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# The effects of drilling parameters and aspect ratios on delamination and surface roughness of lignocellulosic HFRP composite laminates

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## ABSTRACT

Hemp fibre-reinforced polycaprolactone (HFRP) composite has inherent good mechanical properties and benefits which include remarkably high specific strength and modulus, low density and renewability. No doubt, these properties have attracted wider applications of HFRP composite in engineering applications. This paper presents an investigation on the influence of drilling parameters and fibre aspect ratios, AR (0, 19, 26, 30 and 38) on delamination damage factor and surface roughness of HFRP composite laminates utilising high speed steel twist drills under dry machining condition. Taguchi's technique was used in the design of experiment. The results obtained show that increase in cutting speed reduces delamination factor and surface roughness of drilled holes, whereas increase in feed rate causes increase in both delamination factor and surface roughness. Feed rate and cutting speed had the greatest influence on delamination and surface roughness respectively when compared with aspect ratio, while an increase in fibre aspect ratios leads to a significant increase in both delamination factor and surface roughness. The optimum results occurred at cutting speed and feed rate (drilling parameters) of 20m/min and 0.10mm/rev respectively when drilling sample of AR 19.

**KEY WORDS**: Fibres; Laminate; Drilling parameter; Aspect ratio; Delamination; Surface roughness.

**Nomenclature**

| | | | |
|---|---|---|---|
| HFRP | hemp fibre reinforced polycaprolactone | CAD | computer aided design |
| HNF | hemp natural fibre | CC | cemented carbide |
| PCL | polycaprolactone | $V$ | cutting speed, *m/min* |
| NFRC | natural fibre reinforced composites | $f$ | feed rate, *mm/rev* |
| GFRC | glass fibre reinforced composites | $D_{max}$ | maximum diameter of the delamination zone, *mm* |
| CFRC | carbon fibre reinforced composites | $D$ | drill diameter, *mm* |
| GFRP | glass fibre reinforced plastic | $F_d$ | delamination factor, $\frac{D_{max}}{D}$ |
| CFRP | carbon fibre reinforced plastic | $R_a$ | surface roughness, $\mu m$ |
| CNC | computer numerically controlled | $l$ | length of the fibre, *mm* |
| HSS | high speed steel | $d$ | diameter of the fibre, *mm* |
| PCD | polycrystalline diamond | AR | aspect ratio, $l/d$ |

## INTRODUCTION

After many decades of developments of composites manufacturing technology, the desire to improve the machining of these materials based on the numerous areas of application remains a challenge. Today, the attention of many product manufacturers has shifted to natural fibre reinforced composites (NFRC) due to the unease of production and increased tool wear from the use of synthetic fibre-reinforced composites. One of the prominent types of NFRC is HFRP (hemp fibre reinforced polycaprolactone) composite. HFRP composite comprises hemp fibre and bio-polymer as the reinforcement material and as binder respectively. Hemp natural fibre (HNF) is an example of organic dicotyledonous bast plant stem fibre obtained from non-wood natural fibre while polycaprolactone (PCL) is a synthetic matrix that serves as a bio-binder. Hemp is botanically referred to as *Cannabis sativa*, originated from Asia and it is one of the main sources of natural fibres.[1] The choice of HNF among other similar natural fibres depends on its great advantages. HNF is one of the strongest natural fibres, grows very well on several land appropriate for farming with huge production per year. It is suitable for the bio-composite reinforcement due to its relative high density and cellulose contents. The fibre processing of HNF requires less energy. In addition, both HNF and PCL have good mechanical properties, as shown in Table I.[2, 3]

HNF has damage tolerance and impact resistance properties in addition to its non-abrasiveness, high toughness, sustainability, renewability or recyclability, good thermal properties and capability on different reinforcements when compared with synthetic fibres.[2, 39] PCL has a biodegradable nature with cellulose contents. As a result of lower cost of production, higher thermal resistance and environmental superiority, NFRC have started replacing GFRC.[2,4-6] The wider applications of NFRC cut across domestic appliances, automotive, building and food industries.[2,6]

Table I. Mechanical Properties of HNF and PCL[1-3]

| Properties | Value | |
|---|---|---|
| | HNF | PCL |
| Density (g/cm$^3$) | 1.0 – 1.48 | 1.13 |
| Tensile Modulus (GPa) | 30 –70 | 0.4 |
| Moisture content (wt. %) | 10.8 –14.5 | – |
| Tensile (Fracture) strength (MPa) | 310 – 900 | 16–23 |
| Elongation to failure (%) | 1.6 | >700 |

Drilling attracts much significance and consideration among secondary machining operations such as boring, tapping and reaming used in manufacturing industry.[7,8] But, use of conventional metal cutting techniques in drilling composites has resulted in poor finish quality and excessive tool wear. These problems are caused due to the abrasive, heat sensitivity, heterogeneous and anisotropic nature of composite materials, [9] tooling materials, tool geometry and drilling parameters,[10-14] making their drilling a complex operation.[8,15-19] Drilling of composite material has several common problems that include delamination, surface roughness, tool edge chipping, fibre pull-outs and uncut fibre. Among these, delamination is probably the most critical defect [20,37] as it has the highest level of impact on accuracy and quality, followed by surface roughness. The CFRC perform better than NFRC especially in structural applications. But, due to the problems of poor surface quality and higher delamination effect, NFRC have been considering as an alternative. Hence, there has not been much experimental study on the delamination and surface roughness responses of NFRC under different cutting speeds, feed rates and aspect ratios. The fibre aspect ratio is a vital factor to be considered during the materials (composites) selection for engineering applications, as aspect ratio increases with increasing strength of the fibre reinforced composites. The NFRC with a very high fibre aspect ratio has close properties when compared with CFRC of an average fibre aspect ratio.

This paper presents results of an experimental investigation into the effects of drilling parameters and aspect ratios. An experimental design method based on Taguchi's technique is used to investigate the influence of cutting speed, feed rate and aspect ratio on delamination and surface roughness in drilled different HFRP composite laminates.

Delamination in a composite material occurs whereby reinforced fibre plies separate, either by peel up or push-out phenomenon.[9,37] Delamination is prominent at both entry and exit parts of the twist drill when the thrust force is higher than the threshold value,[21] but it reduced significantly when CFRP was stacked and supported by aluminium and titanium layers.[22] Also, this defect occurs at the upper most layer of laminate from the rest of the body and/or on the drill bit's tip which pushes the bottom layers of the laminate respectively. Madhavan and Prabu [19] reported that increase in cutting speed reduced the delamination for HSS drills, whereas the increase in feed rate increased the delamination in the case of carbide drills, but PCD drills had the lowest delamination factor. Similarly, Turki, Habak, Velasco, Aboura, & Khellil [23] reported in their experimental work that increase in delamination factor leads to noticeable increase in feed rate, and that low feed rate produces minor drilling damage on the carbon/epoxy composites. Capello [24] analysed the differences between delamination mechanisms when drilling laminate composites with and without a support device placed under the composite. He concluded that drilling with a supported device drastically reduced delamination. In addition, Park and Jang [40] concluded in their experimental finding that the fibre orientation (directions) determines the extent of delamination area of aramid fibre/polyethylene fibre hybrid composite. Isbilir and Ghassemieh [25] investigated the possibility of delamination free drilling process by the proper selections of drill point geometry and the process parameters: high spindle speed and lower feed rate. They showed that effective tool choice could minimise delamination effect. Most importantly, the use of higher feed rates was achievable provided there was sufficient knowledge of the effects on thrust force and delamination for each selected drill. Tsao and Hocheng [26] used an analytical approach to identifying the process window of chisel edge length concerning drill diameter for delamination-free drilling. They concluded that composite laminates drilling at higher feed rate without delamination damage could be conducted by controlling the ratio of chisel edge length and preferring medium to large hole. Liu, Tang, & Cong [27] stated in their review study that feed rate had the greatest influence on drill wear, thrust force and delamination. Kilickap [28] observed that an increase of HSS drill point angle led to a decrease in delamination effect during unidirectional-ply GFRP composite laminate drilling. During drilling (high speed and conventional) of woven-ply CFR, Gaitonde, Karnik, Rubio, Correia, Abrao, & Davim [29] reported that cemented carbide K20 point angle increases with increase in delamination damage. Some studies 15,17,30 used HSS drills; making it the most widely used tooling material 43 due to its availability, low cost, highest toughness and moderate effects on delamination and surface roughness.

Surface roughness, the average mean of the departures of the roughness profile from the mean line within the evaluation length, has also been widely investigated. Mechanical properties such as creep life, fatigue strength, wear and corrosion resistance can be improved through a desirable quality drilled hole. Babu, Babu, & Gowd [31,32] noticed in their experimental work that HFRC recorded lowest delamination factor and surface roughness when compared with glass, jute and banana fibre-reinforced composites. They concluded that low feed rates coupled with high cutting speeds reduced delamination and prolonged tool life.[27,31,32] Ogawa, Aoyama, Inoue, Hirogaki, Nobe, Kitahara, Katayama, & Gunjima [33] and Abrao, Campos Rubio, Faria, & Davim[34] reported that surface roughness varies at different speeds, but speed is only of minor influence unlike feed rate. They,[33] as well as Rahman, Mamat, & Wagiman [35] concluded that surface roughness of drilled holes increases with increase in feed while cutting speed increases with decrease in surface roughness. Shrivastava and Singh[36] concluded in their experimental study that the aspect ratio increases with the influence of increase in boundary conditions on the buckling load. They stated that aspect ratio is one of the relevant parameters used in the field of design engineering in order to prevent composites failure in terms of buckling. Also, the mechanical properties or performances such as strength of composite materials depend and improve with increasing fibre content.[39, 41]

## EXPERIMENTAL STUDY

### Materials and Method

Five squared 197 x 197mm, thickness 7.5mm HFRP composite laminates designated as samples A, B, C, D and E made up of different aspect ratios, AR of 0 (neat), 19, 26, 30 and 38 respectively were used as specimens for this investigation. The first sample has no hemp fibre reinforcement. All the diameters of the fibre elements present in the HFRP were in the same order of magnitude (Table II), close to 22µm. This means that majority of fibre elements were small bundles size elements or individualised fibres. Therefore, the aspect ratio (L/D) of the samples varied due to the length, L only.

Table II: Analysis of the fibre aspect ratios

| Aspect ratio | 19 | 26 | 30 | 38 |
|---|---|---|---|---|
| Mean fibre element length, L (μm) | 432 | 568 | 708 | 845 |
| Mean fibre element diameter, D (μm) | 22.4 | 21.7 | 23.6 | 22.5 |

An extrusion process was used to prepare the specimens using a resin bio-binder; PCL possessing a specific gravity of 1.1 at 60oC and flash point of 275oC (open cup method). The composites were prepared using a laboratory-scale twin screw extrusion (TSE) Clextral BC 21 (Firminy, France). The extruder has a diameter (D) of 25 mm and a length (L) of 900 mm (L/D ratio: 36). Hemp fibres elements and PCL were introduced either all together in the hopper or in two location. In all cases, a venting zone for water steam evacuation was included. The fibres were mixed with PCL at a concentration of 20 wt. %. The barrel temperature was set at 100°C, and the experiments consisted of varying parametric setup of the extruder: feed rate and screw speed. A triplicate of data sheet from both extrudate neat PCL or 20% wt hemp fiber/PCL composites differing in their average L/D ratio were obtained by Press molding. The press is a two-column automatic laboratory hydraulic press (Carver, Wabash, IN USA) equipped with heating platens. Three types of molds (MGTS, La Neuvillette, France) of all 20cm x 20cm length but differing in their thickness: 5; 6.5 and 8 mm (approx. 340; 280 and 220g on average respectively), were filled with samples and preheated 5mins at 135°C before 1 Ton pressing for 3mins. Data sheets were then cooled down by immersion in distillated water, dry and stored at 65% RH before testing. Two double-fluted standard HSS twist drills were used for the drilling, details are presented in Table III.

Table III**.** Twist Drills Specification

| Set | Diameter (mm) | Length (mm) | Description |
|---|---|---|---|
| 1 | 5.0 | 115.30 | High Speed Steel (HSS) twist drills of different diameters, point angle 118$^o$, two cutting edges and manufactured by DORMER |
| 2 | 10.0 | 206.64 | |

## Machining Set-up and Conditions

Drilling of the composites was carried out on a HURCO VM 10CNC machining centre (Figure1) with a maximum spindle speed of 10,000rpm.The composites were clamped firmly to avoid movement of test specimens, and machining was performed under dry conditions throughout. The cutting conditions implemented are shown in Table IV.

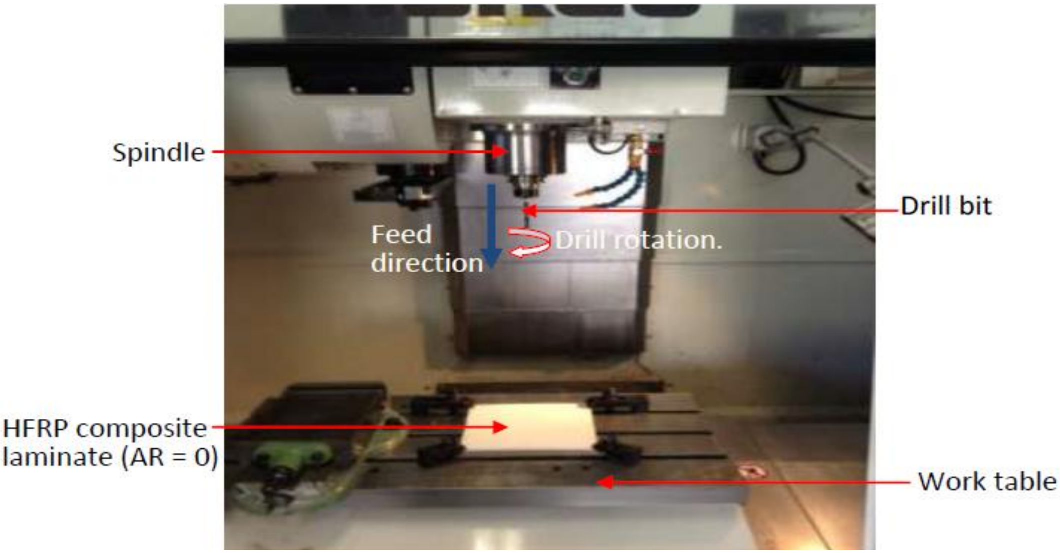
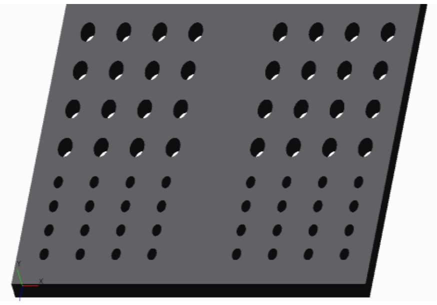
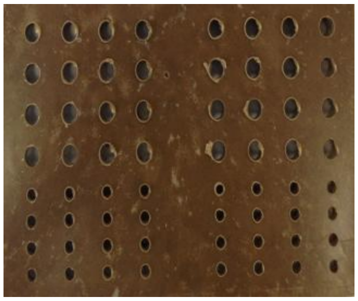


Figure 1. Machining experimental set-up.

**Design of experiments**

The experiments were conducted using an $L_{16}$ ($4^5$) orthogonal array corresponding to sixteen rows equivalent to the test number with two factors at four different levels. These rows imply tests in which first and second columns were allocated to the cutting speed and feed rate respectively, and the remainder were allocated to the five samples or iterations. Surface roughness and delamination are the two responses investigated with respect to different aspect ratios of the five HFRP composite laminates. Pro-Engineer, Creo 2 design software was used to produce the CAD drawing (Figure 2(a)) before drilling operation was carried out to produce drilled composite laminates (Figure 2(b)).





(a) CAD drawing. (b) Drilled laminate.

Figure 2. Drilling experimental plan.

### Experimental procedure

The cutting speed and feed rate were selected for the investigation as indicated in Table IV, being the two most notable drilling parameters that influence the quality of drilled holes. The spindle revolution of drill bits of diameters 5.0mm and 10.0mm, denoted as N5 and N10 was also included respectively. The HSS twist drill bits of diameters 5.0mm and 10.0mm were used for the drilled holes for delamination and surface roughness analyses respectively.

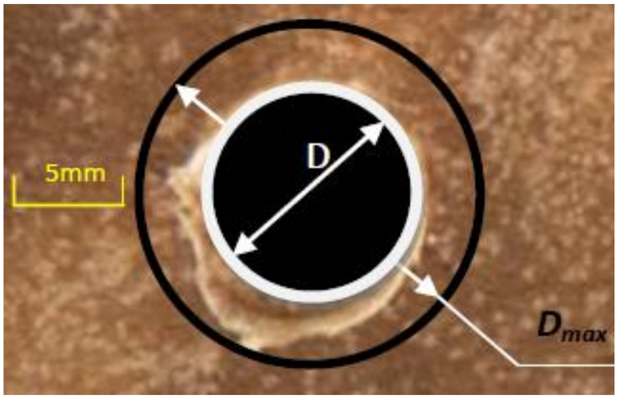
Table IV. Machining Conditions Considered

| Drilling Parameters | Symbol | Level 1 | Level 2 | Level 3 | Level 4 | Unit |
|---|---|---|---|---|---|---|
| Feed rate | f | 0.05 | 0.10 | 0.15 | 0.20 | mm/rev |
| Cutting speed | v | 10 | 20 | 30 | 40 | m/min |
| Spindle revolution | N5 | 637 | 1273 | 1910 | 2546 | rpm |
|  | N10 | 318 | 637 | 955 | 1273 | rpm |

These drilling parameters were programmed into the CNC drilling machine centre for an uninterrupted operation for both first and second sets. Sharp and new double fluted drills were used in order to reduce delamination effect and surface roughness. Observations were made immediately after completion of each set, followed by the measurement of the delamination factor and surface roughness in the laboratory.

### Measurement of delamination factor and surface roughness

An OLYMPUS BX 40 optical microscope with 25x magnification and 1.0µm resolution was used to measure the delamination damage around the drilled holes. The delamination factor is the ratio of the maximum diameter of the delamination zone, $D_{max}$ to the drill diameter, $D$ (5.0mm), [8, 15, 19] as shown in Figure 3. Increasing delamination factor implies that the delamination effect is also increasing.[8, 38]



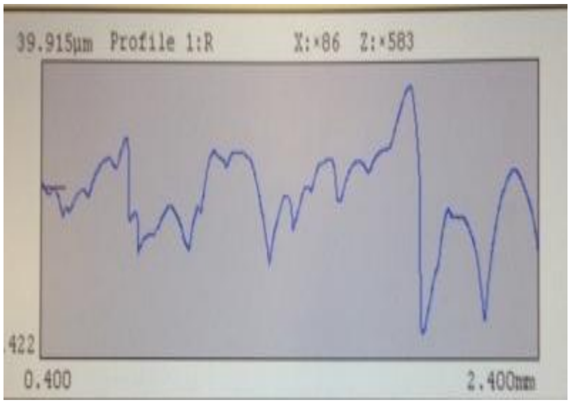


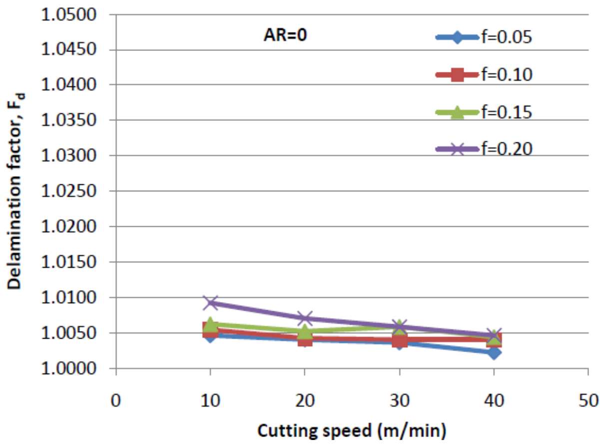
**Figure 3.** Analysis of determination of delamination factor. **Figure 4.** Reading from profilometer used.

The surface roughness, measured in microns (µm), implies the degree of roughness on the circumferential walls of the drilled holes. The average surface roughness was considered throughout this analysis. It is the arithmetic mean of all the vertical deviations from the datum or reference line of the roughness contour. The surface roughness of the drilled 10.0mm holes were measured (Figure 4) using Mitutoyo surface measuring instrument (profilometer), with SURF software having capacity and minimum surface length of 300.0µm and 2.4mm respectively. This software was able to measure the depth of the drilled hole since a sample of 7.5mm thickness each was considered. Figure 4 depicts the magnitude of deviations of the roughness structure from the datum within the measured length. Surface roughness measurement was carried out along the direction of drilling, and analysis of averages was used and readings were taken twice, with trials of the delamination factor and surface roughness before their average values as process outputs were determined.

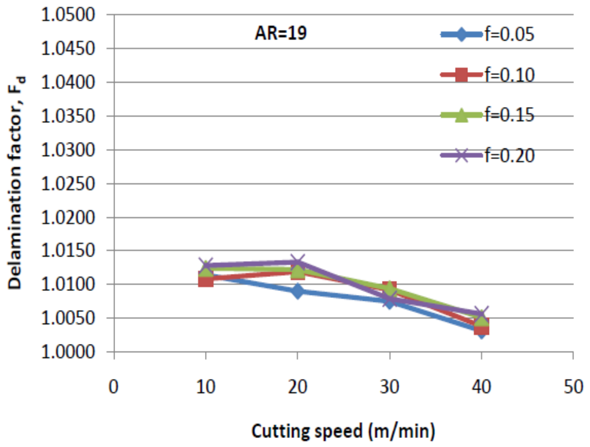
## RESULTS AND DISCUSSION

### Influence of the drilling parameters on delamination factor

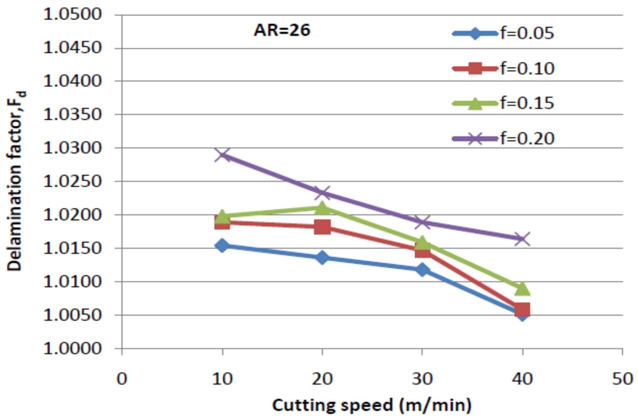
The effects of cutting speed, feed rate and aspect ratio on delamination factor are presented in Figure 5. The results of delamination factors obtained from the HFRP samples were evidently reduced due to the type of drill bit and related drilling parameters used, when compared with similar bio-composites and CFRP composites.[8, 15, 42] Figure 5 depicts that increase in cutting speed reduces the delamination factor, whereas increase in feed rate causes increase in delamination factor. The responses of samples A and B to delamination are very similar as the differences in their delamination factors are very close. This implies that they both responded slowly to the delamination when compared with both samples D and E, which have a sharp response of delamination factor as the feed rate increases and cutting speed decreases. The sample C has an average response to delamination effect. The sample E has the highest values of delamination factor and aspect ratio. The variation in the responses of these samples to delamination can be traced to the proportionality of their aspect ratios. It is also observed that feed rate has greater influence on delamination when compared with cutting speed, as shown in sample E with almost parallel graphs between two successive cutting speeds. Furthermore, samples D and E clearly show the significant effects of the increased feed rate when compared with the first three samples of similar response. This is indicated with the wide gap difference (scatter) in delamination factor at a certain cutting speed.



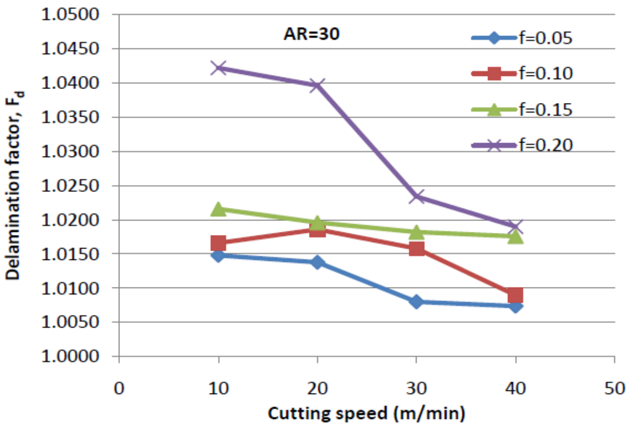
**Sample A**



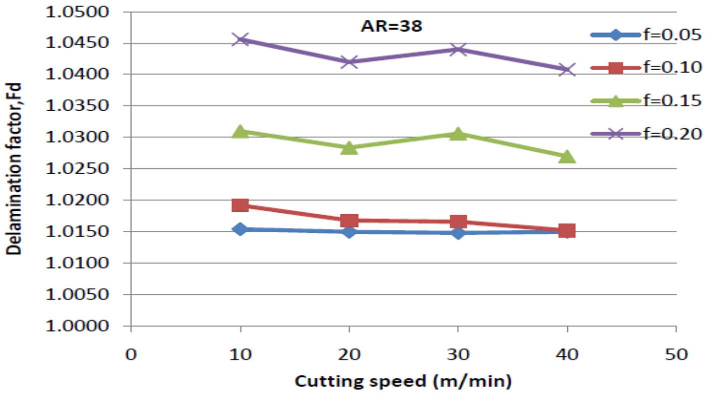
**Sample B**



**Sample C**



**Sample D**

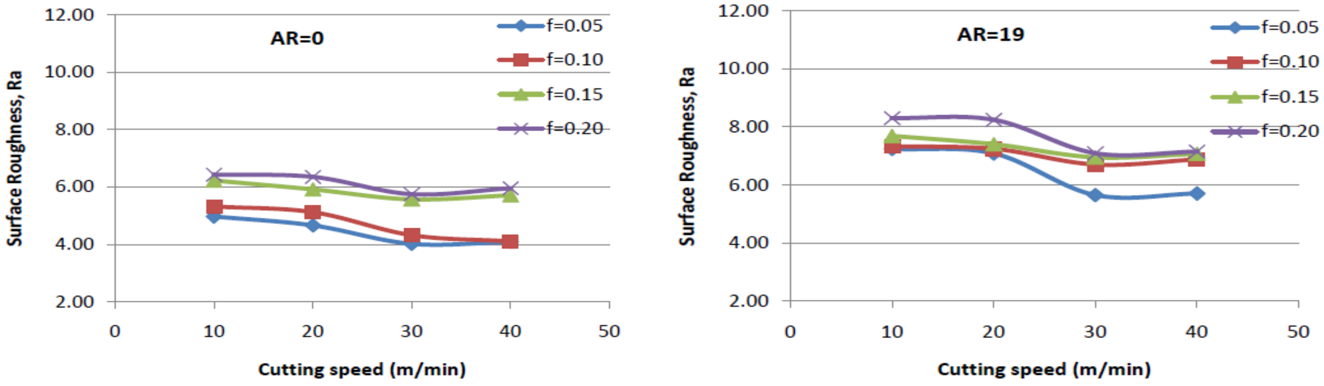


**Sample E**

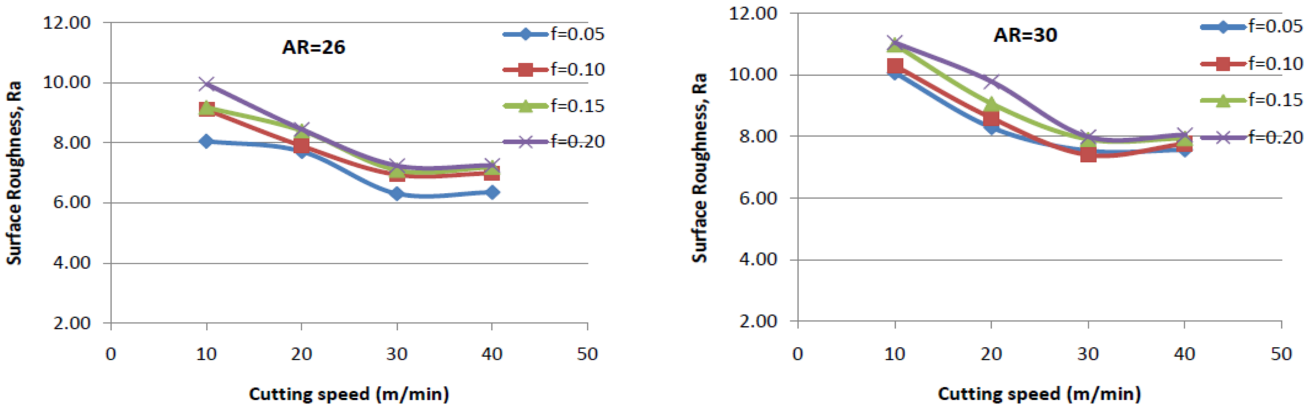
Figure 5. Effect of cutting speed, feed rate and aspect ratio on delamination factor.

## Influence of the drilling parameters on surface roughness

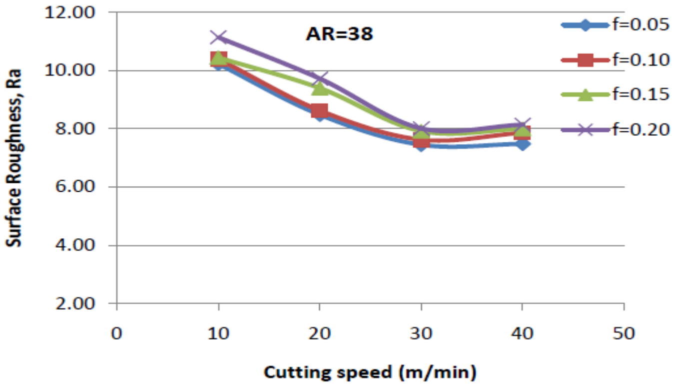
The relationship between surface roughness and cutting speed, at increasing feed rate and aspect ratio are illustrated in Figure 6. The results obtained show that surface roughness increases with increase in feed rate unlike the cutting speed; cutting speed increases with decrease in surface roughness. Figure 6 shows that sample A without reinforcement has the lowest value of surface roughness at highest value of cutting speed and lowest value of feed rate. This trend increases along the five composite samples with laminate E having the highest surface roughness at lowest and highest values of cutting speed and feed rate respectively. Each of the samples has close response to surface roughness, but increases with increasing aspect ratios as feed rate increases and cutting speed reduces. At highest cutting speed, a small increase in surface roughness is observed across all the five drilled samples especially in D and E.



**Sample A** **Sample B**



**Sample C** **Sample D**



**Sample E**

Figure 6. Effect of cutting speed, feed rate and aspect ratio on surface roughness.

The analysis of variance (ANOVA) was performed using the 2-way method and MINITAB16 software. It is observed that the feed rate, f and cutting speed, v have a greater statistically contributions to the occurrence of delamination and surface roughness drilling-induced damage respectively. These results support or agree with the graphical results presented in Figures 5 and 6.

## Influence of aspect ratio on delamination and surface roughness

The fibre aspect ratio is another factor that determines the delamination damage and surface roughness of the composite samples. Figures 5 and 6 depict that increase in aspect ratio leads to increase in delamination factor and surface roughness. The increase in delamination factor and surface roughness across the samples depends on the ratio of their aspect ratios. The influence of aspect ratio on delamination and surface roughness of sample A with zero aspect ratio was the least; almost negligible in case of delamination. This trend increased with increasing aspect ratio. Sample E with highest value of aspect ratio has the maximum values of delamination factor and surface roughness. The increase in fibre aspect ratios leads to a significant increase in both delamination factor and surface roughness, but increase of surface roughness with increasing fibre aspect ratio is found greater when compared with an increase of delamination with increasing aspect ratio. This may be due to the type of drill used, fibres orientation, dimension, concentration and matrix or inhomogeneous arrangement within a specific composite laminate, especially within the area drilled and stylus measured length.[39] In addition, the threshold fibre aspect ratio takes place at 19, which is less than 20 (regarding as a low AR).[39] This implies that when drilling HFRC at cutting speed and feed rate above 20m/min and 0.10mm/rev respectively, to avoid greater delamination effect and surface roughness, the choice of the aspect ratio of the HFRC should be below 19.

Few uncut fibre and fibre pull out were observed in 5.0mm holes especially at feed rates of 0.05 and 0.10mm/rev with cutting speeds of 10 and 20m/min respectively. Minimal burrs occurred at the entrance of the 10.0mm holes at feed rate of 0.05mm/rev with 30 and 40m/min cutting speeds. Short and melted chips formed at lowest feed rate and cutting speed, as depicted in Figure 7(a). Meanwhile, continuous ribbon-like chips formed at 0.20mm/rev and 40m/min feed rate and cutting speed respectively (Figure 7(b)); the higher the feed rate and cutting speed, the wider, longer and lighter the chips.

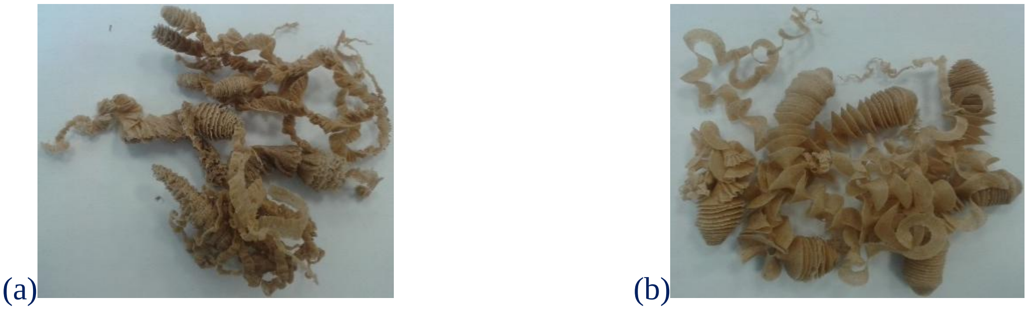


Figure 7. Chips morphology at: (a) f = 0.05mm/rev & v = 10 m/mm and (b) f = 0.20mm/rev & v = 40m/mm.

Almost no wear land was observed in the flank surface of the drill due to the nature of the composite and moderate cutting parameters used.

## CONCLUSIONS

The main aim of this experimental study was to optimise the drilling process of HFRP composite laminates. It was achieved by determining the predictable parameters of drilling in accordance with the aspect ratio of the composites. Hence, the effects of cutting speed, feed rate and aspect ratio have been investigated on delamination and surface roughness of drilled holes of HFRP composite laminates. The following conclusions can be made:

- The effect of feed rate on delamination and surface roughness increased with the aspect ratio. Increase in cutting speed reduced the delamination factor, whereas increase in feed rate caused increase in delamination factor. Hence, low feed rate and high cutting speed minimised delamination effect.
- Feed rate has a greater influence on delamination and surface roughness when compared with cutting speed; surface roughness increased with the feed rate unlike the cutting speed which has a small effect; increase in cutting speed caused decrease in surface roughness.
- Surface roughness increased with the lignocellulosic fibre aspect ratio. This increase was greater when compared with an increase in delamination with aspect ratio.
- Delamination damage was lower in HFRP composite laminates when compared with CFRP composite materials.
- The optimum result was obtained with sample of AR 19, at cutting speed and feed rate of 20m/min and 0.10mm/rev respectively.

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Graphical Abstract: