Analysis and Impacts of Chips Formation on Hole Quality during Fibre-Reinforced Plastic Composites Machining

Sikiru Oluwarotimi ISMAIL[a, 1], Hom Nath DHAKAL[a], Ivan POPOV [a] and Johnny BEAUGRAND [b, c]
[a] *Department of Mechanical and Design Engineering, University of Portsmouth, Anglesea Building, Anglesea Road, PO1 3DJ, United Kingdom.*
[b] *INRA, UMR614 Fractionnement des AgroRessourcesetEnvironnement, F-51686 Reims, France*
[c]*Université de Reims Champagne-Ardenne, UMR614 Fractionnement des AgroRessources et Environnement, F-51100 Reims, France*

Abstract. This work presents the effect of chips formation types on the quality of drilled holes of natural and conventional hemp and carbon fibre-reinforced plastic (HFRP and CFRP) composites respectively. The results depict that variation in chips morphology depends on drilling parameters, drill geometry and composite compositions (matrix and fibre properties). HFRP samples produced continuous brown ribbon-like chips, which were short and melted at lower feed rate and cutting speed, implying that higher feed rate and cutting speed produced wider, longer and lighter chips. CFRP samples generated discontinuous black powder-like chips, with small and abrasive chips at the same applied drilling parameters. These formation and morphology affected quality of drilled holes: lower surface roughness in CFRP, but lower delamination and drill wear in HFRP samples. Evidently, an increased feed rate, cutting speed and drill diameter caused an increase in chips formation, validating the material removal rate (MRR) model results.

Keywords. Chips formation types, drilling parameters, quality of drilled holes.

1. Introduction

The increasing applications of different types of fibre-reinforced plastic (FRP) composite materials in a various sectors of engineering has necessitated a wider and detailed research on machining of these composites. The FRP composites have some inherent desirable and outstanding physical and mechanical properties that attracted for numerous applications. However, the combination of a softer polymer (matrix) and harder reinforcement (fibre) makes the machining of FRP composite materials quite different from the drilling of a conventional metals and their alloys, as reported by Lin *et al.* [1] and Ismail *et al.* [2, 3]. Recently, the composite components are produced to a near net-shape which inevitably requires drilled holes for assembly of parts. This makes drilling of composite materials possibly the most frequent machining operation among other post manufacturing and machining processes. In addition, the durability of an assembly parts significantly depends on the quality of the drilled holes.

The chips are formed within a shearing zone, at the tool (drill)-material (FRP composite) slipping interface after the composite samples have been subjected to a plastic deformation during drilling. Chips generation and control during drilling operation are very important in order to have a good quality of holes. Moreover, both dust-like and very long continuous chips are discouraged as much as possible during machining, because of the evacuation predicament. They both tend to cause a poor quality of hole, if they are not efficiently controlled. To predict the

---

[1] Corresponding Author: sikiru.ismail@port.ac.uk

properties (shapes and sizes) of chips formation, finite element method has been used effectively [4].

It has been experimentally observed that uncoated HSS drill bits produced long and continuous chips, while plasma-nitrided HSS drill bits generated a short and fractured chips [5]. They further stated that both thermal conduction and friction coefficient have great influence on chips formation, and the drill bit wear increased considerably as the chip section increased; showing a very strong relationship between the wear of the drill bits and the chip section. Hence, drill wear decreases hole quality. Several common drilling-induced damage associated with the FRP composites drilling are caused by a little changes during the mechanism of chips generation. A few of these damage are clearly considered within the scope of this experimental research. Therefore, further research on chips formation process for better understanding of FRP composites machining is very essential. The enhanced knowledge will increase the advanced applications and efficient methods of chips control. While few research has concentrated on influence of chips formation on machining of mainly conventional materials in some years ago [1, 6], there has not been much research conducted on the impact of chips formation on the quality of hole during both natural and synthetic FRP composites drilling. Importantly, based on literature, there is no reported work on the same samples considered experimentally. Hence, this present paper focuses on the impacts of chips formation on hole quality during HFRP and CFRP composites machining, using Taguchi method of design of experiment, double fluted high speed steel (HSS) drills, dry machining environment (condition) and conventional drilling technique without chip breaking mechanism.

2. Experimentation

2.1. Materials Specification

MTM 44-1 Carbon fibre-reinforced fibre plastic (CFRP) and Hemp fibre-reinforced plastic (HFRP) composite laminates of approximately 7.5mm thickness were used as workpiece samples for the experimental work. The CFRP samples were fabricated using 980 mbar (29”Hg) low pressure vacuum bag, unidirectional, oven cure and out–of-autoclave methods. It contained 18 plies, bonded by an epoxy resin thermosetting matrix. The HFRP samples were manufactured with natural hemp fibre of 19 aspect ratio (19/HFRP), using a polycaprolactone bio-binder (matrix) of 275^{o}C, 1.1 and 60^{o}C flash point, specific gravity and low melting temperature respectively.

2.2. Experimental Design and Methodology

Taguchi method-based experiment, L_{16} (4^2) orthogonal array, was conducted on the two FRP composite samples, using the following drilling parameters: feed rate (0.05, 0.10, 0.15 and 0.20mm/rev) and cutting speed (10, 20, 30 and 40m/min) under a conventional dry machining environment, with approximately 25mm uniform distance between two successive hole centres. HSS twist drills of diameters 5.0 and 10.0mm, point angle 118^{o}, two cutting edges and manufactured by DORMER were used. The drilling operation was performed on a Proto TRAK VM CNC Machining Centre of a maximum variable spindle speed of 5,000rpm and motor power of 5.75 KW. The samples were supported at the back throughout the drilling exercise in order to minimise the drilling-induced damage around the holes, as shown in Figure 1 (a), while Figure 1(b) depicts the experimental set-up.

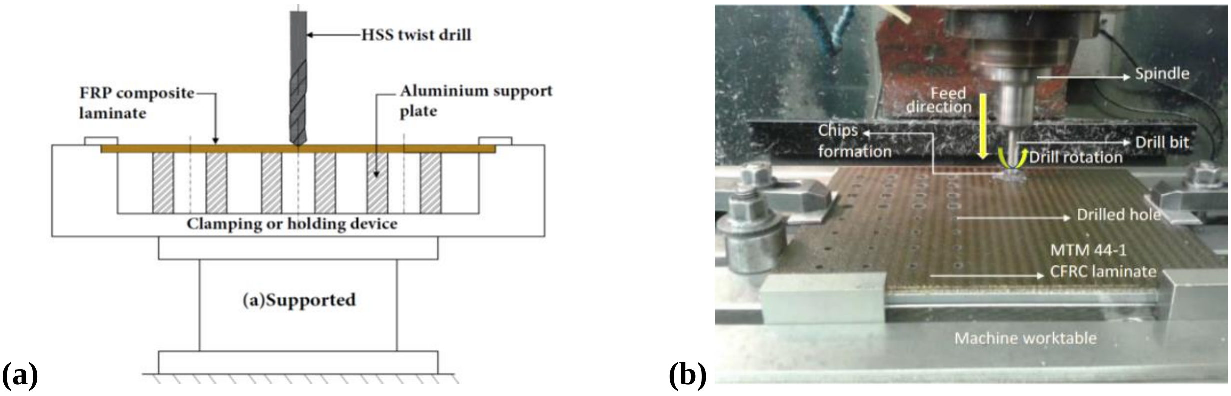

Figure 1. The experimental test set-up showing: (a) supported sample-FRP composite laminates (b) drilling operation.

The material (composite-chips) removal rate is developed as $MRR = 250\ DfV,$ where D, f and V represent the drill diameter (mm), feed rate (mm/rev) and cutting speed (m/min) respectively. Analysis of Average and Variance are used to compute and process the results obtained.

3. Instrumentation and Damage Characterisation

The burr formation, fibre pull-out/uncut, hole surface roughness and delamination drilling-induced damage are considered to characterise the drilled hole quality. In addition to the visual inspection carried out on the burrs formation, fibre pull-out/uncut and mainly delamination around the holes, an optical microscope; OLYMPUS BX 40, with a 25x magnification and 1.0µm resolution was further used to observe, measure and analyse the damage. Delamination factor, F_d is calculated as a ratio of the maximum delamination zone (mm) to the drill diameter (mm). Surface roughness, R_a is measured as the magnitude of deviation and irregularity on the circumferential walls of the drilled holes. It was measured with a profilometer; a Mitutoyo surface measuring instrument of 300.00µm and 2.40mm capacity and cut-off surface length, respectively. Further observations were conducted using a JEOL JSM-6100 scanning electron microscope and Nikon XTH 225 scanner for X-ray computed tomography of the internal damage.

4. Results and Discussion

4.1. Analysis of Chips Formation and Morphology

During drilling operation, a continuous and discontinuous types of chips were separately formed. At both lowest and highest drilling parameters (feed rate and cutting speed), a similar continuous spiral HFRP chips were formed, but more cone-like at highest feed rate and cutting speed (Figures 2a & b). Likewise, a continuous string chips were formed at average drilling parameters. During the drilling of the two samples, the chips formed increased when both the cutting speed and feed rate were increased, but an increase in feed rate and cutting speed caused a significant increase in the chip section and thickness of the HFRP sample, unlike the CFRP sample. In addition, at increased drilling parameters, the HFRP sample produced a continuous brown ribbon-like chips, which was well noticeable at highest feed rate of 0.20mm/rev and cutting speed of 40m/min. But, short and melted at lower drilling parameters, as depicted in Figure 2(a) of HFRP sample. Also, the increase in cutting speed, feed rate and drill bit diameter caused a corresponding increase in the chip length and number of chip curls generated. The HFRP chips became broader, lengthier and brighter at an increased drilling parameters. This is expected due to the ductility and poor thermal conductivity of the HFRP sample.

The nature of the chip formation in HFRP sample can be attributed to adiabatic shear during high cutting speed drilling and composite constituents. The HFRP composite sample is made up of hemp fibre and polycaprolactone (PCL) matrix of a relative poorer thermal conductivity and higher ductility mainly at comparative high cutting speed of 40m/min respectively, when compared with carbon fibre and epoxy resin matrix of CFRP sample. The HFRP chips became longer without breaking. Furthermore, during chip segment formation, the low hardness and higher ductility of HFRP chips caused an increase in the sticky period at drill-chip interface and a reduction in the slip periods, as the PCL began to melt at a higher cutting temperature, usually around 60^0C.

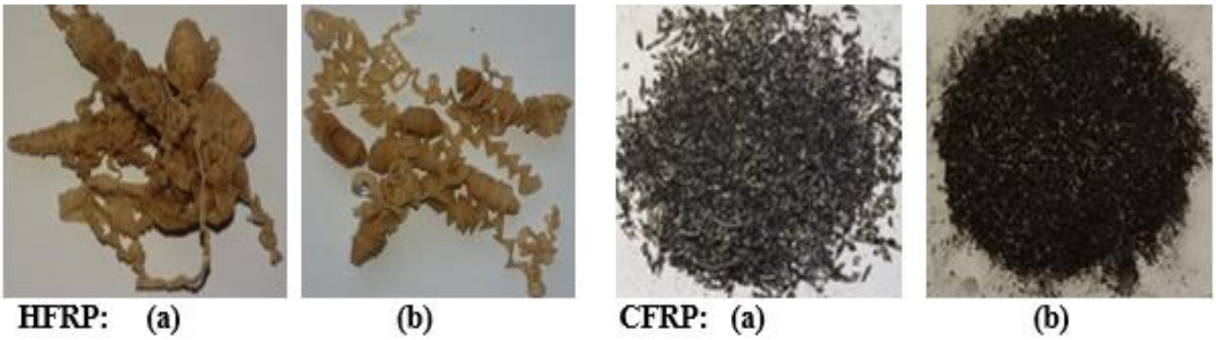

Figure 2. Chips morphology at: (a) f = 0.05 & v = 10 and (b) f = 0.20mm/rev & v = 40m/mm.

On the contrary, the CFRP sample produced a very small sized, powder-like and abrasive discontinuous chips (Figures 2a & b of CFRP sample). This is anticipated during machining of brittle materials. This phenomenon can be attributed to the greater thermal conductivity of the CFRP sample as the chips of CFRP are subjected to more heat, cooled instantly immediately after they are withdrawn from the cutting region or shearing zone and resultantly, became harder, brittle and produced dust-like chip sizes. The CFRP black chips formed have a less strain which characterized generation of a better surface finish. The short chips produced minimum surface roughness on CFRP samples. Considering both surface finish and chips evacuation during drilling, long ribbon-like chips were very difficult to remove, hence, it should be discouraged. The bigger 10.0mm diameter drill produced more chips from the two samples. This agrees with the developed MRR model results in order to analyse the influence of the increase of drilling parameters and drill diameter on the hole quality of the composite samples.

4.2. Effects of Chips formation on the hole quality

4.2.1. Burrs Formation and Fibre Pull-Out/Uncut

A few minimal burrs, known as a ‘Type A’, and fibre pull-out/uncut formation are observed at the upper surface part of some holes of the HFRP samples especially at a low cutting speed of 20m/min, unlike the CFRP samples (Figures 3a & b). The CFRP sample has no burrs and uncut fibre, because it has a higher hardness, brittleness and different nature of compositions. However, the increase in cutting speed drastically reduced and eventually eliminated these damage, while feed rate has no significant effect. The application of the aluminum support plate (Figure 1a) during drilling reduced occurrence of both burrs, fibre uncut/pull-out and push-out delamination type at the exit (back) of the holes.

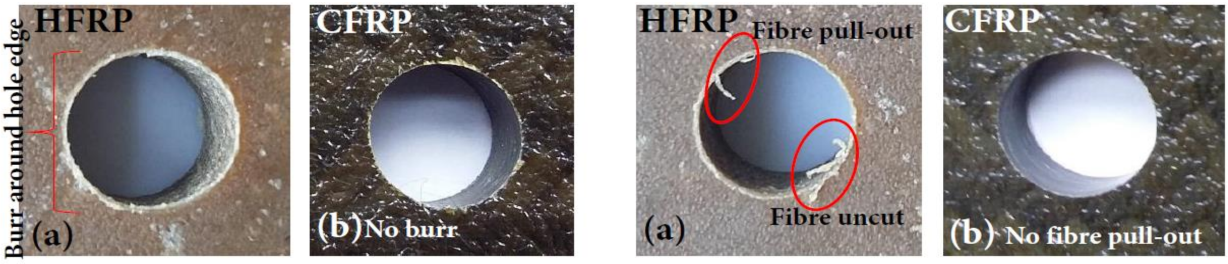

Figure 3. (a) HFRP sample with and (b) CFRP sample without burr formation and fibre pull-out/uncut at cutting speed of 20m/min.

4.2.2. *Hole Surface Roughness and Delamination Damage*

It is observed that increase in feed rate caused an increase in the delamination factor and surface roughness, while an increased cutting speed caused a decrease in surface roughness of the two samples. At increased feed rate, more chips are produced and these chips were not easily removed due to their shapes and properties. This poor evacuation increased the delamination phenomenon as more heat is generated, which later weakened the epoxy resin matrix of CFRP and melted the PCL matrix of HFRP samples over a long numbers of holes. Consequently, it resulted into higher ply peel-up delamination and higher surface roughness in CFRP and HFRP samples, as depicted in Figures 4(a) and (b) respectively. However, these two damage (Figure 4b) gradually reduced when cutting speed increased because more chips are removed out of the hole, resultantly cutting temperature is reduced.

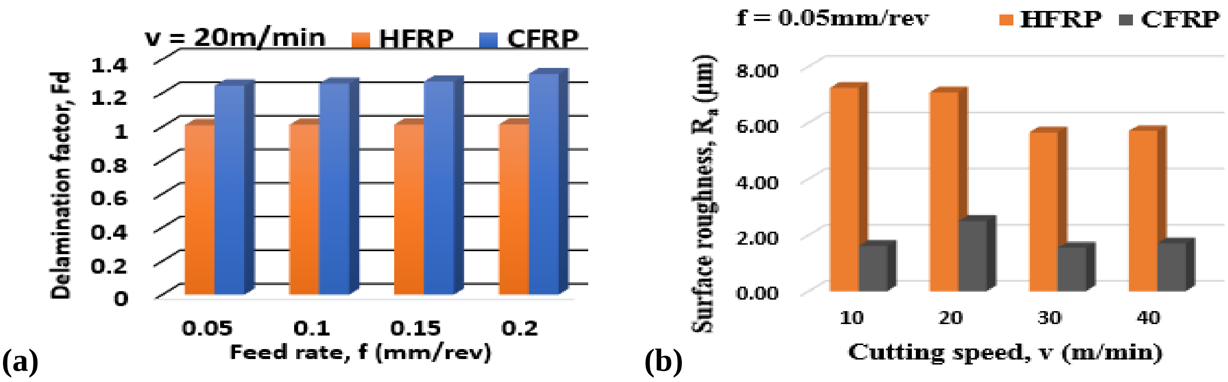

Figure 4. Effects of chips formation on delamination and surface roughness.

5. Conclusions

Based on this experiment, it can be concluded that the chips generation increased when the cutting speed, drill diameter and feed rate were increased, but more characterised by the higher feed rate and bigger drill diameter, which agreed with the MRR model results. In 19/HFRP, the variation in chip length depended on the feed rate. The feed rate increased with a decrease in the chip length as a result of more ribbon-like/cone chips, while lower feed rate favoured formation of long melted chips. The chips production in MTM 44-1/CFRP decreased and became more powder-like in nature and finer as drilling parameters increased. In addition, the black chips formation in MTM 44-1/CFRP has a less strain, with a better surface finish as a brittle material. The constituents of CFRP samples supported production of holes void of burrs formation and fibre pull-out or uncut. The thermoset epoxy based CFRP sample became stronger at the presence of high drill-composite interface cutting temperature, as the number of holes increased. The carbon fibre has a greater decomposition temperature, when compared with the natural hemp fibre. Conversely, the thermoplastic polycaprolactone based HFRP sample enhanced the ductility property of the HFRP sample, consequently, fibre pull-out or uncut and higher surface roughness were observed in HFRP sample holes. This is attributed to PCL matrix melting at high cutting temperature, generated by high friction between the drill bit and the HFRP chip/composite sample. Also, feed rate has an insignificant influence on the burrs formation and uncut fibre. However, an increase in feed rate has a great effect on the occurrence of peel-up delamination type and surface roughness drilling-induced damage. Hence, the quality of the drilled holes are reduced. The increase in cutting speed minimised surface roughness, delamination and fibre pull-out or uncut defects.

Evidently, delamination damage is greater in CFRP samples, while HFRP sample holes are more characterised by surface roughness, fibre pull-out or uncut and burrs formation. Conclusively, these damage make CFRP sample has a better machinability and hole quality, when compared with HFRP samples under the same machining parameters, techniques and conditions.

References

[1] J.T. Lin, D. Bhattacharyya, and W. G. Ferguson, Chip formation in the machining of SiC-particle-reinforced alumin ium–matrix composite, *Composites Science and Technology* **58 (**1998**),** 285-291.

[2] S.O. Ismail, H.N. Dhakal, E. Dimla, J. Beaugrand and I. Popov, Effects of drilling parameters and aspect ratios on delamination and surface roughness of lignocellulosic HFRP composite laminates, *Journal of Applied Polymer Science* **133** (2016), 1–8.

[3] S.O. Ismail, H.N. Dhakal, E. Dimla, and I. Popov, Recent advances in twist drill design for composite machining: A critical review, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* (2016), 1-16.

[4] P. Roud, M. Zetek, I. Cesákova, J. Sklenicka, and P. Kozmin, Using of FEM for chip formation and cutting force prediction when drilling tool steel AISI D3, *Modern Machinery Science Journal***.** Special issue, March (2011), 1-4.

[5] I. Ucun, and S. Kaplan, Determination of tool wear and chip formation in drilling process of AISI1045 material using plasma-nitrided high-speed steel drill bits, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* (2015), 1–10.

[6] I.S. Jawahir and C.A. van Luttervelt, Recent developments in chip control research and applications. *Annals of CIRP – Manufacturing Technology* **42 (**1993), 659-693.