental evaluation of the drilling process yielded the following practical results:

- The quality of a specific diameter drilled hole depends on the drill bit's spindle speed. For small diameters, a higher spindle speed is suitable; a lower spindle speed is suitable for larger diameters.
- Regardless of the reinforcing fiber, the damage to the composite also depends on the properties of the matrix.
- The LG 285 specimen for the hole diameter range up to 5.5 mm was evaluated as the most suitable in terms of strength and machinability parameters based on the experiment. Drilling larger diameter holes requires a tool directly designed for machining the composite and preliminary operations - pre-drilling the hole.
- The LG 120 specimen was evaluated as suitable for a hole diameter of 9.5 mm. This composite material, because of the average characteristics, was chosen as the most suitable for the construction of the battery box.
- The experimental result can be refined by determining the delamination factor Fd on the entrance and exit sides of the drilled hole. For this purpose, extending the experiment with different speed and feed rate values would be advisable. The next level of

qualitative evaluation of the drilling process is to evaluate hole wall damage by Scanning Electron Microscopy, identifying delamination, pull-out, uncut and missing fibers, and determining composite porosity.

Acknowledgments

The research was supported by the Ministry of Education, Youth, and Sports of the Czech Republic and the European Union (European Structural and Investment Funds Operational Program Research, Development, and Education) in the framework of the project "Modular platform for autonomous chassis of specialized electric vehicles for freight and equipment transportation", Reg. No. CZ.02.1.01/0.0/0.0/16_025/0007293, as well as the financial support from internal grants in the Institute for Nanomaterials, Advanced Technologies and Innovations (CXI), Technical University of Liberec (TUL).

Special thanks to Mr. Josef Anděl for cooperation during the drilling process and to Mrs. Petra Prokopčáková for arranging the hardness measurement.

References

1. Abrão, A.M., Faria, P.E., Rubio, J.C. Campos, Reis P. and Davim, J. Paulo: Drilling of fiber reinforced plastics: A review. *Journal of Materials Processing Technology* [online]. 2007, **186**(1–3), 1–7. ISSN 09240136. doi:10.1016/j.jmatprotec.2006.11.146
2. Karataş, A., Gökkaya, Meltem, and Hasan: A review on machinability of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composite materials. *Defence Technology* [online]. 2018, **14**(4), 318–326. ISSN 22149147. doi:10.1016/j.dt.2018.02.001
3. Ramesh, M., Gopinath, A. and Deepa, C.: Machining Characteristics of Fiber Reinforced Polymer Composites: A Review *Indian Journal of Science and Technology* [online]. 2016, **9**(42) [vid. 2022-08-24]. ISSN 0974-5645, 0974-6846. doi:10.17485/ijst/2016/v9i42/101978
4. Chen, W.Ch.: Some Experimental Investigations In the Drilling of Carbon Fiber-Reinforced Plastic (CFRP) Composite Laminates. Tools Manufact. Vol. 37, No. 8. pp. 1097-1108, 1997
5. Piquet, R., Ferret, B., Lachaud, F., and Swider, P.: Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills. *Composites Part A: Applied Science and Manufacturing* [online]. 2000, **31**(10), 1107–1115. ISSN 1359835X. Dostupné z: doi:10.1016/S1359-835X(00)00069-5
6. EL-Sonbaty, I., Khashaba, U.A., and Machaly, T.: Factors affecting the machinability of GFR/epoxy composites. *Composite Structures* [online]. 2004, **63**(3–4), 329–338. ISSN 02638223. doi:10.1016/S0263-8223(03)00181-8
7. Mohan, N S, Ramachandra, A., and Kulkarni, S.M.: Machining of Fiber-reinforced Thermoplastics: Influence of Feed and Drill Size on Thrust Force and Torque during Drilling.
8. Capello, E.: Workpiece damping and its effect on delamination damage in drilling thin composite laminates. *Journal of Materials Processing Technology* [online]. 2004, **148**(2), 186–195. ISSN 09240136. doi:10.1016/S0924-0136(03)00812-4

9. Abrão, A.M., Faria, P.E., Rubio, J.C., Reis P. and Davim, J. P.: The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite. *Materials & Design* [online]. 2008, **29**(2), 508–513. ISSN 02613069. doi:10.1016/j.matdes.2007.01.016
10. Ismail, S. O., Dhakal H.N., Popov, I., and Beaugrand, J.: Comprehensive study on machinability of sustainable and conventional fibre reinforced polymer composites. *Engineering Science and Technology, an International Journal* [online]. 2016, **19**(4), 2043–2052. ISSN 22150986. doi:10.1016/j.jestch.2016.07.010
11. Tsao, C.C. and Hocheng, H.: The effect of chisel length and associated pilot hole on delamination when drilling composite materials. *International Journal of Machine Tools and Manufacture* [online]. 2003, **43**(11), 1087–1092. ISSN 08906955. doi:10.1016/S0890-6955(03)00127-5
12. Tsao, C.C. and Hocheng, H.: Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials. *International Journal of Machine Tools and Manufacture* [online]. 2005, **45**(2), 125–130. ISSN 08906955. doi:10.1016/j.ijmachtools.2004.08.001
13. Tsao, C.C. and Hocheng, H.: Taguchi analysis of delamination associated with various drill bits in drilling of composite material. *International Journal of Machine Tools and Manufacture* [online]. 2004, **44**(10), 1085–1090. ISSN 08906955. doi:10.1016/j.ijmachtools.2004.02.019
14. Khashaba, U.A.: Delamination in drilling GFR-thermoset composites. *Composite Structures*. 2004, 16.
15. Davim, J.P. and Reis, P.: Drilling carbon fiber-reinforced plastics manufactured by autoclave: an experimental and statistical study. *Materials & Design* [online]. 2003, **24**(5), 315–324. ISSN 02613069. Dostupné z: doi:10.1016/S0261-3069(03)00062-1
16. Aoyama, K., Ogawa, E., Inoue, H., and Hirogaki, T.: Investigation on the cutting mechanism in small-diameter drilling for GFFW (thrust force and surface roughness in the drilled hole wall).
17. Caprino, G., and Tagliaferri, V.: Damage development in drilling glass fibre reinforced plastics. *International Journal of Machine Tools and Manufacture* [online]. 1995, **35**(6), 817–829. ISSN 08906955. doi:10.1016/0890-6955(94)00055-O
18. Lachaud, F.: Drilling of composite structures. *Composite Structurex*. **2001**(52), 511–516.
19. Gaitonde, V., Karnik, S., Rubio, J.C.C., De Oliveira Leite, W. and Davim, J.P.: Experimental studies on hole quality and machinability characteristics in the drilling of unreinforced and reinforced polyamides. *Journal of Composite Materials* [online]. 2014, **48**(1), 21–36. ISSN 0021-9983, 1530-793X. doi:10.1177/0021998312467552
20. Gao, T., Li, Ch., Wang, Y., Liu, X., An, Q., Li, H.N., Zhang, Y., Cao, H., Liu, B., Wang, D., Said, Z., Debnath, S., Jamil, M., Ali, H.M. and Sharma, S.: Carbon fiber reinforced polymer in drilling: From damage mechanisms to suppression. *Composite Structures* [online]. 2022, **286**, 115232. ISSN 02638223. doi:10.1016/j.compstruct.2022.115232