Machining of FRP composites with CD and UAD techniques: A comparative and experimental investigation

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Abstract

The enhanced properties and increased application of a natural hemp fibre-reinforced polymer (HFRP) composites have emphasized the need for an innovative and a deeper understanding of their machinability in order to further improve their functionality and applicability. Hence, this paper presents a comparative and experimental investigation of the effects of a dry conventional drilling (CD) and hybrid ultrasonically-assisted drilling (UAD) techniques on both hemp fibre-reinforced/polycaprolactone and vinyl ester (HF/PCL and HF/VE) composite samples. The results obtained depict that HF/PCL composite sample of 19 aspect ratio (AR) has a minimum values of peak thrust force of 90N and 75N during UAD and CD respectively, with the lowest machining time of 30seconds for both techniques, among other ARs. These values produced an optimum drilling and best quality drilled holes, in terms of lowest thrust force and resultant drilling-induced damage. It is observed that there was a very little or no thrust force reduction between UAD and CD when drilling the HF/PCL composites. Consequently, PCL was replaced with VE, to produce another sample of HF/VE composites. Therefore, a substantial reduction in drilling forces (thrust force and torque) was obtained during HF/VE drilling, using UAD technique, when compared with the dry CD technique. Comparatively, the percentage of the forces reduction is approximately 70. The quality of the drilled sample depended on these primary forces. In addition, a significant lower ply delamination defect, burr formation, fibre-uncut/pull-out and surface roughness were observed, as well as an improved chip expulsion, hole roundness, material removal rate and surface finish (hole quality) were obtained with UAD, when compared with CD technique. Evidently, a non-traditional hybrid machining technique, UAD, has enhanced machinability (drilling) of HF/VE composite compared with the CD and HF/PCL composite samples.

Keywords: Natural hemp fibre-reinforced polymer (HFRP), Drilling techniques, Thrust force reduction, Hole quality.

Introduction

The quest of having sustainable materials with an improved properties, lower cost of production (lesser energy consumption), environmental friendliness, high corrosion resistance and structures of a better load bearing capacity in the fields of materials science and engineering has produced the fibre-reinforced polymer (FRP) composites for a numerous applications. The FRP composites are becoming an acceptable and a desirable material systems in many industrial and structural uses

today, when compared with the conventional metallic engineering materials. The outstanding performance of natural (hemp) fibre reinforced composites especially when used as a thermal and acoustic insulation materials has increased the application of these composites, especially in the building industry for external insulation. Drilling, as a manufacturing operation, is a process that involves either the cutting out of circular holes, or the enlargement of existing ones in an engineering material, usually solids. Before and similar to reaming, drilling is a versatile manufacturing operation which forms an integral part of any machine assembly and components mating. The necessity of a drilling operation as a final process during assembly stage of manufacturing activities cannot be under-scored. The history of the drilling operation can be traced back to the ancient times, as it has been one of the major operations that typified different eras in the evolution of civilization. Drilling is one of the mainly applied machining processes, a common and crucial manufacturing process [1, 2]. For instance, in the Airbus A350 aircraft, an estimate of about 55,000 holes are reported to have been drilled to assemble the numerous intricate parts of the aircraft [3].
The possibility of drilling damage-free composite materials, especially a synthetic carbon fibre-reinforced plastics (CFRP) and glass fibre-reinforced plastics (GFRP), still remains a challenging task in manufacturing industries [4]. Several drilling methods have been used to solve drilling-induced damage on a conventional composites (CFRP and GFRP). These damage include, but are not limited to, inter-ply delamination, surface roughness, burrs formation, fibre-matrix de-bonding, fibre-uncut and pull-out (fibre deformation or cratering). Recently, modern drilling techniques such as electric discharge, laser, abrasive jet and ultrasonically-assisted drilling have been effectively used to drill several categories of a conventional fibre-reinforced polymer (FRP) composite materials. In many cases, these techniques performed better than the traditional or conventional drilling (CD) technique, though it depends on the properties of material workpiece and drilling technique. Among these recent techniques, ultrasonically-assisted drilling (UAD) has a numerous outstanding performance than the CD.

Over the years, CD has been the norm of manufacturing operations, but it has a quite limitation in working applicability to some newly introduced composite materials. Hence, there is a need for a better technique of drilling. The CD technique involves the process of creating or enlarging already existing hole in a solid material, using a rotating drill bit that is operated under the concomitant action of drilling forces (thrust and torque), feed rate and cutting speed. The UAD is a hybrid technique that combines a conventional drilling (CD) and ultrasonic oscillation. It is a non-traditional technique of drilling whereby a drill bit is excited under a superimposed high frequency and a low-amplitude vibration, on a drill bit along the feed or axial direction, causing drilling process. UAD has a remarkable advantages over the conventional drilling (CD), especially its high drilling-forces (thrust and torque) reduction. The thrust force depicts the axial force required by the drill bit to initiate the drilling process. Force reduction improves the quality of the drilled holes, reduces power consumption rate and cost of production. However, the setbacks of modern UAD technique include expensiveness of set-up, unpredicted results and chipping effects on the drill bits.

Furthermore, UAD has been effectively used for drilling of both brittle and ductile materials [5]. It has been reported that UAD decreased drilling forces and burr formation when drilling metal matrix composites, causing reduction in both delamination and surface roughness defects respectively [2]. They examined these parameters and demonstrated that the drilling force developed in UAD was significantly lower relative to the conventional drilling technique.

Similarly, the drilling force developed in UAD has been found lower than CD at all vibration frequencies and has optimal quantity [6]. However, similar values of thrust force in CD and UAD at all the cutting speeds and at a constant feed rates in the absence of coolant have been obtained in another experimental study [7]. Though, a small reduction in thrust force of 9.1 N was obtained at a cutting speed of 9.42 m/min. They concluded that the thrust force was maximum at the lowest cutting speed and minimum at the highest cutting speed. Also, they demonstrated that the cutting temperature was similar in CD and UAD at a lower cutting speeds, but different in CD and UAD at a higher cutting speeds. In term of the chip morphology, it was demonstrated that the cutting speed was influential to the morphology of the chips generated in the UAD. From the results obtained, it was observed that the largest type of chip fragments were formed at both the lowest and highest cutting speeds: 0.942m/min and 282.6m/min respectively. At almost all variations in the cutting speed, the most common type of chips formed in the UAD technique was a short broken chip fragments. A similar conclusion has also been reported [8]. They reported a significant decrease in thrust force with an increased cutting speed, and thus recommended the need to employ UAD at a high cutting speeds. Meanwhile, an increase in the feed rate in UAD technique led to an increase in the material removal rate (MRR), as well as material volume removed by one abrasive grain [9]. They noted that a linear relationship existed between the feed rate and the material removal rate in UAD. Also, it has been stated that the temperature gradient in UAD was relatively higher than CD. In the CD, the cutting temperature varied linearly with the feed rate as expected. However, in UAD the temperature rise was almost constant irrespective of the feed rate. This constant rise in cutting temperature experienced in the latter was attributed to the consequence of the effect of vibratory cycles to which the tool was constantly subjected. A maximum temperature of 90.2˚C and 290.8˚C was reported for CD and UAD technology respectively, using the same feed rate of 16 mm/min [1]. Similarly, the tool tip temperature was higher in the UAD of Ti6Al4V than CD, and a linear relationship existed between the vibration amplitude and the temperature variations at the tool tip [10].

Moreover, an effectiveness of UAD over CD was demonstrated in terms of reduction in average thrust force [8]. An excellent correlation between an experimental and a numerical analysis of model was achieved, as both the simulation results generated and the experimental data obtained show a greater advantage of UAD over CD. It should be noted that the thrust force developed during drilling operation plays a major role in obtaining the surface integrity and minimising the delamination tendency. They also studied the effect of cutting speed on the drilling thrust force on both UAD and CD, using both experimental methods and numerical models on a CFRP composite. It was observed that in both UAD and CD, the thrust force decreased with an increase in the cutting speed, as experimental results shows that the decrease in relative thrust force encountered in UAD was considerably higher; 31.1% at 1700 rpm against 15.8% at 260 rpm with an increased cutting speed. The contribution of frictional force in UAD has been studied [8]. It was reported that the generation of intermittence in UAD, caused by the vibration effect was a favourable condition which reduced the effective frictional coefficient at the cutting interface. This reduction of frictional coefficient can be attributed to the increase in relative velocity (the sliding velocity) translated into a tangible reduction in the overall thrust force at the tool-workpiece interface. The results evaluation therefore recommended the need to employ higher rotational speeds when drilling CFRPs [8]. The acoustic softening effect of UAD has been modelled using numerical simulations [11]. It was reported that the vibration effect on the tool in UAD generated an adiabatic heat transfer which further translated into a plastic deformation of the workpiece (CFRP). As a result, this phenomenon caused a softening effect which then ensured that minimum thrust force and torque were used by the tool in this method of drilling, compared to the CD counterpart. It was observed that these favourable conditions of plasticity and reduced thrust forces were crucial to ensuring a better drilling output, as well as to preserve the tool life for a longer period. Some vital information about the effects of UAD on CFRPs has been revealed [1], using a combination of experimental data and mathematical models. The drilling forces, temperature, chip formation, surface finish, circularity, delamination and tool wear were investigated in UAD of CFRPs. The remarkable results presented show that a significant reduction in drilling forces, often in the excess of 80% compared to the CD. Summarily, a general improvements on the UAD outputs were achieved, relative to CD.

In addition, with respect to the morphology of chip formation in UAD and CD techniques, it was reported that the chips formed in UAD were long, helical, curled continuous chips, similar to chip generation during CD of ductile metals. This observation displayed a sudden transformation of the brittle fibre-reinforced composite to a ductile material. This was primarily due to the acoustic softening effect of the vibratory cycles of excitation in UAD. On the other hand, the CD technique produced a small sized crumpled chips which indicated the brittle nature of the CFRP composite. The dissimilarity in the chip formation and morphology of the UAD was attributed to a various factors; the major one among a list of them being the effect of the ultrasonic excitation at the interface of the tool and workpiece. Similarly, it was reported that the feed rate had a direct influence on chip formation, as a lower feed rates produced longer chips, whereas a higher feed rates yielded the shorter ones [1]. Based on the surface roughness of holes drilled with UAD, it was observed that the feed rate had no direct bearings on the surface regularity, as the surface roughness improved significantly even for a feed rate that showed no improvement in drilling forces in UAD. This independence of the end result of surface finish was directed to have been as the positive effect of the multiple vibration excitations to which the drilling system was constantly subjected. Consequently, the drill bit generated the necessary polishing effect over the workpiece surface [1]. Similarly, the microstructure of internally drilled holes has been analysed [7], using the Scanning Electron Microscope (SEM) method. It was observed that there was no significant difference between UAD and CD techniques, when viewed at a lower magnification of 40 x. However, at the exit side of the drilled holes, the fibre pull-out defect was reported which was peculiar to the conventional drilled hole.

From the extensive literature reported above, it is evident that in the recent years, metal matrix and conventional FRP composites have been extensively machined using UAD method. But, there is no a single report on UAD of a natural FRP composite materials, especially on a natural HFRP composite samples. The only very few reports on machining of a natural fibre-reinforced composites are based on CD technique. A lowest conventional drilling-induced damage (delamination and surface roughness) were observed on the HFRP composite, when compared with banana, glass and jute fibre-reinforced composites [12]. An experimental investigation of the effects of drilling parameters (feed and speed) on the damage (delamination) factor during CD of glass, hemp and sandwich fibres of 10%, 20% and 30% fibre volume fractions have been conducted [13]. They reported that fibre-uncut defect was observed at a high feed, and an increase in feed rate caused an increase in the damage factor. The optimum results were associated with a volume fraction and speed of 30% and 40 m/min respectively, coupled with a lower feed rate. Similarly, the effects of a conventional drilling parameters (feed rate and cutting speed) and aspect ratios (00, 19, 23, 30, 38) on delamination and surface roughness of HFRP composites have been experimentally reported [14]. From their results, the influence of feed rate on both damage responses increased with the aspect ratio. Also, the cutting speed decreased with these damage responses and an increase in feed rate significantly increased both damage responses. They concluded that both damage responses were increased with the fibre aspect ratios. The natural FRP composites tend to gain wider application when compared with a synthetic FRP composites. This is due to the sustainability, recyclability, ease of production process and environmental friendliness of the natural FRP composite when compared with a synthetic types. This experimental paper seems to be the first paper that provides more than a birds-eye view on influence of drilling parameters and fibre aspect ratio mainly on the drilled surface quality and integrity of a natural hemp FRP composite samples, importantly under UAD technique. Hence, this present paper focuses on a comparative and experimental investigation into the machining of FRP composite (HF/PCL and HF/VE) samples, using both CD and UAD techniques, under Taguchi method of design of experiment and a dry machining environment or condition.

Experimentation

Materials specification

Squared workpiece of overall dimensions of 140 x 140 mm x 4 mm of HFRP composite samples made up of aspect ratios, AR of 00 (neat), 19, 26, 30 and 38 were used for this experiment. The Aspect ratio is the ratio of the length (mm) to the diameter (mm) of the reinforced fibre (hemp). The hemp fibre is not expensive in terms of cost of production (planting) and process among other bast natural fibres. It is ready available in Europe and Asia in a very large quantity. It is classified as one of the high lignocellulosic fibre, with high mechanical properties, making it a good reinforcement of many fibre-reinforced composites (FRCs) [14, 15]. Each sample contained 4 layers and a lay-up process was used to prepare the HFRP samples, using a resin bio-binder and a synthetic matrix, known as a polycaprolactone (PCL) and vinyl ester resin (VE) respectively. The thermo-mechanical properties of the 19-HF/PCL samples were optimised after the first phase of the experiment. This caused the replacement of PCL matrix with VE resin. The PCL resin is a thermoplastic and biodegradable, while VE resin is a non-biodegradable and thermoset in nature, as summarily depicted in Figure 1.

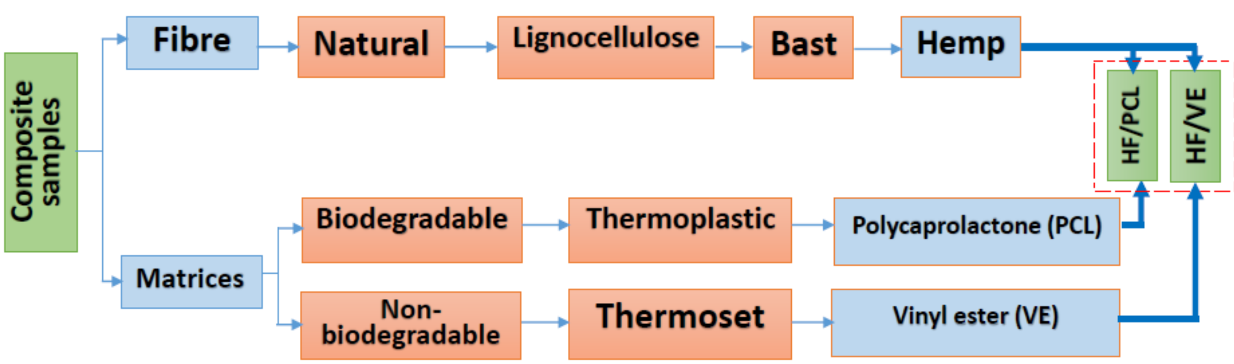

Figure 1. The main compositions, properties and architecture of the FRP composite samples used.

The PCL matrix possessed a specific gravity of 1.1 at 60º C and flash point of 275º C (518 º F) with an open cup method, while the VE has a specific gravity of 1.04g/ml and flash point of 23º - 29º C (74-84 º F).

Experimental Design and Methodology (Drilling Phenomenon)

The design of experiment was based on orthogonal array of Taguchi method, as shown in Figure 2(a). The computer-aided design (CAD) of the sample was carried out prior to the practical drilling process (Figure 2), in order to have an effective plan and manipulation of the samples (Figure 2b). The drilling tests were conducted on a universal standard M-300 Harrison lathe machine, as shown in Figure 2. The machine was adapted to accommodate both CD and UAD techniques. The incorporation of a Langevin-type piezoelectric transducer fixed in the lathe 3-jaw universal chuck and a two-channel (Model 9271A) Kistler^{TM} dynamometer, as the main components, and other specially designed fixtures for the UAD, make the experimental set-up for the UAD quite different from that of CD. The transducer produced the expected ultrasonic vibration on the Ø6.00 mm HSS DORMER ADX jobber carbide twist drill bit mounted on the transducer. A laser vibrometer was used to monitor the vibration amplitude in a free-vibration mode.

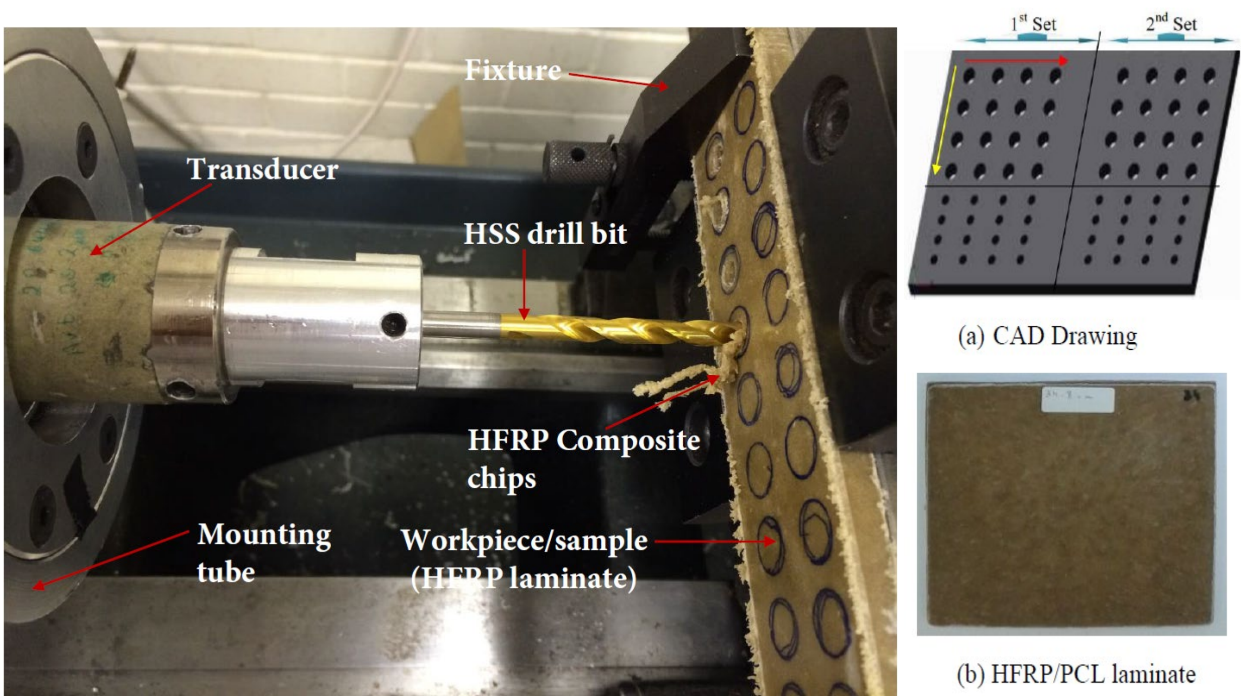

Figure 2. The CD and UAD (machining) experimental set-up and (a) & (b) samples.

The dynamometer was mounted on the lathe cross slide with aids of an angle plate. The angle plate was mounted on the lathe carriage. The sample was firmly clamped, with zero degree of freedom, on the Kistler dynamometer. Both the CD and UAD experiments were conducted using the drilling parameters and condition summarily stated in Table I. A dry drilling environment was considered for both techniques of drilling throughout. This condition was chosen due to the hydrophilic nature of the FRP composites, especially for a natural FRP composites and a high cutting interface temperature, which is rampant in UAD.

TABLE I. DRILLING PARAMETERS AND CONDITIONS CONSIDERED.

		Machining Technique		
Drilling Parameter	**Symbol**	**CD**	**UAD**	**Unit**
Drill bit diameter	Ø	6.00	6.00	mm
Spindle speed	N	40.00	40.00	rev/min
Feed rate	f	0.10 (10%)	0.10 (10%)	mm/rev
Cutting speed	v	0.75	0.75	m/min
Vibration frequency	F	-----	24.75	kHz
Vibration amplitude (at bit's tip)	α	-----	8.00	µm
Condition	----	Dry	Dry	-----

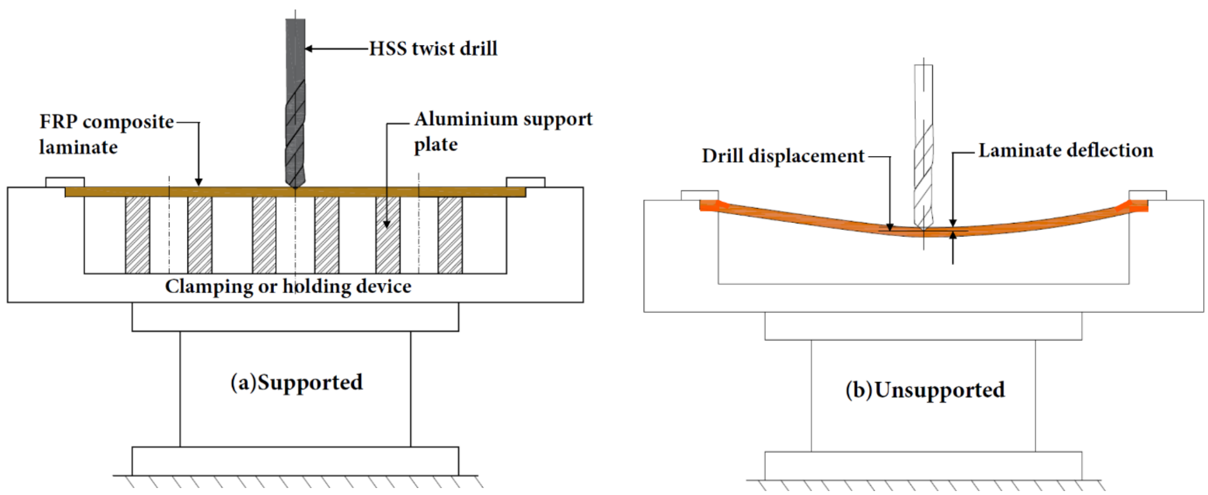

Figure 3. The drilling set-up of: (a) supported and (b) unsupported FRP composite samples.

In an attempt to further reduce the drilling-induce damage that are associated with drilling of FRP composite materials, the samples were supported at the back using a pre-drilled aluminum plate, as depicted in Figure 3(a). In addition, this method is required in order to prevent bending (Figure 3b) of the samples due to thrust force during drilling process and the considerable thickness 4 mm of the samples used.

Instrumentation and Damage Characterisation

The drilling forces (thrust and torque) obtained were measured using the aforementioned Kistler™ dynamometer. The amplification of the force signals from the dynamometer were performed using a charge amplifier. These signals were further converted and transmitted to the computer system through an analogue-digital converter, known as a digital PC oscilloscope Picoscope™ 4424. These data were post-processed with a Matlab™ software. Each set of the CD and UAD experiments was repeated three times under the same drilling set-up, conditions and parameters to consider consistency and reproducibility of results. An analysis of average was used to evaluate the thrust forces and torques developed.

In addition to the visual, physical observations carried out on each of the samples after drilling exercise, optical, JEOL JSM-6100 scanning electron and Nikon XTH 225 X-ray computed tomography microscopes; OM, SEM and X-ray CT respectively were used for further detection and analysis (characterisation) of some drilling-induced damage. Basically, the drilling forces (thrust and torque) are measured and analysed within the scope of this experimental work in order to predict the possibility of occurrence of other drilling-induced damage. For the reason that some of these critical damage, especially delamination effect, fibre-uncut and pull-out are mainly caused by the thrust force and torque developed during FRCs drilling [14, 16].

Results and Discussion

Evolution of Drilling (Thrust) Forces

Figure 4 depicts the thrust force profiles, characterises by six distinctive main stages. A rapid increase in the thrust force is observed at stage 1. This increased force is required by the twist drill bit in order to gain an initial entry into the sample. This continues into Stages 2 and 3, where the peak thrust force is observed. Most of the drilling-induced damage on FRP composites occur at either of these crucial stages, such as delamination. Stages 4 shows a noticeable decrease in the force, which continues into stage 5, before the force is reduced to zero at stage 6. This marks the end of the drilling evolution, as reaming operation replaces drilling at nearly zero thrust force.

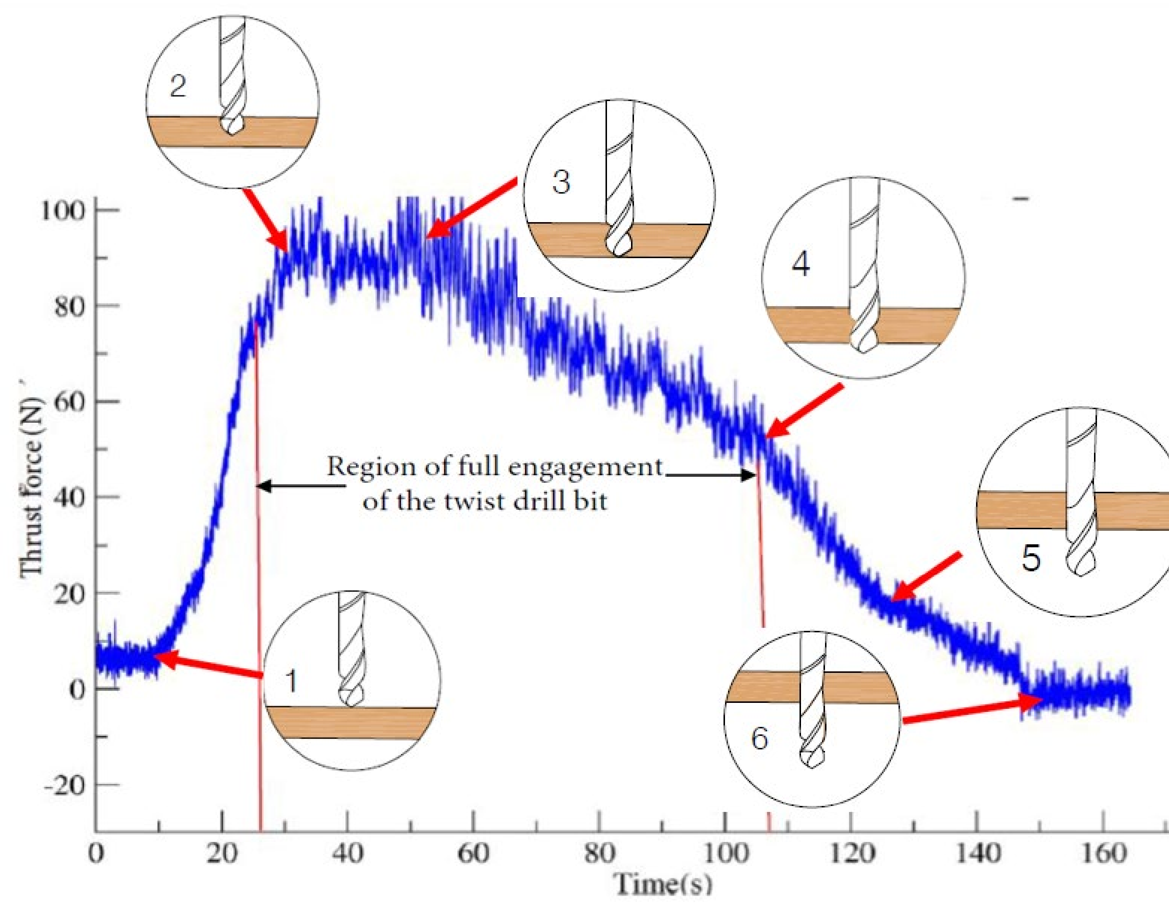

Figure 4. An interaction between the thrust force and time during drilling evolution.

Effects of Thrust Force on the hole quality of HF/PCL composite samples

Figure 5 depicts that the HF/PCL composite samples with AR of 00 (neat), 19, 23, 30 and 38 have the peak thrust forces of 110 and 100N, 90 and 75N, 105 and 88N, 110 and 88N, and 120 and 110N, at machining time of 40, 30, 32, 38 and 50 seconds, using UAD and CD techniques, respectively. Also, it shows that the thrust force increased with the aspect ratios of the HF/PCL samples. The surface quality of the HF/PCL samples reduced as their aspect ratios increased. The heavy winding of the graphs (Figure 5) are caused due to the dynamics of the vibrating drill, resulting into ultrasonic waves propagating in the excited drill cutting at a frequency above 20Hz.

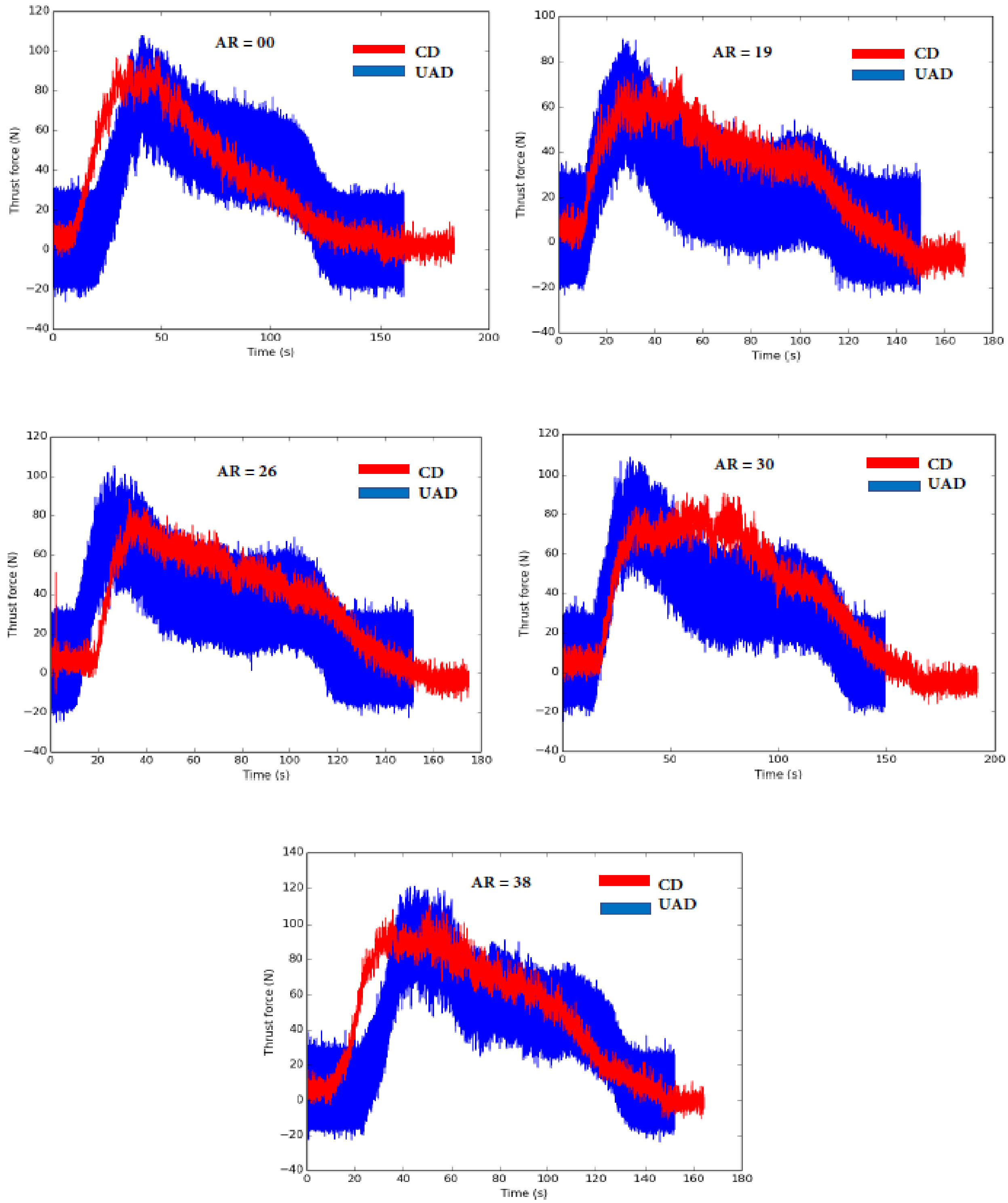

Figure 5. Comparison of CD and UAD techniques on HF/PCL composite samples, showing insignificant drilling-thrust force reduction at feed rate of 0.10 mm/rev and spindle speed of 40 rev/min.

Evidently, both UAD and CD techniques on the HF/PCL sample with AR 19 (19-HF/PCL) recorded the minimum values of thrust force and machining time, especially with the UAD, when compared with other aspect ratios. The 19-HF/PCL composite sample has a peak thrust force of 90N and 75N during UAD and CD respectively, with the lowest machining time of 30 seconds for both techniques. Consequently, the optimum drilling and best quality drilled holes were achieved on 19-HF/PCL composite sample, in terms of lowest force reduction and drilling-induced damage, including mainly burrs formation, fibre-uncut and surface roughness. This result is in close agreement with the results previously obtained when CD technique was only used [14]. The HF/PCL composite samples possess a higher modulus of elasticity than HF/VE samples due to the presence of the ductile PCL matrix. However, the optimal sample of 19-HF/PCL has more burnt chip-materials attached on the drilled holes during UAD than CD, which was worse at AR 38 (Figure 6a). The UAD effect produced a very high surface roughness (Ra), up to 13 µm. These problems occurred due to the 60^{O} C melting temperature of PCL resin [17], quite lower than 56-90.2^{O} C and 265-290.8^{O} C composite-tool interface temperature during CD and UAD respectively [1]. The special benefits of a significant drilling/thrust force and machining time reduction using UAD technique were relatively achieved on 19-HF/PCL composite, but at expense of a good quality of the drilled holes when compared with the CD. The ultrasonic energy was absorbed and then heat generated, which made no significant force reduction and no clean cut surface. Comparatively, the use of CD technique favours this sample in terms of quality of holes.

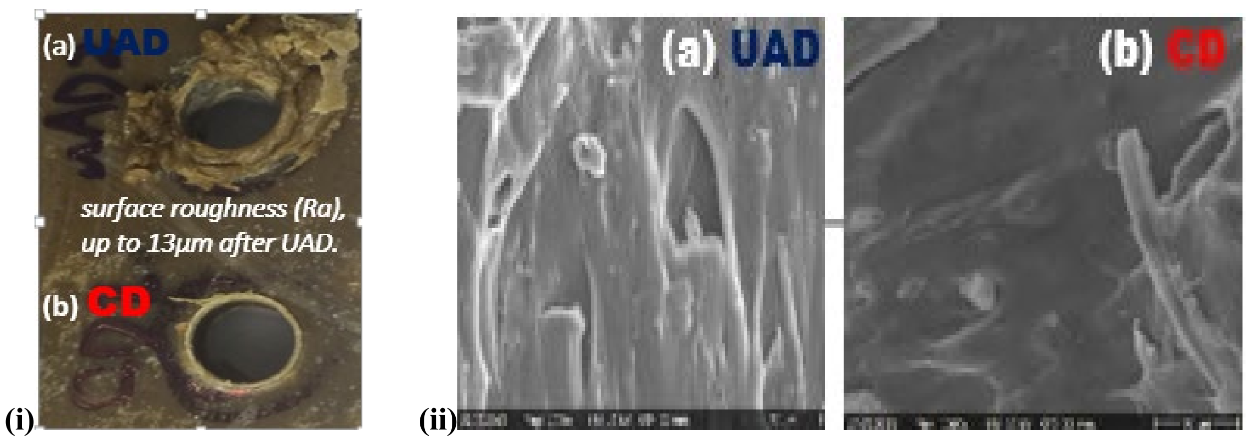

Figure 6. (i) Physical or Visual appearance and (ii) SEM micrographs, showing poorer surface quality after: (a) UAD of HF/PCL, when compared with (b) CD technique.

Effects of Thrust Force on the hole quality of HF/VE composite samples

The main importance connected to the invention and application of UAD technique in materials machining is the cutting force reduction. The experimental results obtained evidently depicts that there is an insignificant force reduction in UAD of HF/PCL samples (Figure 5) compared with CD technique, unlike the CFRP [1]. This led to the replacement of the PCL (HF/PCL sample) with VE resin (HF/VE sample). Conversely, the HF/VE composite sample performed excellently, as depicted in Figures 7 and 8. From Figure 8(a), it is evident that the drilled holes roundness on HF/VE samples are more accurate. There are many drilling factors responsible for these better quality holes. These include better chip removal and high MRR, without much melting, cratering, burrs, fibre-uncut, fuzzing and pull-out damage.

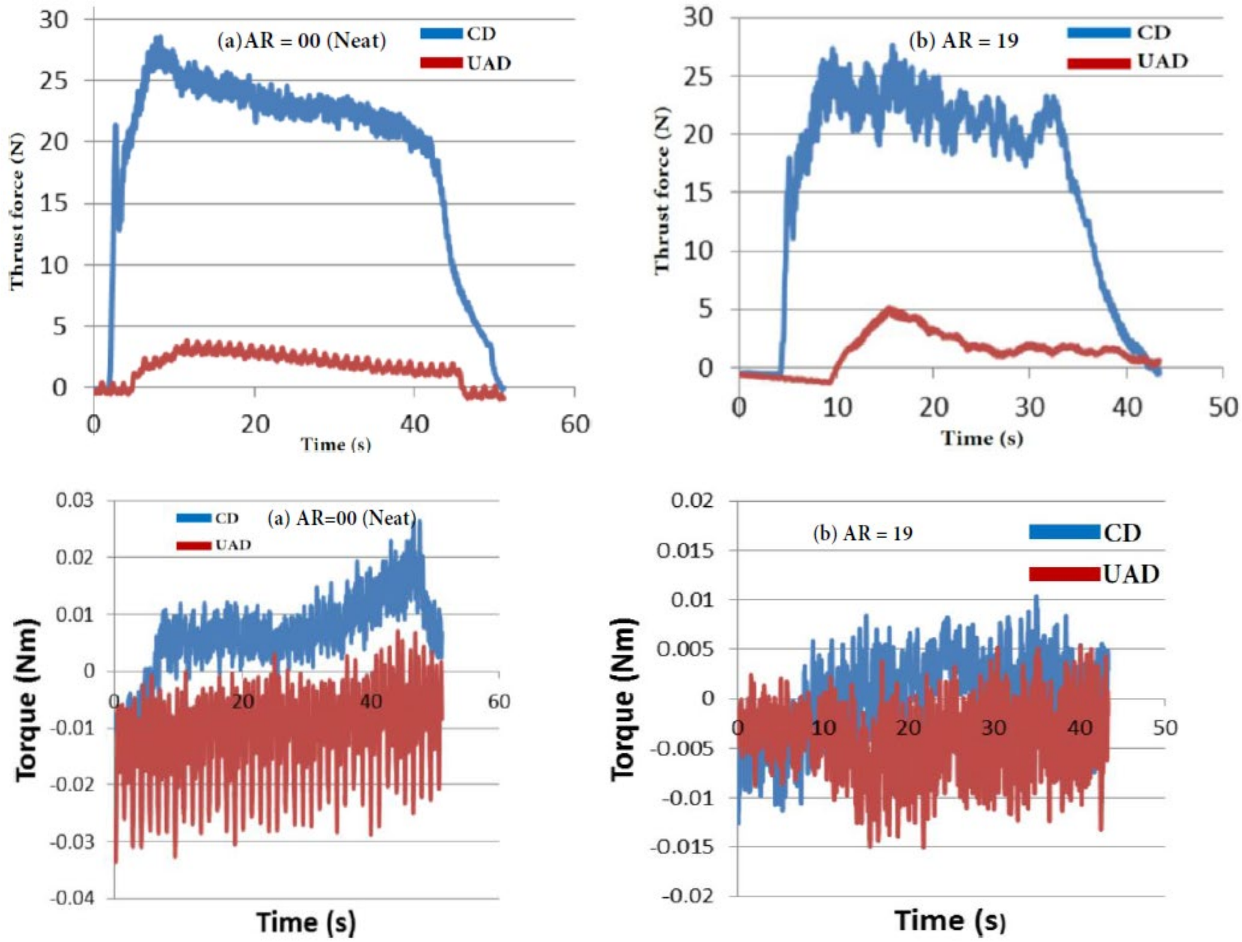

Figure 7. A Substantial drilling forces (thrust and torque) reduction during UAD of HF/VE, compared with CD.

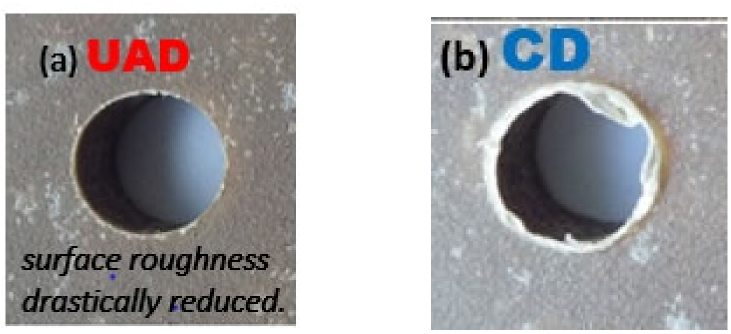

Figure 8. An improved surface quality with UAD, compared with CD.

The magnitudes of both thrust force and torque, as a required drilling forces from both UAD and CD techniques are obtained. A comparison on their damage effects and the quality of the drilled holes produced are presented (Figure 8). Figure 7 shows that there is a great reduction in the drilling forces, particularly in the thrust force using UAD technique on HF/VE sample, when compared with CD technique, and HF/PCL samples. When there is a force reduction, the quality of the drilled holes proves better and cost of production reduces due to the lesser power consumption rate. Furthermore, this reduction is attributed to the properties of the VE matrix. The VE resin has a relatively higher thermo-mechanical (melting) properties than PCL. At this juncture, it can be established that the effectiveness of the application of the UAD technique strongly depends on the properties of both the reinforcement (fibre) and the matrix (binder). During composite drilling, the nature of the chip formation using UAD technique implied an occurrence of a brittle-to-ductile transition. This is traceable to the high frequency, more than 20 kHz used during UAD.

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Conclusions

A dry conventional drilling (CD) and a novel ultrasonically-assisted drilling (UAD) techniques have been comparatively experimented on both HF/PCL and HF/VE composite samples. The special benefits of a significant drilling forces (thrust force and torque) reduction using UAD over CD technique have been comprehensively analysed and experimentally achieved. Based on the results obtained, the following summaries are hereby drawn:

- A nearly 70% of an average forces reduction was observed by using UAD technique, when compared with the CD of HF/VE composite samples under a certain drilling condition and parameters.
- The mechanical properties of the HFRP composites increased with the aspect ratio of the hemp fibres; the reinforcement and strength of the composite samples increased with the aspect ratio. These are observed through the increased thrust force and machining time recorded during drilling of the samples. Therefore, an increase in aspect ratio facilitated an increase in the occurrence of flaws with reference to the drilling-induced damage which include, but are not limited to, delamination, surface roughness and matrix melting.
- The outstanding performance of the UAD technique, better than the CD, can be traced to the intermittent, vibro-impact character of the operation, as well as the tendency of a decrease in friction and material hardness during drilling.
- The surface quality of the HF/PCL samples decreased as their aspect ratios increased. The surface roughness of the 38-HF/PCL composite sample was the highest and comparatively, higher with UAD than CD technique, indicating that UAD technique is not exactly suitable for the machining of natural FRP composites with higher aspect ratio and a lower matrix melting point or decomposition temperature. The cutting (tool-workpiece interface) temperature generated by the higher AR of the hemp fibre was too high for the PCL to withstand without occurrence of melting or burning.
- However, these challenges of drilling HF/PCL composite samples with UAD was drastically reduced when thermoplastic PCL matrix was replaced by thermoset VE, for an optimized 19-HF.

- Conclusively, the total quality of a drilled holes of a natural FRP composites, such as HFRP, greatly depends on the drilling technique and properties of constituents of the FRP composite (matrix and fibre) used.

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