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Full Length Article

Comprehensive study on machinability of sustainable and conventional fibre reinforced polymer composites

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ABSTRACT

The conventional homogeneous materials can no longer effectively satisfy the growing demands on product capabilities and performance, due to the advancement in products design and materials engineering. Therefore, the fibre reinforced composites (FRCs) with better properties and desirable applications emerged. These enhanced qualities of the FRCs have emphasized the need for analysing their machinability for further improvement of performance. Hence, this paper presents a comprehensive investigation on the machinability effects of drilling parameters (feed rate, cutting speed and thrust force), drill diameters and chips formation mainly on delamination and surface roughness of hemp fibre reinforced polymer (19/HFRP) and carbon fibre reinforced polymer (MTM 44-1/CFRP) composite laminates, using high speed steel (HSS) drills under dry machining condition. The results obtained depict that an increase in feed rate and thrust force caused an increase in delamination and surface roughness of both samples, different from cutting speed. Also, increased drill diameter and types of chips formation caused an increase in both delamination and surface roughness of both samples, as the material removal rate (MRR) increased. Evidently, the minimum surface roughness and delamination factor of the two samples for an optimal drilling are associated with feed rates of 0.05–0.10 mm/rev and cutting speed of 30 m/min.

1. Introduction

Recently, there has been growing interest in the composites technology. The composites technology has enabled the production of outstanding FRCs with respects to better damage tolerance, impact resistance, toughness, sustainability, renewability, strength, electromagnetic transparency, biodegradability, environmental superiority, cost and ease of productions, part count reduction, stiffness, design flexibility, low weight, mechanical damping, strength properties as well as chemical, thermal, high corrosion and wear resistance when compared with the conventional metallic engineering materials [1–6]. These desirable general inherent and better properties have increased the areas of application of these heterogeneous materials as both functional and structural components. The areas of application include, but are not limited to, telecommunication, automotive, oil and gas, building and construction, sports and recreation, aviation, biomedical, marine (naval), electronics, defense or military, power generation, consumer products, food and packaging industries [1–4,7–15]. Also, the environmental and economic global treats today have called for the production of natural fibre reinforced, bio-resourced and sustainable composite materials as a substitute for a synthetic (conventional) fibre reinforced polymer (FRP) composites [5,10]. For instance, based on the directive issued by the European Union, it requires that the greatest percentage of 85%, followed by 10% and just only 5% of all new automobiles should be reusable (recyclable) by weight, for energy recovery and used in landfills respectively, starting from year 2015 [16]. However, the application of some synthetic fibre reinforced composites has not been totally replaced with the natural fibre reinforced composites in engineering structures, because of the remarkable properties of these synthetic or conventional FRCs which include, but are not limited to, relative high tensile and impact strengths, strong fibre–matrix interface adhesion and high melting points.

The hemp fibre is a bast lignocellulosic natural fibre, which reinforced a fully biodegradable thermoplastic matrix, known as polycaprolactone (PCL), while the carbon fibre is an inorganic and synthetic fibre, which reinforced a non-biodegradable

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thermoset matrix, known as Epoxy resin (EP) [5]. Therefore, the hemp fibre reinforced polymer (HFRP) is an example of a natural (sustainable) fibre reinforced composite, while carbon fibre reinforced polymer (CFRP) is referred to as a synthetic (conventional) and inorganic composite, as shown in Fig. 1. Drilling holes on a FRP composites is an indispensable and inevitable operation that is required for an assembly operation [6,8,17].

The quality and the integrity of the holes obtained during drilling of various fibre reinforced composite laminates are quite different from that of drilled metals [17]. The drilled metal surfaces are smoother and more regular than the drilled composite surfaces under the same conditions [18], due to the abrasive nature, heterogeneity and anisotropy of fibre reinforced composite (FRC) materials [17]. In addition, the combination of the poor thermal conductivity of the resin matrix as well as the tough and abrasive properties of some FRCs cause their poor machinability. The effects of these properties on a drilled composite result in some severe drilling-induced damage, including delamination, surface roughness, crack development, fuzzing, spalling, fibre-uncut and pull-out, matrix sintering or burning and de-bonding, as well as drill edge chipping and excessive wear which are associated with drills [9,19–22]. These damage make drilling of high quality holes on FRP composites with a little or no damage a serious challenge [7]. The delamination and surface roughness defects have been reported as the most critical defects on drilled composite materials [7,23,24].

Delamination is simply defined as the main form of failure of laminated composites whereby the laminates or layers separate along their interfaces [1]. Delamination sometimes forms as a crack between the adjacent plies; it occurs often between two anisotropic and heterogeneous materials as an interface crack. Furthermore, it occurs under a tensile loading, bending loads, but it grows mostly under the critical compressive and fatigue loading conditions [1]. Many researchers have reported causes of delamination, namely; it was reported that increase in feed rate increased the delamination, whereas an increase in cutting speed reduced the delamination [25,26]. Therefore, low feed rates coupled with high cutting speeds reduced delamination [27–29], meanwhile the feed rate, among other drilling parameters, has the greatest influence on delamination [27]. Principally, the acted thrust force on the chisel edge of drills caused delamination defect [7,8]. Capello [30] concluded that drilling with a supported plate significantly reduced delamination defect. The use of HSS drills is rampant due to its availability, low cost and highest toughness, making it the most widely used tooling material, as reported by Ismail et al. [22], Davim and Reis [31], Che [32] and Hocheng and Tsao [33].

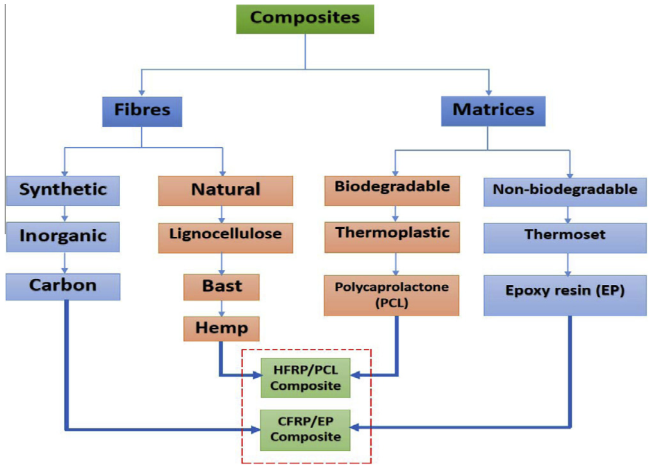

Fig. 1. The main compositions, properties and architecture of the FRCs (workpiece) used.

Surface roughness, R_a is defined as the average mean of the deviation of the roughness profile from the average line within the estimated length. Surface roughness is a very vital quality in a drilled hole, because mechanisms of creep, wear, fatigue and corrosion depend on it. Babu et al. [28,29] performed experiment on HFRP and recorded lowest delamination factor and surface roughness when compared with glass, jute and banana FRCs. Surface roughness differs at a various cutting speeds, but feed rate has a significant effect than the cutting speed [34,35]. It was concluded that an increase in feed rate resulted to an increase in surface roughness of drilled holes, while an increased cutting speed caused a decrease in surface roughness of the drilled holes of the materials used [34,36]. In addition, the drill diameter, MRR and types of chips formation during drilling process have significant effects on the quality and integrity of the drilled holes. It has been reported that an increase in diameter of the drill bit produced an increase drill designed geometries such as chisel edge, web thickness and area of cut. Likewise, an increase in these drill bit geometries caused an increase in the drilling forces (thrust force and torque) [37]. The occurrence and intensity of both delamination and surface roughness depend mostly on these forces, developed during drilling operation. The increase in MRR leads to an increase in the types of chips formation. Also, the outcomes (Pareto's front) of the research study conducted by Sardinas et al. [38], using genetic algorithm evidently showed the relationship between the MRR and the maximum delamination factor. It was reported that the maximum delamination factor increased with the MRR. The greatest value of MRR, also known as the point of maximal productivity produced the greatest value of delamination factor (point of worst surface roughness or quality). The lowest delamination factor was produced at a point of corresponding value of the lowest MRR. Therefore, a lower MRR produced by a smaller diameter, lower feed rate and moderately higher cutting speed favoured the reduction of delamination drilling-induced damage on FRC materials.

While much research has concentrated on synthetic or conventional composites, but very little is known about the machinability of natural or sustainable composites, and a deep comprehensive experimental study of these two classes of composites, mainly on the material samples considered under the same drilling parameters and condition, is very rare and scarce. Consequently, this paper presents the results of an experimental analysis of the effects of drilling parameters (feed rate, thrust force and cutting speed), drills diameters and types of chips formation mainly on drilling-induced damage, known as delamination and surface roughness in the samples HFRP and CFRP composites, using Taguchi technique for design of experiment.

2. Experimentation

2.1. Materials and methods

The 197 × 197 mm, 5 mm thickness MTM 44-1/CFRP and 19/HFRP samples were used as experimental samples, simply referred to as CFRP and HFRP respectively. The HFRP was made up of aspect ratio (AR) of 19. The AR is the ratio of the fibre length to its diameter (L/D). The mean fibre element length, L and diameter, D are 432 μm and 22.4 μm respectively. The HFRP composite samples were fabricated using an extrusion process. A resin bio-binder; PCL, a semi-crystalline polymer having a specific gravity of 1.1 at a low melting temperature of 60 °C, as well as a flash point of 275 °C, was used. It was provided by Perstop (UK) (Capa© 6800). The hemp fibres reinforced the PCL at 20 wt% concentration. The hemp fibre used was Fedora 17 specie, delivered by FRD©. The hemp fibre is a very strong lignocellulosic natural fibre that requires less processing energy. The low pressure vacuum bag

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Out-of-Autoclave (OoA) moulding method is used. The sample has 0% void content, as stated by the manufacturer of the HFRP composite samples. A common prepreg form hand layup process is adopted. An oven cure (OC) curing process and unidirectional (UD) methods were used for the manufacture of the CFRP composite laminate samples. The CFRP laminate sample is one of the carbon fibre composite laminates, with a reactive formulation and low exothermic risk, used in manufacturing of primary and secondary aircraft or space structures. It has a high damage tolerance, excellent mechanical properties, superior temperature performance, superb drape and tack, controlled matrix flow in processing, excellent translation of fibre properties, availability on different reinforcements and excellent impact resistance. Also, the CFRP prepreg contained 18 plies hand lay-up with a high strong EP (matrix) acting as a binder. The process was carried out under a minimum of 980 mbar (29″ Hg) vacuum bag pressure with 1–2 °C (1.8–3.6 °F) per minute ramp rate. The CFRP composite laminates were supplied by Umeco Structural Materials Company. The brief and main compositions, properties and architecture of the two composite laminates (workpiece or samples) used for the experimental investigation have been illustrated earlier in Fig. 1.

A Proto TRAK VM CNC machining centre (Fig. 2c) was used for the vertical conventional drilling of the two samples. The machine has a maximum variable spindle speed and motor power of 5000 rpm and 7.5 hp (5.75 kW) respectively. The 5.0 and 10.0 mm diameters of HSS twist drills (Fig. 2c) were used, under a dry machining condition (no coolant) throughout.

2.2. Design of experiment and drilling condition

The L_{16} 4^2 orthogonal array of Taguchi method of design of experiment for feed rate and cutting speed to produce the spindle revolution were used, as depicted in Table 1. This is an efficient technique for obtaining near optimal design of experimental parameters for cost effective, bettertime management, performance, optimisation and accuracy of experimental results [11,39]. Prior to the drilling operation, a computer aided design (CAD) of the drilling plan (Fig. 2a) was carried out using Pro-Engineer (Creo 2 version) software, before programming the design into the CNC machining centre. In addition, drilling was performed with the support of an aluminium plate at the back of the composite samples. There are two different diameters hole, 5.0 and 10.0 mm that were considered, for the analysis of the two damage responses. The samples were firmly clamped in order to achieve zero degree of freedom throughout the drilling operation.

Table 1
Machining parameters considered.

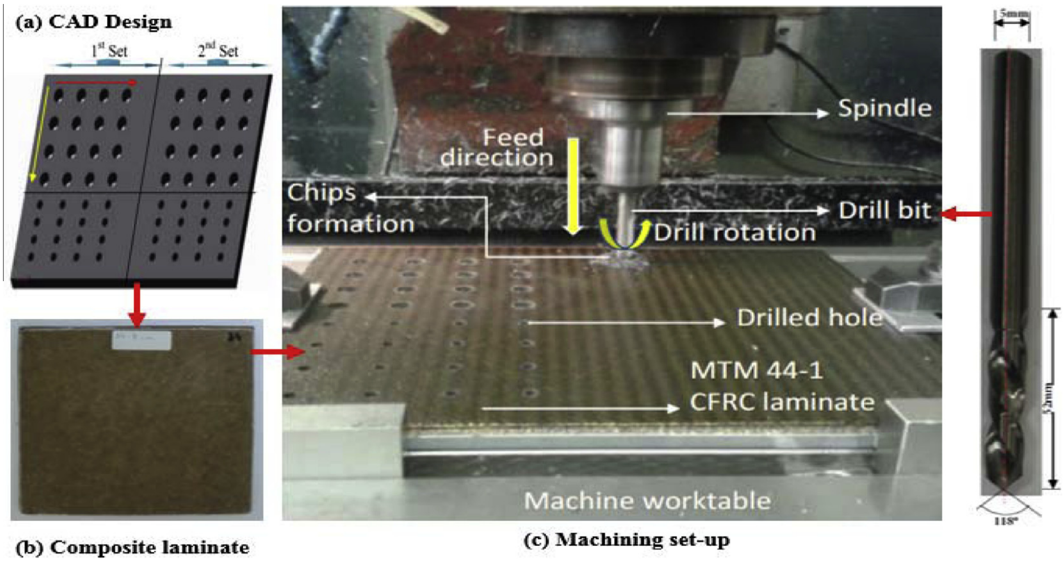
Drilling parameters	Symbol	Level				Unit
		1	2	3	4	
Feed rate	f	0.05	0.10	0.15	0.20	mm/rev
Cutting speed	v	10	20	30	40	m/min
Spindle revolution	N_5	637	1273	1910	2546	rpm
	N_{10}	318	637	955	1273	rpm

The dry machining (drilling) condition is considered throughout this experiment due to the limiting effects of wet machining on the structural quality and integrity of FRCs. The use of liquid coolant known as wet machining was discouraged, because it supports the high possibility of absorption of liquid coolant or cutting fluid by the FRCs, especially the hydrophilic nature of natural fibre reinforced composites (HFRP samples) at high temperature, though with the exception of Cindolube V30 ML liquid coolant. This is one of the limitations of composites machining under wet condition, unlike metals.

2.3. Drilling-induced damage examinations and measurements (instrumentations)

The two main damage measured and analysed are delamination and surface roughness, in addition to other defects such as uncut-fibre and minimal burrs formation defects. Burr formation occurs only for ductile material which is the case for HFRP sample. It never occurs to CFRP sample given the brittle nature of the matrix and fibres. The delamination defect around the drilled holes, known as delamination damage zone (Fig. 4b) of the samples is a microscopic phenomenon. Therefore, it is observed and measured using an OLYMPUS BX 40 optical microscope. It was operated on a 25× magnification and 1.0 μm resolution. The delamination-induced damage was quantified by delamination factor, F_d expressed as thus:

$$F_d = \frac{D_{max}}{D_o} [3,9,25] \tag{1}$$



(b) Composite laminate

(c) Machining set-up

Fig. 2. The drilling experimental set-up based on Taguchi technique.

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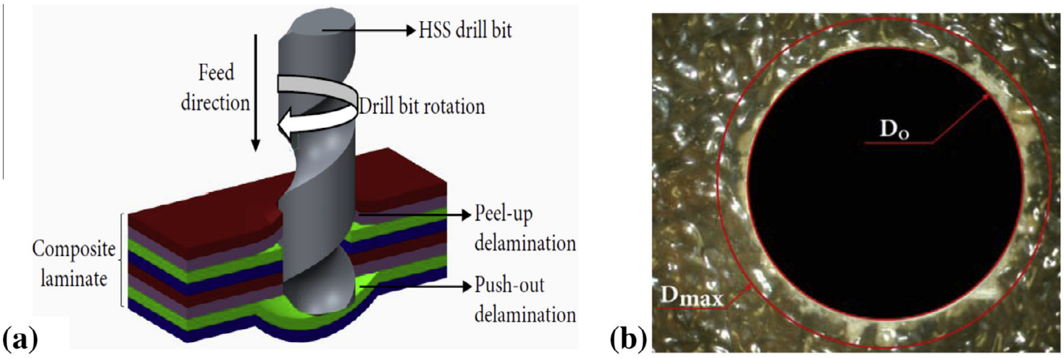

Fig. 3. Delamination: (a) phenomenon and (b) analysis (or quantification).

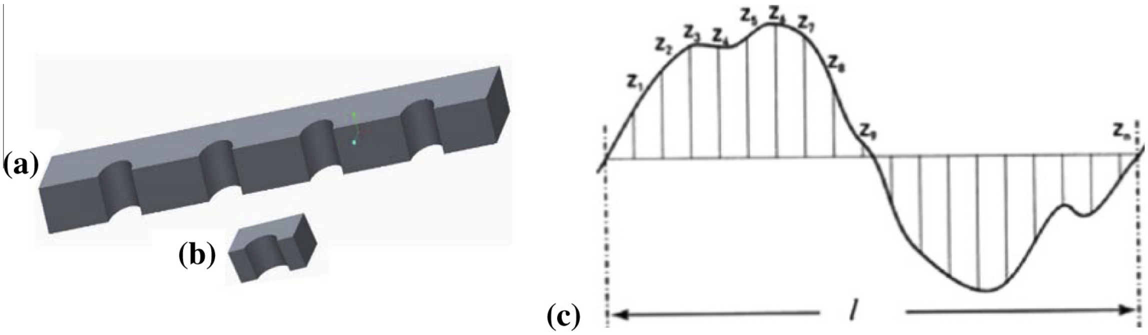

Fig. 4. The sectioning technique for drilled hole wall for: (a) surface roughness measurement (b) SEM examination sample, and (c) surface profile.

where F_d = delamination factor; D_{max} = maximum delamination zone (mm); D_o = drill bit diameters (5.0 mm), as shown in Fig. 3b.

The surface roughness indicates the level of irregularity on the machined holes' circumferential walls. This is measured in standard unit, usually in microns (µm). It implies the arithmetical average of all the perpendicular deviations from the roughness contour datum line. During the instrumentation process, the average surface roughness, commonly denoted by *Ra* was adopted throughout. The measurement of the roughness of the surface walls of all the drilled holes was performed with aid of a profilometer; a Mitutoyo surface measuring instrument with a probe stylus and SURF software. This laboratory measuring apparatus has a capacity of 300.00 µm and minimum or cut-off surface length of 2.40 mm. These are the settings at which the instrument was used to perform the surface roughness measurement. Fig. 4(c) depicts the magnitude of deviations of the roughness structure from the datum line, at a particular measured length, *l*.

The surface profile and average surface roughness are measured, mathematically represented as thus:

$$R_{a^*} = \frac{1}{l}\left\{\int_0^l |z(x)|dx\right\} \tag{2}$$

$$R_a = \frac{1}{3}\sum_{j=2}^{3}|y_j| \tag{3}$$

where R_{a*} = surface profile; $z(x) = y$ = measured roughness contour; and $j = 1$ (for trial readings), 2, 3 and 4 (for actual readings); R_a = arithmetical average surface roughness (µm); l = sample measured length (mm).

The surface roughness measurement, based on Eq. (2), was carried out along the direction of drilling, at different locations which were axially parallel to the drill direction based on ANSI standard. This location was carefully maintained for all the measurements taken. All the drilled composite laminates were carefully sectioned into two halves, as shown in Fig. 4(a). This sectioning is required so that the probe stylus of the profilometer would be able to measure the hole wall surface uninterruptedly and in order to make the samples (Fig. 4b) ready for the scanning electron microscopic (SEM) examination. Analysis of averages, according to Eq. (3), was used and readings were taken four times, with first trials of the surface roughness before the average values of other three actual readings as a process outputs were determined. Also, analysis of variance (ANOVA) was carried out using IBM SPSS and Minitab 16 software to determine the drilling parameter that has the higher performance contribution and effect.

Furthermore, the rate of the composite removal is manipulated using the model formulated by Lee et al. [40] for metal. The material (composite chips) removal rate (MRR) during drilling is therefore expressed as in Eq. (4):

$$\text{MRR} = 250DfV \tag{4}$$

where D = drills diameters (5.0 and 10.0 mm), V = cutting speed (m/min) and f = feed rate (mm/rev).

Moreover, in an attempt to further effectively detect, observe and characterise the drilling-induced damage such as surface integrity, delamination flaw, fibre-uncut and pull-out, on the two samples, more non-destructive examination techniques were conducted. These include scanning electron microscopy (SEM) and X-ray computed tomography (X-ray CT). The SEM and X-ray CT examinations were carried out on the samples with aid of a JEOL JSM-6100 scanning electron microscope and Nikon XTH 225 scanner respectively. These techniques further revealed the micrographs of the damage areas. The SEM machine has a highest magnification of ×100, 000 and resolution capacity up to approximately 40 A for imaging the areas of interest. The micrographic results obtained are shown in Fig. 10.

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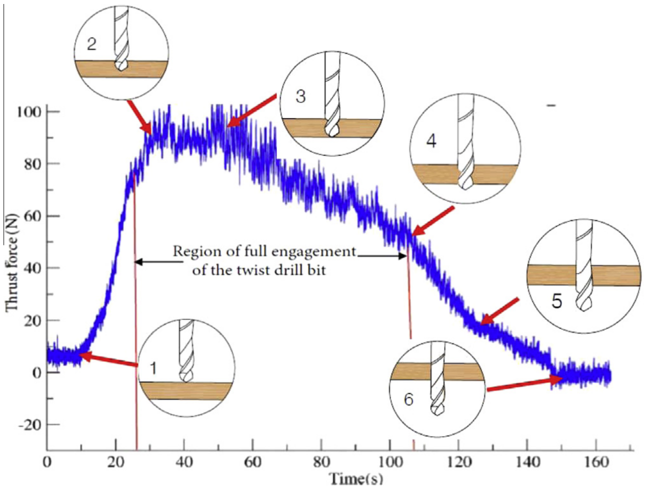

Fig. 5. Phenomenal penetration of the drill bit showing the interaction between the thrust force and time during drilling operation.

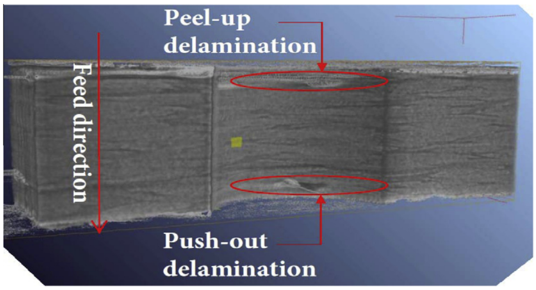

Fig. 6. X-ray CT CFRP sample micrograph showing inter-laminar delamination at stages 1 (peel-up) and 3 (push-out) when drilling at f = 0.20 mm/rev and v = 10 m/min.

3. Results and discussion

3.1. Delamination and surface roughness drilling-induced damage

The increase in feed rate caused an increase in delamination and surface roughness of both samples, unlike the delamination and surface roughness of both samples which increased with a decrease in cutting speed, as depicted in both Figs. 7 and 8. Delamination occurs mainly by an exceeded thrust force (Fig. 5), resulted from feed rate. Therefore, further analysis of the influence of thrust force on the drilling process are hereby presented.

3.1.1. Effects of drilling (thrust) force

The drilling force, mainly thrust, induced by the twist drill bit on the composite materials was noted during the conventional drilling technique used with a different drilling parameters, as earlier discussed in Table 1. The complete evolution of the process is depicted in Fig. 5; illustrating thrust force profile, and characterised by six distinctive main drilling operational stages. At inception (Stage 1), the thrust force increased drastically because of the increasing force required by the twist drill bit to gain the initial contact and entry into the composite sample (workpiece), immediately after the penetration of the chisel edge and the point angle of the drill bit. There was a gradual increase in the contact length between the composite laminate and the cutting edges. Later, the engaged radius increased from initial zero to the drill bit radius. The developed thrust force during penetration depends on the engaged radius. Stage 1 is sometimes characterised with peel-up type of delamination (Fig. 6), caused by the rapid increased force and tool-composite interface temperature [3,22]. Secondly, stage 2 shows that the force increased further as the second cutting edge of the drill bit gained full entrance to the composite sample. The creation of a blind hole occurred at this drilling stage concomitantly with an increased material removal (chip formation) rate. Stage 3 is a crucial stage that determines the quality of the drilled holes, whereby the highest force is recorded at the drill bit's tip due to the exceeded critical thrust force. The forced started decreasing at this steady state region. This can be attributed to the material properties such as the softening phenomenon of HFRP sample, especially at high cutting interface temperature, though both samples have a similar force signal. The drilling tool cut through the last or bottom ply or plies of the composite laminate, tending to push the last plies down. The possibility of a drilling-induced damage, known as the push-out delamination (Fig. 6), is very high at this stage, especially on CFRP samples.

Immediately after stage 3, a sharp decrease in the force is observed in stage 4. This occurred because the drill bit's tip has just penetrated through the last ply of the back of the composite laminate. Stage 4 describes a further sharp reduction in the force at an increased time, while the drill bit gained more exit from the sample. Next is the stage 5, where there was decrease in the contact length of the cutting edge of the drill bit, and caused more gradual decrease in the force. These phenomena are similarly reported by Ramesh et al. [9]. Lastly, the force reduced to zero at stage 6. At this final stage, there was no drilling operation, rather the reaming operation occurred.

3.1.2. Effects of feed rate and cutting speed

Comprehensively, from the results obtained on delamination factors, it is evident that the HFRP composite samples have a smaller and close values while the values of CFRP samples are higher and wide. The smaller and close values of delamination factors are rampant in bio-composites that are similar in properties [2,8], under the same drilling parameters, machining conditions (with supported back plate and dry environment) and type of drill bit. It is observed that an increase in the cutting speed caused a gradual reduction in the delamination factor. However, the delamination factor of the two samples increased with an increase in the feed rate, as shown in Fig. 7. An increase in feed rate caused an increase in drilling (thrust) force. Also, the optimum drilling conditions, hole surface finish and quality are associated with a low feed rate (0.05–0.10 mm/rev) and high cutting speed (30 m/min). These experimental results are in close agreement with that of Ramesh et al. [9], Shunmugesh and Panneerselvam [6]. Evidently, an increase in the feed rate led to a proportional gradual increase in the surface roughness. However, an increase in cutting speed caused a non-linear decrease in the surface roughness of the two samples, but very inconsistently in CFRP samples (Fig. 8). This may be attributed to the location of the fibre and the nature of the measured area of the drilled holes. The effect of each of these drilling parameters was further determined and supported using a 2-way method of analysis of variance (ANOVA) with IBM SPSS and Minitab 16 statistical software, using 95.0% confidence interval. The cutting speed responses of −0.888 and −0.860 are recorded for HFRP and CFRP samples respectively, while feed rate responses of 0.255 and 0.302 are recorded for HFRP and CFRP samples respectively. Hence, cutting speed and feed rate have a greater contributions to the responses of surface roughness and delamination statistically, respectively.

3.1.3. Effects of drill diameter and material removal rate

It is observed that the MRR has a direct proportionality to diameter, feed rate and cutting speed; it shows that the MRR increased with these drilling variables. The MRR has a great influence on the rate, efficiency and cost of production. Due to the abrasive and

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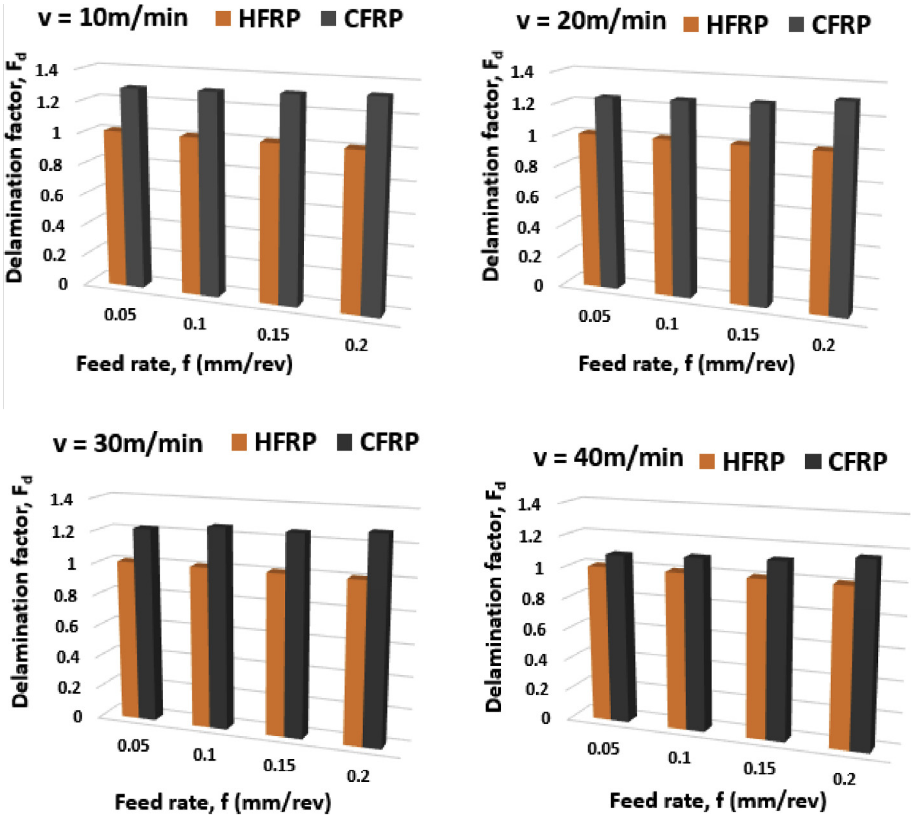

Fig. 7. Effects of the drilling parameters on delamination.

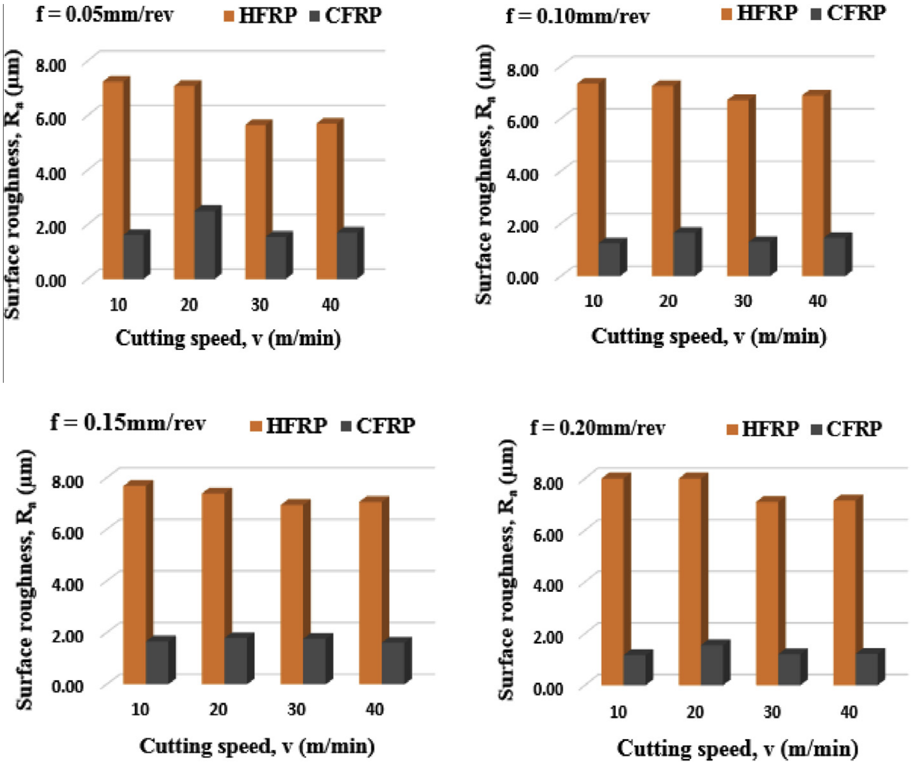

Fig. 8. Effects of the drilling parameters on surface roughness.

powdery nature of the CFRP composite laminates as well as the discontinuous chip formation during drilling operation, there was a tendency of much chips clogging on the flute of twist drills, increased at higher feed rate, cutting speed and when using bigger drill diameter (10.0 mm). This resulted into much surface damage. An insufficient chips removal and air cooling between the sample

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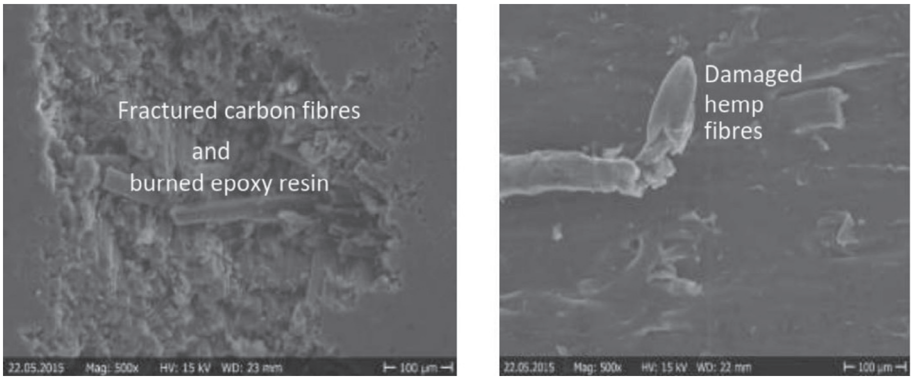
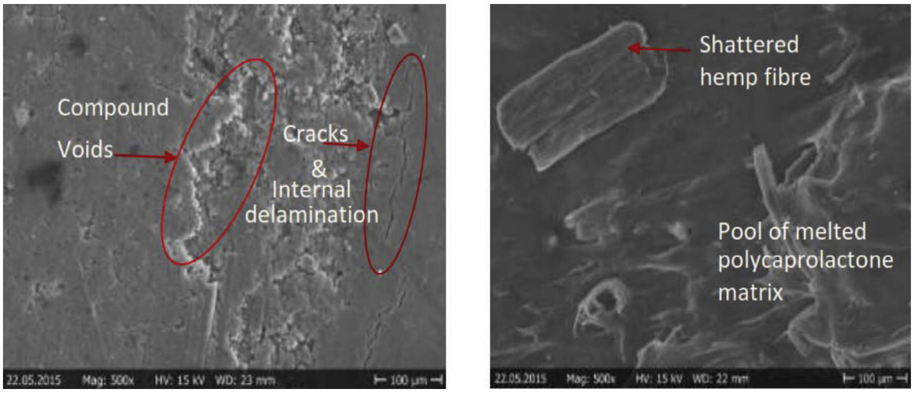


(a) CFRP (b) HFRP

Fig. 9. SEM micrographs of the samples with 10.0 mm diameter hole drilled at f = 0.05 mm/rev and v = 20 m/min.



(a) CFRP (b) HFRP

Fig. 10. SEM micrographs of the samples holes of 5.0 mm diameter drilled at f = 0.15 mm/rev and v = 30 m/min.

and drill bit interface, when there are too much of blockage on the drill flank and narrow helical flutes of a twist drill, increased the interface temperatures which aided the delamination (cracks) propagation and compound void formation. The application of a low feed rate coupled with a small diameter drills favoured minimum delamination, for an improved quality holes, especially on CFRP samples, as recently reported by Abilash and Sivapragash [7]. Comparatively, the optimum drilling conditions and better hole surface quality are associated with the use of the smaller drill diameter 5.0 mm. In order to reduce these resultant challenges of poor surface quality and delamination defects, among others, it is advisable and better to begin drilling operation with a drill bit of smaller diameter than the exact drill diameter for final expected hole, and progressively increasing the diameter of hole for the quantity of the material/chip removal rate to be minimised. Though, this proposed method is not really cost effective.

A severe fractured carbon and hemp fibres as well as the burnt matrices, causing porosity on the drilled surfaces of the holes were observed when using higher drill diameter, as shown in Fig. 9. These defects occurred at the lowest feed rate of 0.05 mm/rev and cutting speed of 20 m/min, this was expected due to the effect of an increased drill diameter on the surface integrity. The bigger 10.0 mm diameter drill bit has a greater chisel edge, web thickness and area of cut. Consequently, these increased drill bit geometries produced a higher drilling forces (thrust force and torque). Therefore, the defects observed especially in Fig. 9(a) would have been caused by the increased drilling forces, induced by the greater drill bit diameter 10.0 mm used. Furthermore, with the use of greater diameter, more dust or powder-like chips are formed. The formation of more chips supported a high interface-temperature between the composites and cutting edges of the drill bit, as the chips evacuation reduced at the averagely lower cutting speed and dry machining environment. Resultantly, this frictional generated temperature weakened the fibres and melted the binders greatly, as indicated in Fig. 9(b). This high temperature is produced around the primary cutting region, most prominently when the drilling is performed in a dry environment. The increased temperature facilitated the drill wear as more molecules of the drill gained more kinetic energy to aid diffusion and adhesion mechanisms of tool wear. These mechanisms of wear formation led to the minimal drill wear observed at the drill flank after drilling CFRP samples when compared with insignificant wear on drill after drilling the same 64th hole on the HFRP samples. The drill wear plays an important role in formation of these drilling-induced defects. Also, this can be attributed to the higher hardness, abrasive and brittle nature of the CFRP sample, and relative softness and ductility of the HFRP sample. The wear comparison between the used (worn) drill and the new type was observed by mere physical and visual inspection. In addition, the increased interface temperature sometimes causes another drilling-induced damage, known as fibre/matrix catering, fibre poll-out and matrix/binder thermal softening or de-bonding effects.

3.2. SEM quantification of delamination and surface quality (roughness)

The micrographs (Figs. 9 and 10) depict the roughness developments, fibre and matrix damage in form of peaks and valleys, at the same drilling conditions. The deep valleys and the high peaks illustrate the melted or burnt matrix and waved lumpy textured fibres, causing voids (or cavities), resultantly produced higher roughness and delamination defects on the surface of the HFRP and CFRP holes, respectively. These defects occurred prominently at a low feed rate of 0.05 mm/rev and a cutting speed of 0.20 m/min with a bigger drill diameter of 10 mm (Fig. 9) as well as at a high feed rate of 0.15 mm/rev and a cutting speeds of 30 m/min with smaller drill diameter of 5.0 mm (Fig. 10). Therefore, the cracks propagated in Fig. 10(a) occurred due to the high feed rate of 0.15 mm/rev and cutting speed of 30 m/min used. In addition, feed rate increased with the thrust force and torque. Therefore, both thrust force and torque are the responsible factors for the occurrence of the compound voids, cracks, internal delamination and matrix melting of the two samples, as depicted in Fig. 10(a) and (b).

Moreover, Figs. 9(a) and 10(a) show a compound void and cracks propagated in the CFRP composite by delamination and de-bonding phenomena respectively. The propagation of the cracks is more prominent in a brittle materials than the ductile materials. The CFRP composites are more brittle than the HFRP composite due to their different reinforced fibres and binders. The PCL matrix of HFRP is a ductile material, which increased the toughness of its constituent composite and consequently, reduced the possibility of having cracks and internal delamination drilling-induced problems, unlike the CFRP composites when subjected to the same drilling condition and parameters. The EP of CFRP composites is a thermoset polymer matrix while PCL of HFRP is a thermoplastic polymer matrix. Typically, thermosets are relatively brittle, but they possess better chemical resistance and stronger interfacial bonds. Also, the decomposition and glass transition temperatures of EP are greater than PCL matrix. The damages observed in the CFRP composite samples are point concentrated defects, while that of HFRP are uniform damage, mainly caused by the melted and sintered PCL matrix.

3.3. Chips formation morphology and characterization

Chips are generated immediately when the composite materials undergo a plastic deformation, generally at the drill-material slipping interface within a shearing region. During the chip formation, neither a dust-like nor a very long continuous chips is encouraged during drilling operations. The powdery chips from the CFRP composites are not easily evacuated from the drill flutes, causing a chip clogging due to high friction and forces developed, while a long continuous chips often results into a serious chip evacuation predicaments. These problems have a high propensity of causing decrease in drilled holes quality, tool (drill) life and drill breakage, if they are not properly managed.

The chips formation increased during drilling of both samples at an increased feed rate and cutting speed, which was well prominent at 0.20 mm/rev and 40 m/min feed rate and cutting speed respectively. A continuous brown ribbon-like chips formed during the drilling of HFRP sample, while the size of the CFRP discontinuous black powder-like chips generated was very small, fine, powdery and abrasive in nature, due to the properties of their fibres and matrices. The higher the feed rate and cutting speed, the wider, longer, more ribbon-like and lighter the HFRP chips and conversely, the powdery or dusty, smaller and darker the CFRP chips formation, as shown in Fig. 11. These types of chips formation produced a lower surface roughness in the CFRP samples, delamination and drill wear in HFRP samples. Conclusively, the type of chips formation also affected the mode and possibility of formation of drilling-induced damage both on the samples and the drill bit used.

3.4. Other drilling-induced damage

Further non-destructive examinations on the samples were conducted with aid of X-ray computed tomography (X-ray CT) technique. In addition to the discussed defects, drilling-induced damage such as uncut-fibre and burrs formation were observed. Fig. 12 depicts the occurrence of both small burrs and few uncut-fibres in HFRP composite samples, especially at the entrance and exit of some of the drilled holes. The uncut-fibres damage occurred at a lower feed rate and cutting speed, whereas the minimal burrs were observed at a lower feed rate and average cutting speed. However, the CFRP composite samples have none of these defects. These defects reduce the integrity of the holes and machinability of the HFRP samples. There are needs for some post-machining operations to be performed in order to remove these defects, such as de-burring and probably, reaming. Therefore, they tend to increase the total machining time and cost of manufacture. The use of the CFRP composite laminates should be encouraged when burrs are highly prohibited and cannot be compromised.

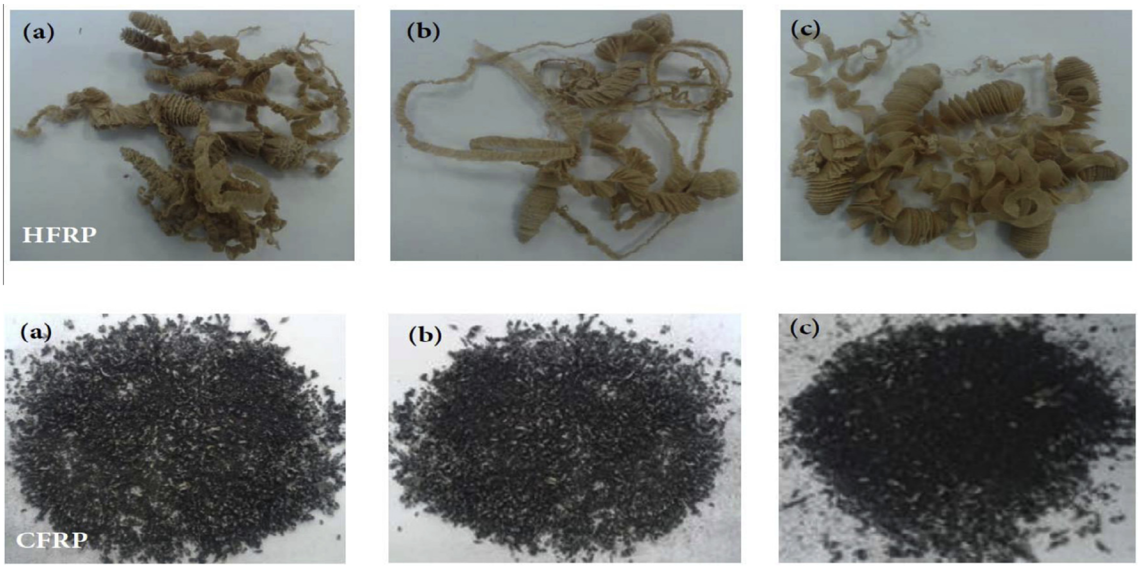


Fig. 11. Chips morphology at different drilling parameters: (a) $f = 0.05$ and $v = 10$; (b) $f = 0.15$ and $v = 30$; (c) $f = 0.20$ mm/rev and $v = 40$ m/mm.

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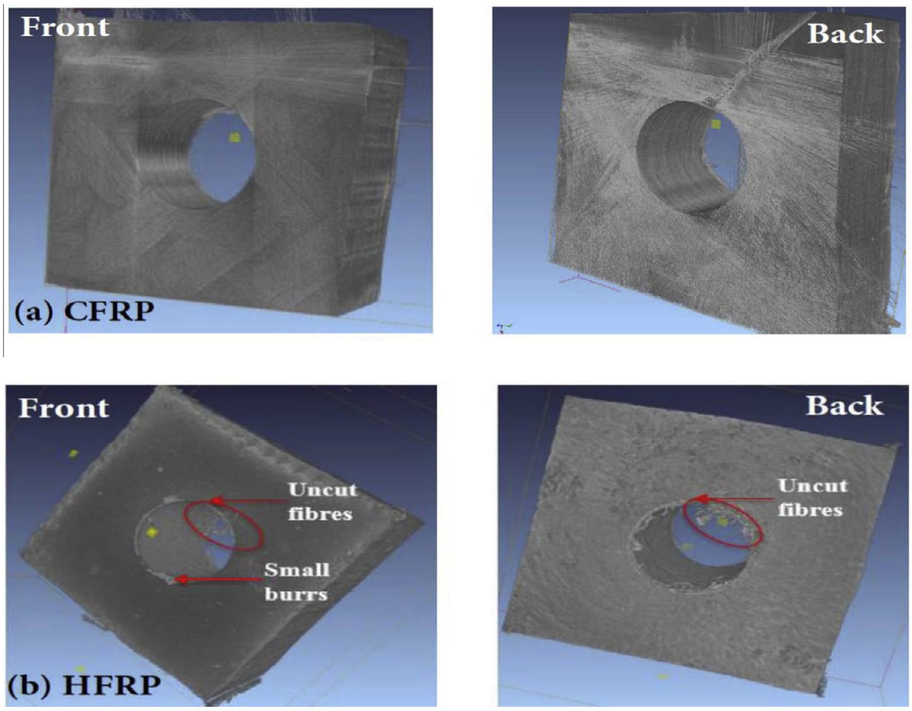

Fig. 12. The X-ray CT scanning micrographs, showing: (a) CFRP-without fibre-uncut and burrs and (b) HFRP-with fibre-uncut and burrs damage.

4. Conclusions

The drilling-induced damage analysis, mainly on delamination and surface integrity of drilled lignocellulosic 19/HFRP and UD MTM 44-1/CFRP OC composite samples, has been carried out experimentally. The following results obtained are hereby summarily highlighted:

i. Evidently, the drilling-induced damage are more protuberant and severe in the CFRP than the HFRP samples when considered under the same conditions. There are more fractured carbon fibres than the hemp fibres, most importantly at an increased feed rates of 0.15 and 0.20 mm/rev.
ii. The damage on both FRC samples significantly depend on the drilling parameters and properties of their constituents (fibres and matrices). An increase in drilling parameters affected the drilled hole quality of both HFRP and CFRP samples, because the hemp fibre and its PCL matrix of HFRP sample have a lower thermo-mechanical properties, while the carbon fibre and its EP matrix are greater.
iii. The SEM micrographs show that an increased drill diameter affected the surface integrity of both samples more than causing delamination defect, because the bigger drill diameter produced greater MRR and chips. The X-ray CT examination depicts that minimal burrs formation and few uncut-fibre defects are associated with the HFRP composites drilling. However, these damage are not commonly observed on the CFRP composite sample due to the properties of its constituents, but CFRP sample is mainly characterised with inter-laminar cracks and delamination.
iv. There was a discontinuous chips formation, which was abrasive and powder-like in nature during drilling of CFRP composite laminates, unlike a continuous chips formation, long and coiled, which characterised that of HFRP composites. These types and quantity of chips formation determined the type and severity of the drilling-induced damage occurred.
v. The minimal drill wear is noticeable after drilling 64 holes, 32 holes using diameter 10.0 mm and 5.0 mm each, of CFRP composites while there was an insignificant or null wear evident on the HSS twist drill used after drilling HFRP composite samples.
vi. The minimum surface roughness and delamination factor of the two samples for the optimum drilling are associated with a feed rate of 0.05–0.10 mm/rev and cutting speed of 30 m/min. Therefore, the optimum drilling conditions, surface finish and hole quality on the samples appeared to occur at a low feed rate, moderate high cutting speed and a small drill diameter employed.
vii. Lastly, based on the ANOVA and other statistical results obtained, the CFRP sample has a lower surface roughness (better surface finish), while HFRP composite sample exhibited a lower delamination drilling-induced damage. Both samples are considered and analysed within the same drilling condition and parameters. Hence, the choice of their engineering applications should depend on their responses to these damage.

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