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Machinability of natural-fibre-reinforced polymer composites: Conventional vs ultrasonically-assisted machining

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Abstract

Natural fibres as alternative reinforcement in polymer composites have many advantages over man-made glass and carbon fibres such as low cost, high renewability, recyclability and biodegradability while still providing reasonable mechanical properties. Good machining of natural-fibre-reinforced polymer (NFRP) composites is needed to yield damage-free components with good surface finish and low cutting forces or power consumption. This study focuses on a comparative experimental analysis of the effects of conventional drilling (CD) and a hybrid machining process, namely, ultrasonically-assisted drilling (UAD) of a hemp fibre-reinforced vinyl ester composite laminate. The results obtained indicate that UAD is more efficient when compared to CD for a range of drilling conditions. It yields lower cutting (thrust and torque) forces and energy resulting in reduced machining-induced damage in the composite, including diminished burr formation and fibre pull-outs. The holes drilled with UAD exhibit improved surface finish and hole quality when compared to those produced with CD. **The study demonstrates the applicability of UAD as a viable machining process for improved machinability of heterogeneous composite materials reinforced with natural fibres.**

Keywords: Natural-fibre-composite; ultrasonic drilling; Machining; Machining-force reduction.

1. Introduction

In recent years, a demand for natural-fibre-reinforced polymer (NFRP) composites has increased steadily. NFRPs are ideally suited for applications in secondary or tertiary structures such as automotive panels, packaging applications, etc., where the demand for advanced mechanical properties is less important. This demand is primarily driven by a need to reuse and recycle composites at their end-of-life [1]. Fibre-reinforced plastics reinforced with glass or carbon fibres are notoriously difficult to recycle, to such an extent that their direct disposal in a land-fill or incineration is preferred [2]. To mitigate these problems, the use of so-called ‘eco-composites’ with a lower environmental impact became important.

NFRPs have several advantages: first, the use of natural organic materials in replacement for traditional mineral (inorganic) ones allow for a considerable reduction in the use of non-biodegradable materials from non-renewable resources. Fibres in NFRPs are usually drawn from relatively abundant plants, making them economically viable and environmentally sustainable. Production processes involved in manufacturing of NFRPs are less dangerous and pose lower risk to personnel handling the material (in contrast, carbon fibres/fillers pose risk of inhalation during their manufacture). Additionally, NFRPs can be engineered to possess beneficial properties such as thermal and acoustic insulation and lower specific weight in comparison to their mineral-filled counterparts [3]. Among natural fibres, hemp fibre is relatively cheap to produce and process; it is readily available in Europe and Asia in large quantities. It is classified as one of high lignocellulosic fibres, with good mechanical properties, making it an ideal reinforcement for many fibrous composites [4-14].

To facilitate assembly of functional components, machining of NFRP composites is unavoidable in many cases. Drilling is of particular interest as holes need to be machined for

bolts or rivets. This machining process is known to induce various modes of damage in the machined composite parts such as delamination, fibre pull-outs and inter-laminar crack propagation resulting i.a. in hole-roundness errors. Several factors contribute to the extent of drilling induced damage in composite materials, including cutting parameters and the geometry of the tool used in machining. A common aspect which is inherent in these observations is the need to reduce machining forces to as it contributes in reducing drilling induced damage [15].

Some limited studies in drilling of hemp-fibre composites exist; typically, they recommend a low feed rate and a high cutting speed to reduce delamination [16, 17]. Some studies into hemp-fibre-reinforced vinyl-ester (HF/VE) composites showed that machining parameters and aspect ratio of fibres affected machining-induced damage [17]. From an industrial perspective, there is a clear need to improve the machining processes to yield damage-free components, for which a fundamentally new approach of using hybrid machining is required. Ultrasonically assisted drilling (UAD) is one such hybrid machining process, in which high-frequency low-amplitude vibration is superimposed on drill-bit movement during the cutting process. Prior experimental studies in aerospace-grade carbon/epoxy composites showed a significant reduction in thrust force - up to 30% and more - with a concomitant improvement in hole quality and surface topography [18, 19, 20].

In this paper, machinability of HF/VE NFRP composites is studied using both conventional and ultrasonically assisted drilling. The paper is organised as follows: in Section 2, descriptions of the experimental setup (including various characterisation instruments used) is presented along with details of a workpiece material and cutting tools. Section 3 comprises measurement results and associated discussion. The paper ends with some concluding remarks in Section 4.

2. Experimental work

2.1 Materials specification

In this study, hemp-fibre-reinforced vinyl-ester composite plates with dimensions 140 mm×140 mm×4 mm were used as workpiece material. The aspect ratio and volume fraction of the fibre were 19 and 26% respectively, with a nominal fibre length of 432 μm and its nominal diameter of 22.4 μm . The choice of this fibre aspect ratio was based on prior machining studies that showed reduced delamination in conventional drilling [17]. Each composite plate was made up of 4 layers of non-woven hemp with fibre volume fraction of 0.26. A combination of hand lay-up and compression moulding method was used to prepare the HF/VE composite samples. Non-woven hemp fibre randomly oriented mat was first dried at 100°C to remove storage moisture. A measured quantity of vinyl ester resin was mixed with a catalyst (MEKP) for rapid curing/cross linking. The detailed manufacturing process was followed as similarly described by the work carried out by Dhakal et al. [21]. The VE matrix had a specific density of 1.04 g/ml and flash point of 23-29°C (74-84°F). The composite lay-up was subjected to compressive (compaction) pressure of 1 MPa for 1.5 hours and left for 24 hours at room temperature for curing. Subsequently, the samples were post-cured for 4 hours at 80°C, using a standard oven. Thermo-gravimetric results obtained (Fig. 1) depicts a thermal-decomposition process of the HF/VE composite. No significant reduction in weight of the sample was observed below ~300°C after which the composite started to degrade.

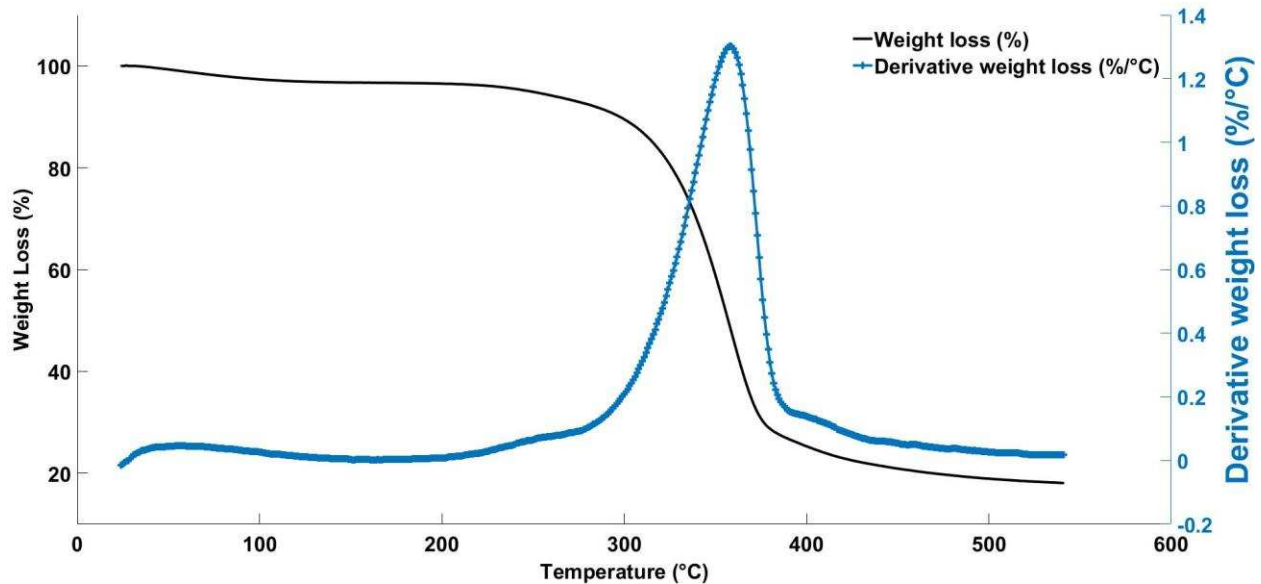


Fig. 1 Thermo-gravimetric analysis of decomposition of HF/VE composite with temperature.

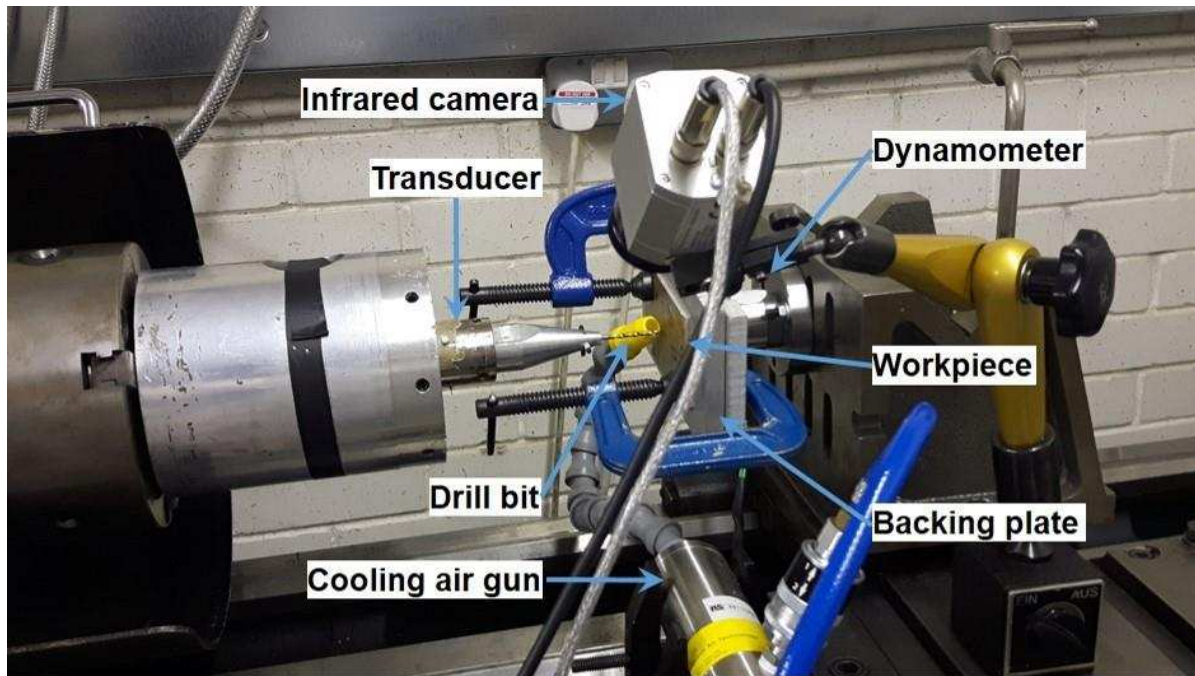
2.2 Experimental setup

Machining experiments were conducted on a universal Harrison M-300 lathe machine with a maximum spindle speed of 2500 rpm. The lathe was appropriately modified to integrate a Langevin-type piezoelectric transducer with a maximum power rating of 106.6 W. The transducer consists of piezoelectric ceramics rings, a backing mass, a front mass, a horn and a pre-stressed central bolt; it produced mechanical vibration by converting electric energy based on a piezoelectric effect. The vibration generated by the piezoelectric transducer was such that, effectively, an axial vibration was superimposed on a rotating drill bit. A high-speed steel (HSS) two-flute Ø3 mm Jobber carbide twist drill, with a point and helix angles of 135° and 28°, respectively, with strengthen web thickness (Fig. 2(b)) was used for the drilling experiments, Prior studies in drilling of carbon/epoxy composites show that a TiN coated HSS drilling tool

was ideal as it helped reduce tool wear [19, 22] which is an important factor when drilling composite material. Details of the drill used are listed in Table 1.

A Kistler 9345b piezoelectric two-component dynamometer was placed on the cross slide of the lathe, fixed on an angle plate to measure thrust force and torque in the process of drilling. The dynamometer is capable of force and torque measurement up to 10 kN and 25 Nm, respectively. The force and torque data measured by the dynamometer were obtained using charge amplifiers, by converting and transmitting the data through an analog-digital converter (digital oscilloscope Picoscope) connected to a computer. The acquired data in digital format were further processed using MatlabTM.

Temperature measurements were performed with an infrared camera (MICRO-EPSILON thermoImager TIM 400) during the drilling process in real time. The thermal camera was calibrated using a K-type thermocouple to ensure accuracy of measurements, considering the workpiece material and ambient lighting conditions. The camera was positioned to focus on an area at the point of contact between the tool and the workpiece at the entry surface. The emissivity of the workpiece and the drill bit were evaluated to be 0.29 and 0.27, respectively, which were set in the software. Details of the thermal imaging system are listed in Table 2. A cooling system consisting of a cold-air gun vortex tube, a pressure regulator, a gauge meter and a compressor was used to cool the machined area.



(a)



(b)

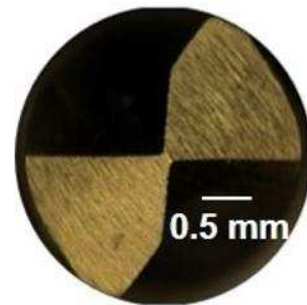


Fig. 2 (a) Experimental set-up; (b) HSS TiN 3 mm Jobber carbide twist drill

Table 1 Drill properties

| Parameter | Unit | Value |
|---------------------|------|-------------------|
| No. of flutes | | 2 |
| Point angle | ° | 135 |
| Point angle | ° | 135 |
| Helix angle | ° | 28 |
| Chisel edge angle | ° | 112 |
| Chisel edge length | mm | 0.14 |
| Land | mm | 0.4 |
| Flute length | mm | 33 |
| Cutting edge length | mm | 1.4 |
| Web thickness | mm | 0.1(Strengthened) |

Table 2 Specification of the infrared camera

| Model | TIM 400 |
|---------------------|------------------|
| Optical resolution | 382 × 288 pixels |
| Temperature range | 0-250°C |
| Spectral range | 7.5 to 13 μm |
| Image frequency | 80 Hz |
| Thermal sensitivity | 80 mK |
| Accuracy | ±2°C or ±2% |

2.3 Measurement of vibration amplitude

A vibration amplitude of the tool tip in UAD was measured using a Polytec™ laser vibrometer (OFV-3001), capable of measuring vibration at a velocity up to 10 m/s with resolution of 0.08 μm/s. This process was employed to tune the frequency and the amplitude of the drill tip in free vibration. For UAD, the system was tuned at 37.9 kHz with the vibration amplitude of 32.3 μm peak-to-peak.

2.4 Experimental methodology

Drilling tests were carried out using a constant feed at 0.03 mm/rev and five spindle speeds - 85, 370, 540, 800 and 1200 rpm. CD tests were carried out first, followed by UAD. This was repeated three times for each machining condition, to ensure accuracy and repeatability of experimental results. Drill bits were changed after completion of tests for each feed rate to ensure that tool wear did not affect results. To reduce the drilling-induced damage, the HF/VE samples were supported with a pre-drilled aluminum backing plate (Fig. 2 a).

2.5 Damage characterisation and hole quality

Damage in the composite caused by drilling was observed, measured and assessed using light microscopy. Alicona InfiniteFocus microscope with magnification of 2.5× was used with a field of view X and Y at 5716 μm and 4351 μm, respectively. Next, surface topographies of the

exit surface of drilled holes were studied by employing TalyMap 4.0 software, which provides the contour plots with spikes illustrating fibre pull-outs. To assess hole quality, a coordinate measuring machine (CMM) (Metris LK Ultra 627134) with a SP25 analogue scanning probe and a $\varnothing 1$ mm stylus was used to measure diameter and circularity of the drilled holes. These parameters were obtained for depths of 0.5 mm, 2 mm and 3 mm from the drill-entry surface.

3. Results and discussion

3.1. Cutting forces and energy

Cutting forces (thrust force and torque) imposed by the tool on the HF/VE composite were recorded in real time for different machining parameters. A typical experimental result demonstrates a noticeable reduction of the thrust force and the torque in UAD when compared to CD, as depicted in Fig. 3. The process can be divided into four main stages. Stage 1 corresponds to the initial drill contact with the workpiece. Stages 2 and 3 indicate the onsets of full drill engagement and exit, respectively. While Stage 4 represents full drill penetration. For CD, the thrust force gradually increased with time after the initial engagement. When the drill tip was fully engaged with the workpiece (Stage 2), the force reached a plateau with minor oscillations recorded due to the inherent heterogeneity of the composite material, vibrations in the drilling equipment and high sensitivity of the measurement system. When the drill bit fully penetrated the workpiece, the force reduced to zero. As expected the force was observed to increase from Stage 1 to Stage 2 with the increasing tool tip engagement. Beyond Stage 2 the forces were somewhat stabilised (in CD) until Stage 3 when the tool started to exit the workpiece. We observe a larger temporal duration corresponding to drill exit (Stage 3 to Stage 4) which was partially responsible for fibre push-out.

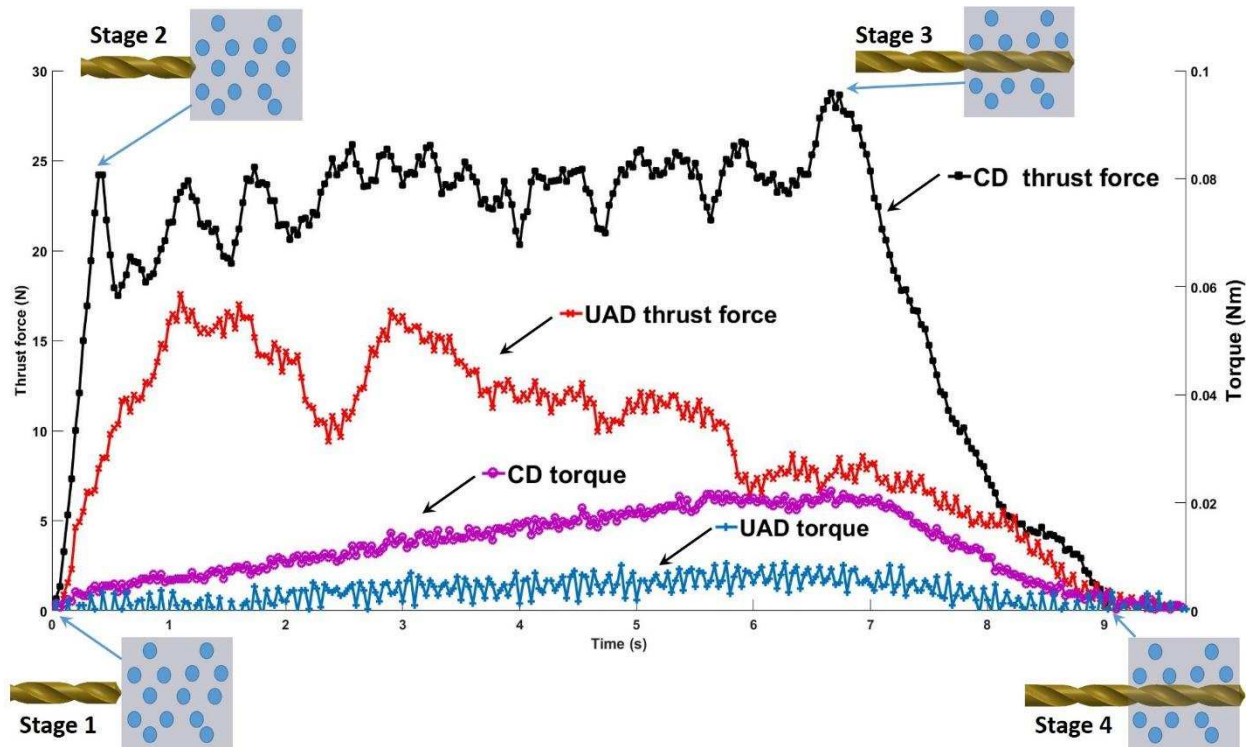


Fig. 3. Evolution of thrust force and torque in HF/VE drilling at feed rate of 36 mm/min

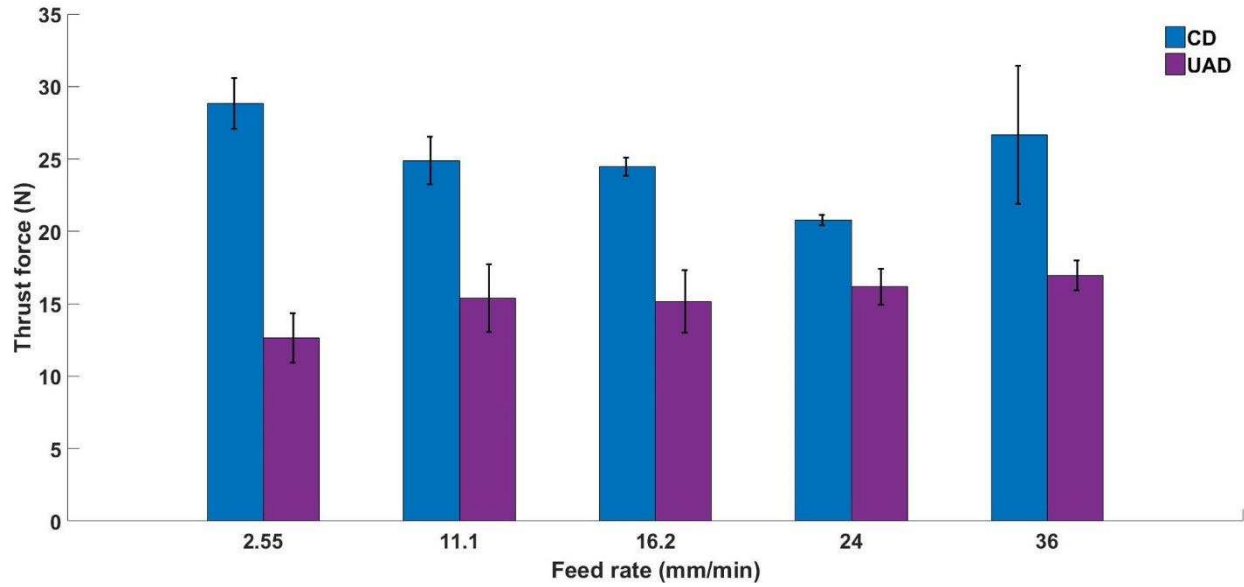
The maximum levels of thrust force and torque during the period of complete engagement of the drill bit are reported in Fig. 4 for the five sets of feed rates (calculated as spindle speed \times feed per revolution). For the range of feed rates studied, UAD shows reductions in excess of 20% and 30% in the level of thrust force and torque, respectively. These reductions for the studied range of drilling parameters can be as high as 56% and 74%, respectively (see all relevant data in Table 3). Generally, the net reduction of machining forces (when compared to conventional machining) decreased with an increase in the feed rate (Fig. 4), which is due to a decrease in the intermittent nature of the ultrasonic cutting process. The CD cutting forces were observed to be higher for 36 mm/min than that of 24 mm/min. The wider variation in the recorded averages indicates an unstable machine regime, which ultimately resulted in poor

drilling quality. Overall, the transition to UAD showed improvements in reducing machining forces.

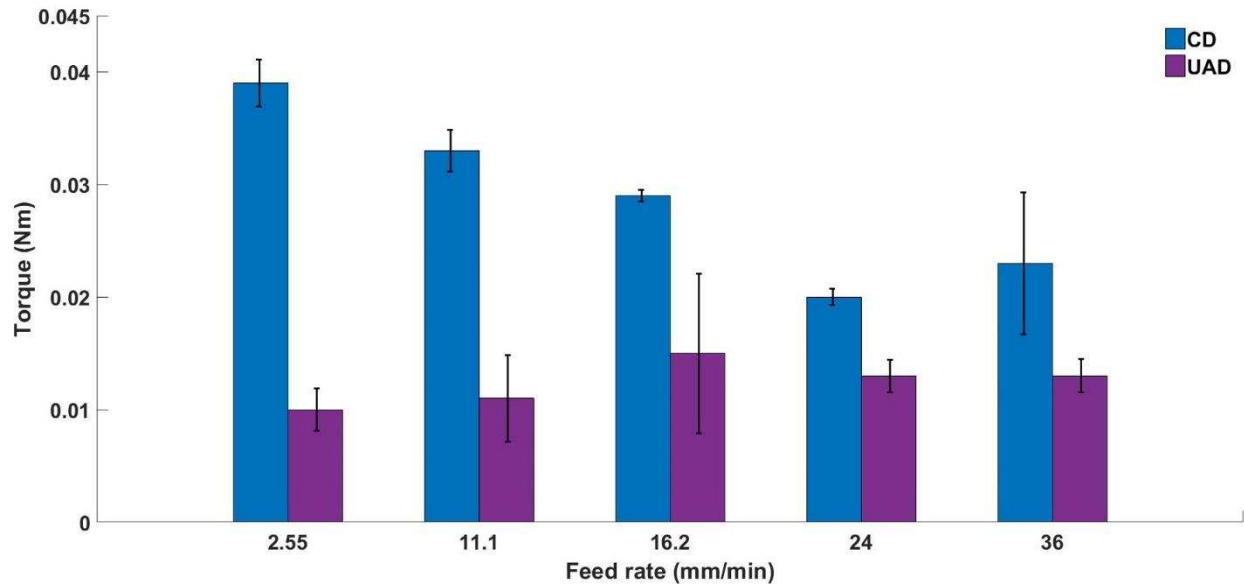
A critical machining parameter indicating effectiveness of the drilling process is energy (E) required to drill a hole. This can be evaluated from the thrust force and torque with the following expression:

$$E = \int_0^l F dl + 2\pi \int_0^l \frac{T}{f} dl , \quad (1)$$

where F is the thrust force, T is the torque, f is the feed per revolution and l is thickness of the drilled workpiece [23]. The data calculated with Eq. 1 reveal that E was dominated by the contribution from the torque in both studied drilling processes. As an example, for a feed rate of 36 mm/min, the energy required in CD was 14.3 J with the torque component contributing 99.3% to it. While in UAD, the drilling energy was 3.9 J with the torque contributing 98.6% to the net energy. Our studies indicate that with the hybrid machining process there is a nominal reduction in excess of 50% and up to 84% in drilling energy spent using UAD in producing holes in the HF/VE composite. The energy expenditure for all feed rates studied is presented in Table 4.



(a)



(b)

Fig. 4. Comparison of maximum cutting forces thrust (a) and torque (b) for UAD and CD

Table 3 Maximum cutting forces (with reduction for UAD when compared to CD)

| Feed rate (mm/min) | Thrust Force (N) | | Average Force reduction | Torque (Nm) | | Average Torque reduction |
|-----------------------|------------------|-------|----------------------------|-------------|-------|-----------------------------|
| | CD | UAD | | CD | UAD | |
| 2.55 | 28.82 | 12.65 | 56% | 0.039 | 0.010 | 74% |
| 11.1 | 24.89 | 15.38 | 38% | 0.033 | 0.011 | 67% |
| 16.2 | 24.45 | 15.16 | 38% | 0.029 | 0.015 | 48% |
| 24 | 20.78 | 16.18 | 22% | 0.020 | 0.013 | 35% |
| 36 | 26.67 | 16.96 | 36% | 0.023 | 0.013 | 43% |

Table 4 Reduction of cutting energy in UAD when compared to CD

| Feed rate (mm/min) | Energy (J) | | Energy reduction |
|-----------------------|------------|-----|---------------------|
| | CD | UAD | |
| 2.55 | 20.3 | 3.2 | 84% |
| 11.1 | 22.0 | 3.9 | 82% |
| 16.2 | 13.6 | 6.6 | 51% |
| 24 | 16.3 | 6.7 | 59% |
| 36 | 14.3 | 3.9 | 73% |

3.2. Hole quality

The purpose of any drilling process is to ensure acceptable quality of produced holes. Hence analysis of cutting forces was accompanied by assessment of finish quality including an analysis of drilling-induced damage in the composite for the two studied techniques.

A reduction in cutting forces typically leads to reduced machining-induced damage. An assessment of such damage was carried out for holes drilled using UAD and CD. Observations were made with light microscopy, and the obtained results are shown in Figs. 5 a-d; this was followed by a surface topography scan of the drilled specimens (Figs. 5 c-d). Burr formation was reduced in UAD, which was observed from the images taken at both entry and exit surfaces. The results show that CD induced more exit hole damage with fibre push-out at the surface having more perturbations in comparison to UAD. Fibre push-out at the exit side in CD was greater than that in UAD, showing larger permanent deformation of the ply. Thus, UAD incurred significantly lower visible damage in the ply. This could be further attributed to the non-woven hemp mat used as reinforcement and a combination of hand lay-up and compression moulding used in the manufacturing process of composite. Similar observation has been reported on experimental and analytical study of the effect of manufacturing process on drilled hole quality of glass fibre [24].

Hole quality was assessed in UAD and CD for various feed rates and is summarised in Fig. 6. First, the nominal hole diameter in UAD was observed to be closer to the drill-bit diameter of 3 mm than that in CD. UAD at a feed rate of 16.2 mm/min and 24 mm/min yield the best results with regard to the hole diameter. The hole circularity was also assessed; it is defined by evaluating the maximum-peak (P) and -valley (V) deviation of the drilled hole from a circle. Thus a circularity of 0 indicates a perfect circle. From Fig. 6 b, it can be observed that the circularity in UAD when compared to CD did not improve at lower feed rates- from 2.55 to 16.2 mm/min. However, with an increase in the feed rate, improvement in the nominal circularity was observed in UAD. It was noted that improvement in circularity was not always consistently observed in UAD (due to wide statistical scatter); however, it has the potential to demonstrate advantage at feed rates beyond a critical value. Thus, from our study, a feed rate of 24 mm/min yielded a favourable result in terms of circularity and hole diameter.

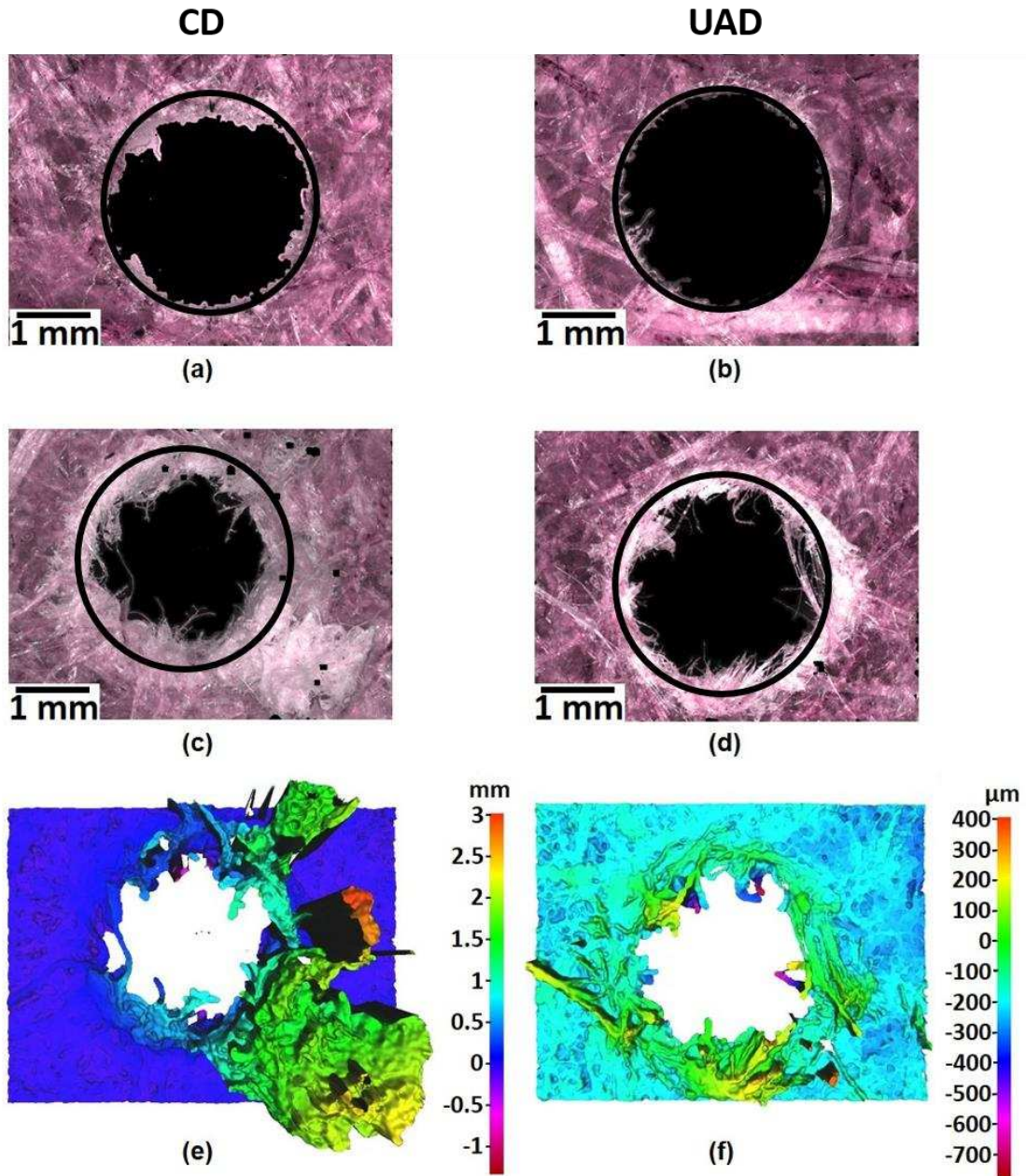
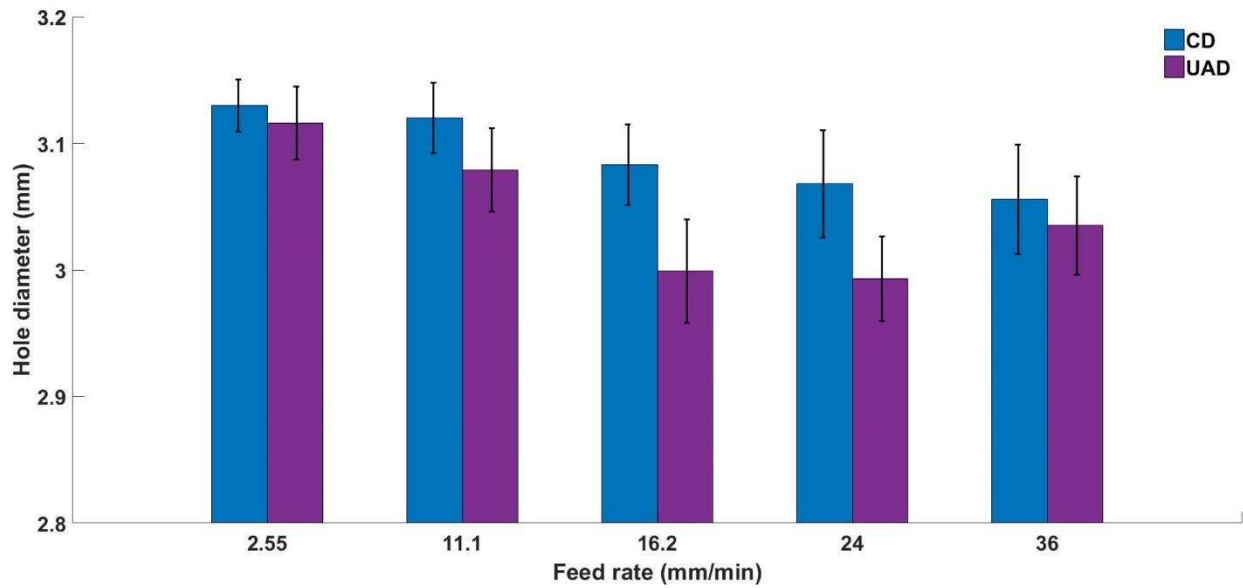
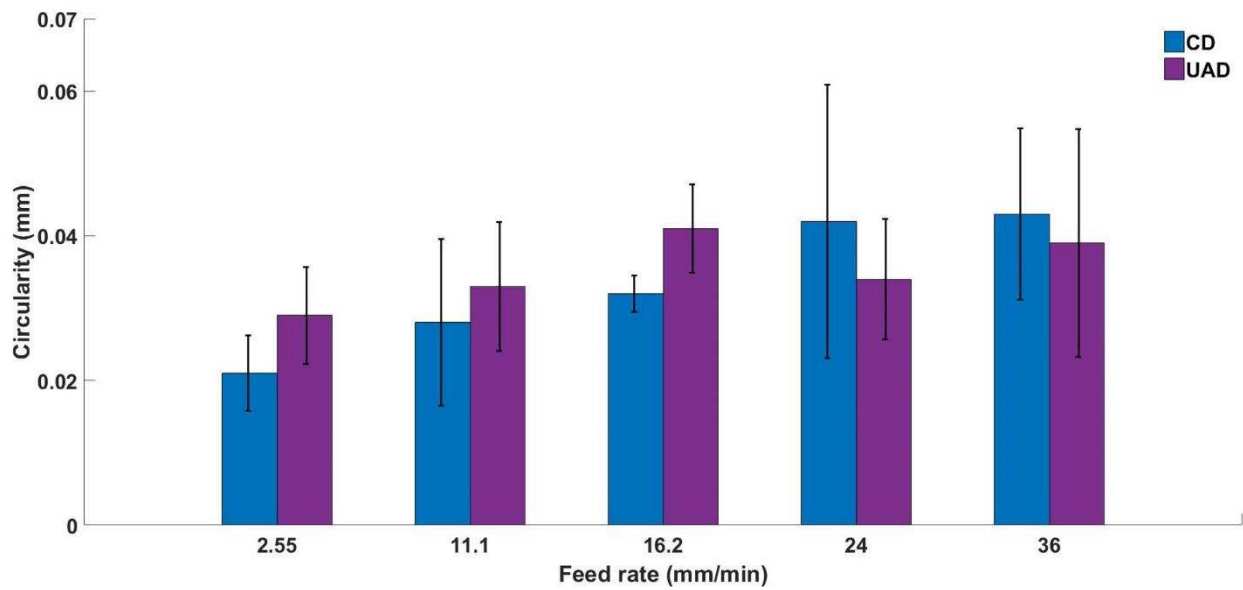


Fig. 5. Light microscopy image of holes for CD at entry (a), UAD at entry (b), CD at exit (c), UAD at exit (d) and surface scans with fibre push-out and burrs for CD (e) and UAD (f) after drilling process at feed rate of 36 mm/ min. A black circle corresponding to the drill diameter is sketched in (a)-(d) for clarity.



(a)



(b)

Fig. 6. Hole diameter (a) and circularity (b) in UAD and CD at varied feed rates

3.3. Thermal results

Temperatures in a process zone during the drilling process were captured with an infra-red thermal camera (Fig. 7) for the machining condition with air cooling. Maximum

temperatures that were recorded are listed in Table 5. Some key observations can be made from the experiments. First, UAD generated more heat in the process zone when compared to CD. This is primarily due to the process of repetitive impact at the tool-workpiece interface in UAD, which inevitably led to a temperature rise in the process zone due to increased friction and plastic work at the interface. This phenomenon was also observed in ultrasonically assisted turning of metals [25]. At the lower range of feed rates, the rises in temperature in CD and UAD with an increase in feed rates were measured. In CD, the maximum temperature was observed to increase from the room temperature to 44 °C when the feed rates were increased from 2.55 to 36 mm/min. In UAD, the temperature increased from 71 to 94 °C with the feed rates from 2.55 to 24 mm/min. These temperature rises were obvious as the shearing energy and friction effects became more with high speed cutting. The temperature was found to surge with an increase in the feed rate both in CD and UAD to 36 mm/min and 24 mm/min respectively, while further increases in feed rate caused no significant effect in both regimes but rather a decrease of the temperature was observed. The main reason for this phenomenon is because of shorter engagement time of the drill bit with the workpiece material. The shorter engagement time made less heat generation during the machining process. This study indicates that there is a critical feed when the cutting speed does not have much effect on the temperature produced during the drilling process. We found different critical feed rates for inducing higher temperatures in CD and UAD of the composites. This was also observed in the drilling of bone using ultrasonic vibrations [26].

An important point with regard to the temperatures recorded in UAD was that it was well below the degradation temperature (Fig. 1); therefore, thermal decomposition was not the cause for force reduction in UAD.

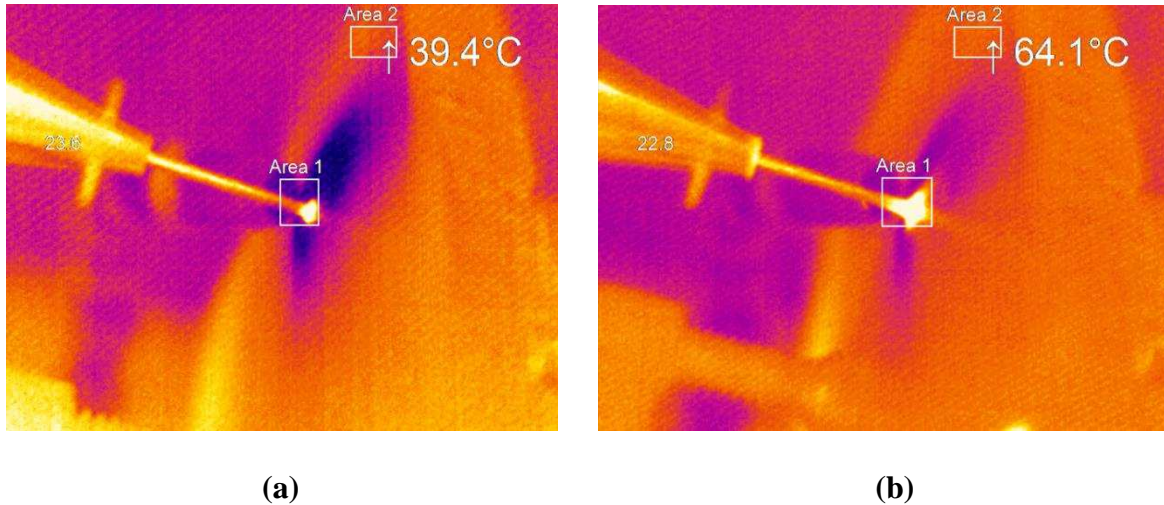


Fig. 7. Snapshots with infra-red camera for CD (a) and UAD (b) at 36 mm/min with cooling

Table 5 Maximum cutting temperature at various feed rates in CD and UAD.

| Feed rate (mm/min) | Engagement Time (s) | Maximum Temperature (°C) | |
|-----------------------|------------------------|--------------------------|------|
| | | CD | UAD |
| 2.55 | 94.1 | RT* | 71 |
| 11.1 | 21.6 | RT* | 82.7 |
| 16.2 | 14.8 | 37.9 | 90.4 |
| 24 | 10 | 39.8 | 94 |
| 36 | 6.7 | 44 | 65 |
| 51 | 4.7 | 43.3 | 56.5 |

*RT: Room temperature in the range of 18-22°C

4. Concluding remarks

In this paper, a hybrid dry machining process – ultrasonically-assisted drilling – was used to demonstrate improvements in machining of the HF/VE NFRP composite material. Based on the results obtained, the following conclusions were drawn:

- A significant reduction in cutting forces and energy was observed in UAD when compared to CD of such materials.

- Quality of holes drilled with UAD was better in terms of both hole diameter and circularity.
- Drilling-induced damage in the composite decreased in UAD.
- Temperature in the process zone in UAD was higher than that in CD; however, the measured temperature was significantly lower than the temperature, at which thermal degradation starts in the HF/VE composite.

The study demonstrated the potential of UAD in improving machinability of heterogeneous composite materials reinforced with natural fibres. We note that the use of the lathe for the drilling experiment was essentially to impose a consistent rotational speed and a feed rate. If implemented in a top down drill, the results would be consistent with the presented results.

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