Cutting forces in ultrasonically assisted drilling of carbon fibre-reinforced plastics

Farrukh Makhdum, Luke T Jennings, Anish Roy and Vadim V Silberschmidt
Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, LE11 3TU, UK
E-mail: f.makhdum@lboro.ac.uk

Abstract. Ultrasonically assisted drilling (UAD) is a non-traditional hybrid machining process, which combines features of conventional drilling and vibratory machining techniques to obtain remarkable improvements in machinability of advanced materials. The experiments are conducted on commercially available samples of a carbon fibre-reinforced plastic (CFRP) at a feed rate of 16 mm/min. In this study, a thrust force reduction in excess of 60% is observed in UAD when compared to conventional drilling (CD). Lower delamination was observed when compared to CD techniques. Optical microscopy revealed that the material is removed as a continuous chip in UAD whereas in case of CD we observe powdered dust. Light and scanning electron microscopy of CFRP chips obtained in drilling elucidate fundamental differences in the underlying machining processes in UAD of CFRP.

1. Introduction
Carbon fibre-reinforced plastics (CFRPs) are widely used in aerospace, automobile and other structural application due to their superior mechanical and physical properties. CFRPs outperform conventional metals in durability, high strength to-weight-ratio, stiffness and density [1-4]. In modern aircraft the part of their total weight composed of composites ranges from 22% in the Airbus™ A380 to 50% in Boeing™ 787 [4, 5]. Typically, CFRP parts are manufactured to near net-shape, but machining cannot be avoided when it comes to component assembly [6]. Holes need to be drilled to facilitate riveting and bolting of components. It is well known that conventional drilling in CFRP induces different type of damages such as cracking, fibre pull-outs and delamination (the most critical type of damage) [7- 9]. Such barely visible damage in CFRPs decreases the load-carrying capacity of the composite parts and affects the structural strength adversely. Additionally, rapid tool wear is caused by abrasives of CFRPs resulting in increase of manufacturing cost.

With the development of new materials, novel machining techniques are continually being developed. Ultrasonically assisted drilling (UAD) is one such hybrid machining technique, which has been used to improve machining of conventional metals and advanced composites. In UAD high-frequency (typically in excess of 20 kHz) vibration is superimposed on a standard twist drill bit, preferably, in the axial direction. This vibration is generated by piezoelectric transducers and applied to enhance the cutting process [10]. There are several advantages of UAD over conventional drilling (CD) such as the reduction in thrust forces and torque, better surface finish, low tool wear and elimination/reduction in burr formation [11-14]. As drilling-thrust forces have a direct effect on machining-induced damage,
we consider the drilling forces as the primary factor affecting the quality of the drilled component. [15-16].
Several studies performed over the last few years [10, 13, 17-23] indicate that vibrating the drill bit in
the axial direction yields the maximum reduction in drilling-induced damage. The paper presents the
UAD and CD experiments on CFRPs conducted at Loughborough University together with damage
analysis in the vicinity of the drilled hole carried out using advanced imaging technique.

2. Experimental setup
A standard M-300 Harrison lathe was adequately modified to incorporate an ultrasonic drilling head.
A 6 mm TiN-coated Jobber carbide twist drill bit (Figure 1(b)) was mounted in the ultrasonic
transducer and the transducer was held in a three-jaw universal chuck of the lathe. The workpiece was
a 10 mm-thick industrial-grade CFRP clamped on a two-channel Kistler™ dynamometer (type
9271A). Finally, the dynamometer was mounted on to the cross slide of the lathe using an angle plate
(see Figure 1(a)).

Our experiments were performed at a spindle speed of 40 rpm and feed rate of 16 mm/min. A
resonance frequency of the ultrasonic transducer with the drill bit was achieved at 27.8 kHz and a free-
vibration amplitude at that frequency was 12 µm. The thrust force and torque signals from the
dynamometer were amplified using the charge amplifier. The signals from the drilling experiments
were acquired with a Picoscope™ 4424 PC oscilloscope and processed in Matlab™. Each test was
repeated four times to consider reproducibility.

3. Results and discussions

3.1. Thrust force and torque
Remarkable reduction of thrust force and torque were obtained in UAD when compared to CD for the
same drilling parameters. The average magnitudes of the peak thrust force in UAD were measured to
be 151 N and while in CD it was 456 N (Table 1). The measured magnitude of torque in UAD
vanished, with the torque fluctuating between ± 50 N-cm (Figure 2). The magnitudes for torque and
thrust force were obtained based on several repetitions to assure the representativeness of results. The
significant reduction of drilling force can be attributed to combinations of the following features of the
UAD process:
1. The intermittent character of the drill engagement causes diminishment of the average drilling forces.
2. Dynamic frictional effects lead to a reduction in the effective co-efficient of friction at the drill-workpiece interface, and subsequently, a decline of the frictional component in cutting forces.
3. The ultrasonic softening effect which was observed in tensile tests of materials [27], can also contribute to force reductions.

The exact contribution of each of the above factors is difficult to quantify and needs to be investigated separately. Currently, an approach based on finite element modelling of UAD is being developed with the aim of elucidating the phenomena contributing to the reduction of drilling forces.

| Table 1: Thrust force and torque |
|----------------------------------|
| Feed rate (mm/min) | Spindle speed (rpm) | Average thrust force at full drill engagement (N) | Force reduction | Average torque at full drill engagement (N-cm) |
|---------------------|---------------------|-----------------------------------------------|-----------------|-----------------------------------------------|
|                     |                     | CD | UAD | CD | UAD |
| 16                  | 40                  | 456 | 151 | 66.8% | 160 | 0 |

![Figure 2](image)

**Figure 2.** Evolution of torque (a) and thrust force (b) in two drilling techniques

3.2. *Chip analysis*
Light microscopy of chips obtained in our drilling experiments was carried out using a Nikon™ optical microscope model SM22T. The observed difference in the cutting behaviour in UAD manifests in completely different morphology of the chip. In case of CD the chip was highly fragmented, powder-like, as observed in traditional machining of CFRP, but in the case of UAD a continuous spiral chip was observed (Figure 3). This indicates that the underlying deformation mechanisms in UAD were significantly different from those in CD. Such a transition is similar to previous observations for ultrasonically assisted machining of brittle materials that demonstrated a brittle-to-ductile transition under the change from the UAD to CD regime. [26].

In addition to optical microscopy, scanning electron microscopy analysis was conducted using a Liks Analytical™ system (model 5431)
machine on the chips obtained in the UAD experiments. The observations revealed fusing of carbon fibres into the matrix (Figure 4); this indicates elevated drilling temperatures in UAD. Further tests using a thermal camera are planned for the future to quantify the heat generated during this machining process.

3.3. Delamination study

Delamination in CFRP due to drilling is a major concern for successful application of fibre-reinforced composite materials in various industries. Determination of the size of the delamination zone after drilling is essential in assessing the effectiveness of UAD in comparison to CD. To this end, micro-computed tomography (µCT) was performed to quantify the damaged area of CFRP in the vicinity of the drilled hole. The measurements were carried out using an X-tech System™ XTH-160 machine. Each sample was exposed to X-ray radiation and rotated by 360° about a vertical axis to capture the images for 3-D re-construction. The X-ray voltage and current were set at 80 kV and 75 mA respectively [25]. The details of µCT for two drilling techniques are given in Figure 5. Analysis of composite plies near the drill entry and exit demonstrate significantly reduced delamination zones after UAD when compared to those in CD (for visualisation purposes the delaminated area is shaded in red in Figure 5).

![Figure 5](image)

**Figure 5.** Delamination analysis: entry delamination after CD (a) and UAD (b); exit delamination after CD (c) and UAD (d)

Conclusions

A non-traditional hybrid machining process, UAD, was used to demonstrate improvements in the machinability of CFRP composites compared to CD. The following conclusions can be drawn from the experimental study carried out:

- UAD can reduce the thrust force by up to 60% when compared to a conventional drilling process. This was achieved at a drill spindle speed of 40 rpm and linear feed of 16 mm/min.
- The material removed in the form of a chip in case of UAD as compared to CD
- The chips obtained in UAD showed brittle-to-ductile transition of the composite material when subjected to ultrasonic vibration. A further study is planned to characterise this effect.
- Ply delamination was reduced significantly, both at entry and exit.

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