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A study of an improved cutting mechanism of composite materials using novel design of diamond micro-core drills

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ABSTRACT

Core drilling at small diameters in carbon composite materials is largely carried out using diamond electroplated tools consisting of hollow shafts and simplistic geometries that are likely to work in an abrasional/rubbing mode for material removal. The paper reports a step change in the performance of small diameter core drilling by facilitating a shearing mechanism of the composite workpiece through the utilisation of a novel tool design. This has been achieved by laser producing core drills from solid polycrystalline diamond, incorporating controlled cutting edges where the geometries are defined. To evaluate the efficiency of the shearing vs. abrasion/rubbing cutting mechanisms, a critical comparison between the novel (defined cutting edges) and the conventional electroplated tools (randomly distributed micro-grains) has been made with reference to thrust forces, tool wear mechanisms and their influences on the hole quality (e.g. delamination, fibre pullout). This work has been augmented by studies using high-speed thermal imaging of the two tool types in operation. The examinations have shown that, based on the concept of defined cutting edges in solid diamond, there is the possibility to make significant improvements in core drilling performance, (ca. 26% lower thrust force, minimal tool surface clogging, lower drilling temperatures) resulting in improved cleanliness of fibre fracture and a reduced tendency of material delamination.

1. Introduction

Micro-drilling (nominal diametric range: 0.03–3.0 mm) can be considered as a key manufacturing enabler for a number of applications such as printed circuit boards in the electronics industry, fibre composite structures in the aerospace industry, lenses/glasses for optical applications and for orthopaedic procedures in the medical industry [1]. Conventional fluted micro-drills are generally produced from carbon steels or tungsten carbide that are readily workable using processes such as mechanical micro-grinding or electro-discharge machining [2].

With their non/quasi homogeneous structures and intense erosional behaviour on the cutting tools, the machining of composite materials has been an intense topic for research [3]. Milling and especially drilling operations are of particular interest as they facilitate the assembly of composite-based structures. Nevertheless, these operations pose particular challenges to avoid material structural damage e.g. fibre pull-out, resin depletion and material burning. Such occurrences are exacerbated by the wear of tool cutting edges (leading to increased cutting forces and therefore higher surface workpiece damage). Understandably the stress applied through the chisel of conventional twist drills to the composite structure can lead to greater levels of delamination compared with core drills of the same diameter, as the thrust force is applied over a smaller tool-workpiece contact area [4,5]. Nevertheless, spiral milling results in lower thrust forces and has been reported to generate holes in composite materials without delamination. Whilst this might be an effective solution at larger hole diameters it becomes challenging with the reduction of the hole dimensions due to the reduced tool stiffness. Either for minimising thrust force and/or to allow access to small hole diameters, the core-drilling method has become an established manufacturing process for hole making in composite materials. Additionally, core drills have an advantage over conventional twist drill configurations in allowing initial cutting edge engagement with a workpiece surface that is angled or curved, with minimal drill deflection.

Due to its extreme properties, diamond is an attractive cutting tool material providing the potential for improving the performance and increasing the durability of micro-drills [6]. However

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diamond is generally more difficult to process using conventional methods, particularly where the dimensions are small. As a result, micro-drills produced, for example from solid sintered polycrystalline diamond on a tungsten carbide backing are typically limited to basic geometric tool configurations (produced using EDM/micro-grinding) [7]. Alternatively diamond abrasive around the periphery/end of a metal shaft can be employed for the production of micro-drills using an electrolytically deposited (Nickel) bond or by an electroforming processes. However this results in tools with random cutting edge geometries (e.g. negative rake angles, protrusions, densities) which do not necessarily present the optimal solution for the machining and removal of material.

Pulsed laser ablation has become a highly successful technique for the generation of controlled micro-cutting features in solid diamond structures [8]. It offers the opportunity to produce novel diamond micro-core drills incorporating specifically designed micro-features having defined cutting edges for composite material drilling applications. This arrangement is likely to offer a significantly different cutting action to that offered by diamond abrasives. To date there have not been any reports on such an approach.

In order to improve the surface quality of small core-drilled holes in composite materials, tools offering a more efficient material removal mechanism are required. A novel design of diamond core-drill equipped with micro-teeth incorporating defined cutting edges is proposed. To demonstrate the efficiency of this approach, the paper reports on:

- an in-depth study of the material removal mechanisms in core-drilling of composites
- an evaluation of the process outcomes when using novel vs. conventional designs of core-drill. This refers to both workpiece surface quality (e.g. fibre pull-outs, delamination) and tool performance (e.g. wear behaviour, chip evacuation)
- the explanations for the improved performance of novel core-drill design in terms of reduced cutting forces and temperatures

2. Mechanisms of abrasion and defined edge cutting in micro-core drilling

The current design of small diameter core drills, employing diamond electroplated matrix structures have a strong resemblance with grinding tools featuring variations in locational distributions, sizes, shapes, orientations and protrusions of diamond abrasives from the containing bond. It has been well established for superabrasive grinding that the process presents abrasives generally characterised by micro-geometries of varying degrees of (negative) rake and clearance angles to the workpiece [9]. Abrasives presenting minimum clearance angles or large negative rake angles are therefore likely to cause rubbing with the composite materials [10] which can be exacerbated by the materials having lower stiffness, i.e. the increased push-off from the tool causing a reduction in cutting during the machining process. Furthermore, the abrasive action is likely to be of a progressive nature due to the varying locations of the abrasives around the tool's periphery and their heights of protrusion from the containing bond. The effect can become more pronounced as the tool wears with local abrasive attrition.

On the other hand, it has been established that during the machining of composite materials with tools of defined edges, i.e. turning, milling tools, where the rake and clearance angles have been defined, a cleaving/shearing action takes place during the cutting of the fibres [11]. With such tools, the specific cutting process can be optimised by the selection of the appropriate tool geometry to suit the application, resulting in reduced cutting forces and surface finishes.

In this context, it was considered of key importance to design a core-drill with defined cutting edges [12], as presented in Fig. 1a so that the material removal mechanism is dominated by shearing, enabling the reduction of cutting forces and temperature, with an ultimate outcome of increased workpiece quality. These positive outcomes would enable the optimisation of process parameters and hence, improvement of capability of the core drilling operation.

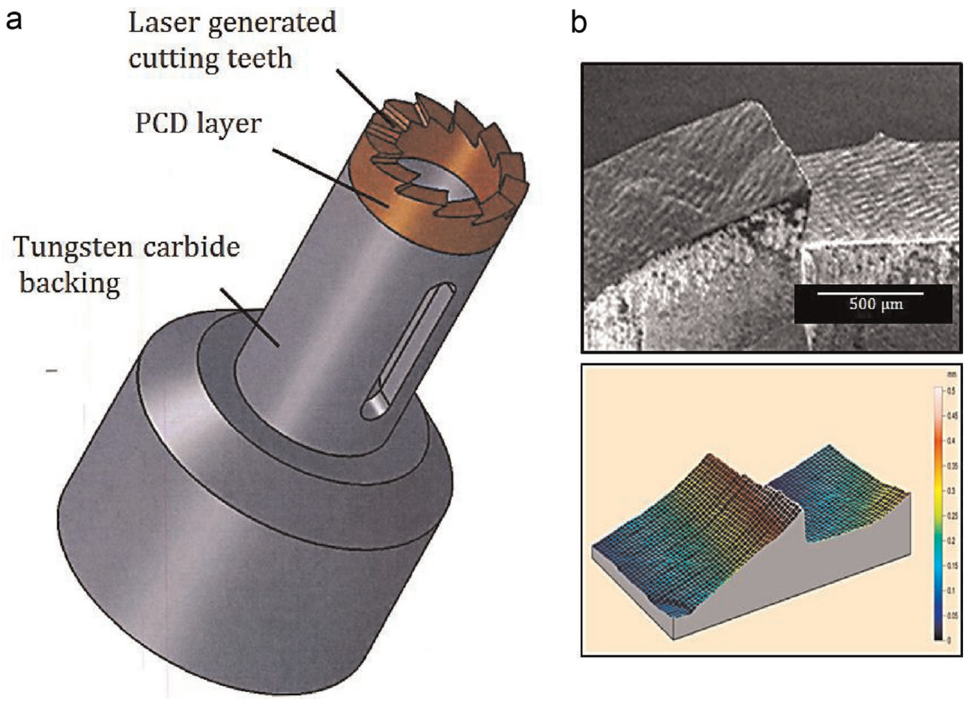

Fig. 1. (a) Conceptual design of laser generated PCD core drill and (b) SEM image of laser generated tooth profile in PCD and profilometric measurement image of its geometry.

3. Experimental setup

For the reasons mentioned above, the novel design of micro-core drills were produced using pulsed laser ablation from solid polycrystalline diamond (PCD) structures sintered onto a tungsten carbide backing (CMX850 from Element Six). A preliminarily optimised cutting tooth edge geometry ($\alpha=15°$; $\gamma=5°$) was based on the assumption that positive rake and clearance angles would provide a predominantly shearing action [13,14] while facilitating the evacuation of the cutting debris rather than the abrasion/rubbing action as would be anticipated with conventional electroplated diamond tools. Moreover, using solid diamond as cutting edge material would eliminate the use of binder thus increasing the tool wear resistance and heat dissipation capabilities.

PCD blanks were initially precut using a micro-wire EDM (Sodick AP200L; wire diameter = 0.1 mm, max servo voltage = 100 V, max wire feed = 6 mm min^{-1}) and subsequently ground to a nominal 3 mm outer diameter required for the drill. To produce the inner core diameter of the drill, the PCD and backing tungsten carbide were initially drilled using the laser discussed above and subsequently cut to an internal diameter of 2 mm using the micro-wire EDM. The micro-tool fabrication was realised by employing a Nd-YAG Q-switched laser (wavelength = 1064 nm, spot size = 40 µm at pre-optimised operating parameters (power density = 11.14×10^6 W cm^{-2}, pulse frequency 50 kHz, beam speed 400 mm s^{-1}) [8,15]. The cutting teeth in the PCD structure were individually generated followed by an indexing operation. A metrological evaluation of the frontal cutting edges of the laser generated core-drill was subsequently performed, revealing the following: angular pitch = $36° \pm 50'$; rake angle = $5° \pm 35'$; clearance angle $15° \pm 1°40'$. With such edge definitions (Fig. 1b) the new core-drill design, although these could be further optimised, is nonetheless more likely to remove material through shearing than abrasion/rubbing.

4. Evaluation of core drilling performance

To evaluate and understand the different mechanisms of cutting associated with the electroplated diamond and laser generated micro-core drills, 1 mm thick CFRP composite plaques were manufactured in-house from unidirectional carbon fibre prepreg. The material consisted of MTM44-1 toughened epoxy matrix (Cytec Industrial Materials) combined with 12 K HTS 5631 carbon fibre (Toho Tenax). The fibre areal mass in the prepreg was 145 gsm and the resin content was 34 wt%. The laminates were laid up on a 2 mm thick polished steel plate in a balanced symmetrical configuration (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°) to avoid warpage, 0° being the latitudinal fibre direction. After vacuum debulking, the assembly was vacuum bagged and cured in an autoclave under a pressure of 6 bar. The temperature was ramped to 180 °C at a rate of 2 °C min^{-1} and then held for 2 h. The moulding was air cooled within the autoclave to 40 °C before demoulding. The individual fibre filaments have a tensile strength of 4300 MPa [16] resulting in typical in-plane tensile and shear strengths of 2159 MPa and 113 MPa respectively [17] for each ply in the fibre direction. The laminate architecture is typical of those used in many industrial applications and was chosen to highlight fibre fractures more easily compared with more complex architectures such as woven or stitched materials. UD materials are also typically more homogeneous at the mesoscale, eliminating issues with local material variability relative to hole position.

For the drilling evaluations a Makino A55 5-axis machine tool, equipped with a Kistler 9317B 3-axis dynamometer (signals acquired at 10 kHz and processed, e.g. filtered, drift correction, using a proprietary code in Matlab) has been employed (Fig. 2). This arrangement was located separately to allow the force to be measured for the drilling of an individual hole following the sequence of multi hole drilling which was used to generate wear on the tools under controlled conditions.

To ensure that the drilling experimental results of the multi holes were not affected by inconsistencies in workpiece deflection under the thrust force, a back clamping plate containing an array of 36 clearance holes of 6 mm diameter was employed, thereby offering similar localised support around each hole. The load signals were captured for the first hole drilled with an unused tool of each type, and measured again for the 108th hole and subsequently for the 216th hole (i.e. after 3 and 6 plates of 36 holes). Inspections were made of the resulting internal surfaces, following the above sequence, using a Philips XL30 ESEM.

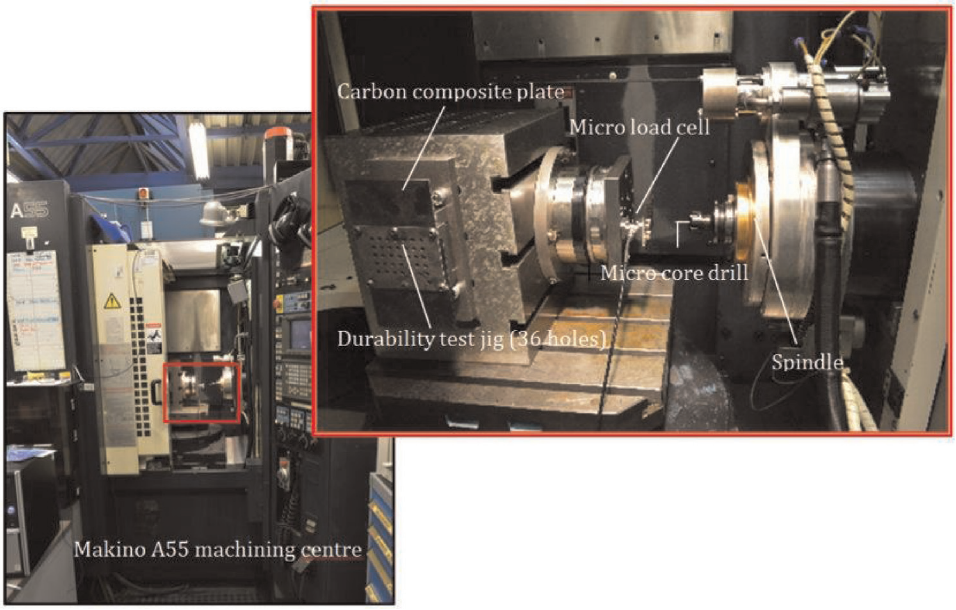

Fig. 2. Experimental setup showing load measurement and durability test arrangements.

The tools were inspected after every hole drilled and in the case of core entrapment in the drill tube, the material was carefully removed using a sharp probe, while taking care not to interfere with the cutting surface of the tool.

Tests were continued until it was evident that a significant extent of material failure was observed (i.e. fibre pullout, uncut fibre strands, structure delamination). Additionally, the quality of the core-drill cutting surfaces were analysed using the SEM before and after holes 108 and 216, in order to determine the wear characteristics of the tools as the tests progressed. All drilling tests for this assessment were carried out at a spindle rotational speed of 4000 rev min^{-1} using a constant feed rate of 20 mm min^{-1}. All testing was carried out under dry conditions.

In order to obtain a better understanding of the cutting behaviour for the two types of core-drills, a separate experimental arrangement was set up using a high speed thermal imaging camera (FLIR SC7000, spatial resolution: 15 μm, measurement accuracy: $\pm 1^\circ$ C) to capture thermographical images from the back (exit) surface of the composite plate (Fig. 3) as the drill penetrated through the material. The arrangement was set up to offer unrestricted access to the exit face of the composite plate for the thermal imaging to take place and provide a clean environment for operation of the imaging camera. The camera was initially calibrated using a mat black field and set to capture 1000 frames at a frame rate of 50 per second with a maximum temperature threshold of 210° C. The use of a precision linear stage (Aerotech ALS130) and high speed spindle (NSK EMS 3057) allowed identical parameters to be employed to the Makino machining centre setup. A clamping arrangement provided sufficient support to material around the drilling site whilst preventing interference with the thermal effects of drilling. In addition, glass microscope slides were placed around the drill site to allow the capture of a maximal quantity of uncontaminated drilling debris for later SEM examinations.

5. Results and discussion on drilling behaviour

Evaluations of the two different drilling mechanisms under investigation are presented in terms of tool wear progression and hole surface quality.

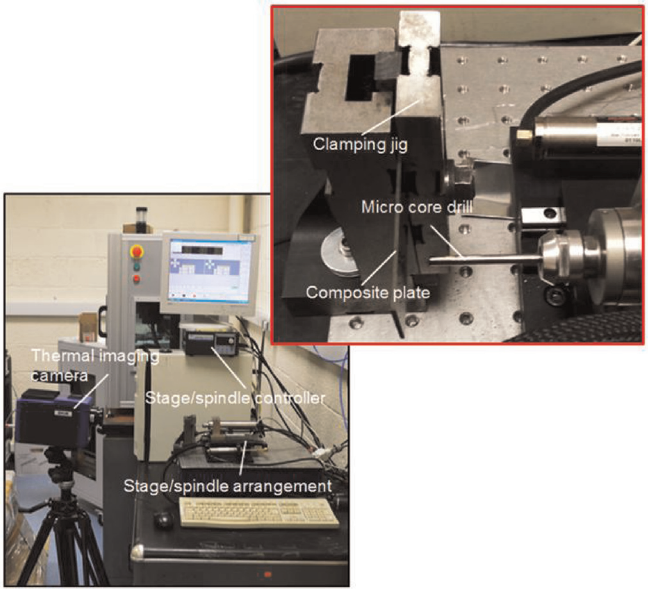

Fig. 3. Experimental setup showing high-speed thermal imaging camera and the precision linear stage and drill spindle.

SEM micrographs of a PCD core drill show the defined micro-cutting teeth in the unused state (Fig. 4a) and after generating 216 holes (Fig. 4b). Whilst minor micro-chipping exists and with evidence of some resin residue on the tooth edge profile of the worn drill, the overall cuttings edges around the periphery of the drill face appear in good condition. The drill therefore remains completely serviceable due to the observed sharpness and exposure of its cutting teeth.

An unused electroplated diamond micro-core drill bit is shown in Fig. 4c which exhibits a typical stochastic distribution of the diamond grains (Nominal size: D76) on the cutting surface and down the flanks of the tool. Some evidence of nodular galvanic growth of the nickel is also apparent.

Fig. 4d shows the electroplated diamond tool after 216 holes. There is clear evidence of crystal fracture and a general reduction in protrusion from the surface of the Nickel bond layer. There are also witness scratches on the surface of the Nickel bond from rubbing contact with the workpiece. In addition to these effects, significant amounts of debris build up is apparent on the leading edges of the tool, in some cases partially enveloping the diamond abrasives.

SEM micrographs of the first hole produced with a laser-generated PCD micro-core drill (Fig. 5a) show a highly-defined exit edge of the hole produced by the action of the laser-produced cutting teeth. The drilled hole's internal surface is of a regular texture exhibiting a covering of resin as shown in the SEM images of higher magnification. By comparison, the hole drilled with an electroplated diamond micro-core drill (Fig. 5b) shows a well defined exit edge, however even with this unworn tool there is evidence of micro-plucking of the outer layer of fibre bundles around the hole periphery shown in the magnified images. Such micro-plucking or pull out is likely to be as a result of tearing and de-bonding of the fibre bundles from the composite resin by the abrasive action of the diamond grains and rubbing of the Nickel bond of the as the drill passes through the fibre layer. Such characteristics are likely to have been caused from a combined action of the abrasives residing on the front face as well as on peripheral flank of the drill. Furthermore, the hole surface shows irregular grooves and fibre-covered resin protrusions, where the hole surface grooving relates to the topography of the protruding diamond abrasives down the peripheral flank of the electroplated diamond tool, as shown in Fig. 4c.

While little wear of the two tools were observed from the first to the respective 108th holes, differences in their wear characteristics became more apparent as the tests progressed. At the end of the test, micro-wear of the PCD tool became evident (micro-chipping, local resin deposits). However, this appeared to have only a small effect on the cutting ability of the tool which is visible from the surface of the 216th hole (Fig. 5c), i.e. a regular surface texture and the presence of resin rich areas characterised by a defined exit edge having a small extent of ‘micro-furriness’. The 216th hole produced by the electroplated core drill (Fig. 5d) shows extensive delamination local to the exit surface and jagged fracture of the carbon strands of the outer layers. There is also evidence of fibres fracturing away from the resin rich hole exit interface, suggesting that the fibres were not sheared off but underwent a more complex failure mechanism. Ultimate fibre separation could have been as a result of tensile fracture caused by the drill rotation. It is also interesting to observe that the texture of the hole becomes smoother as the extent of abrasive protrusions reduce from the surface of the bond with wear (refer to Fig. 4d).

The debris, consisting of loose resin particles and fractured fibres, collected during drilling with the unworn and worn tools provided further evidence of the different cutting behaviour between the two core drill types. While some differences in the cleavage angle was observed on the fibre ends, most likely due to

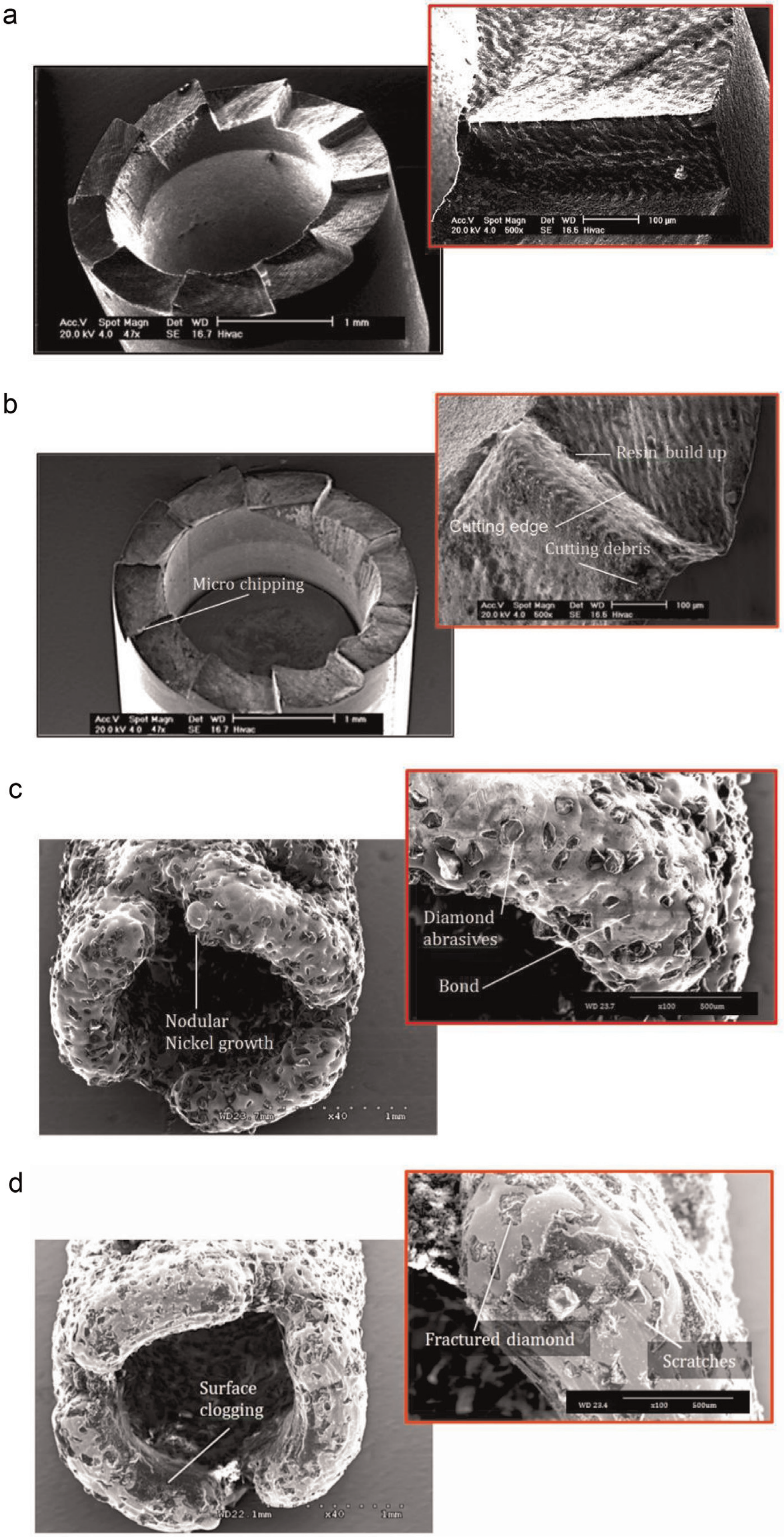

Fig. 4. SEM micrographs of (a) unused PCD micro-core drill, (b) PCD micro-core drill after 216 holes, (c) unused electroplated diamond core drill and (d) electroplated diamond core drill after 216 holes.

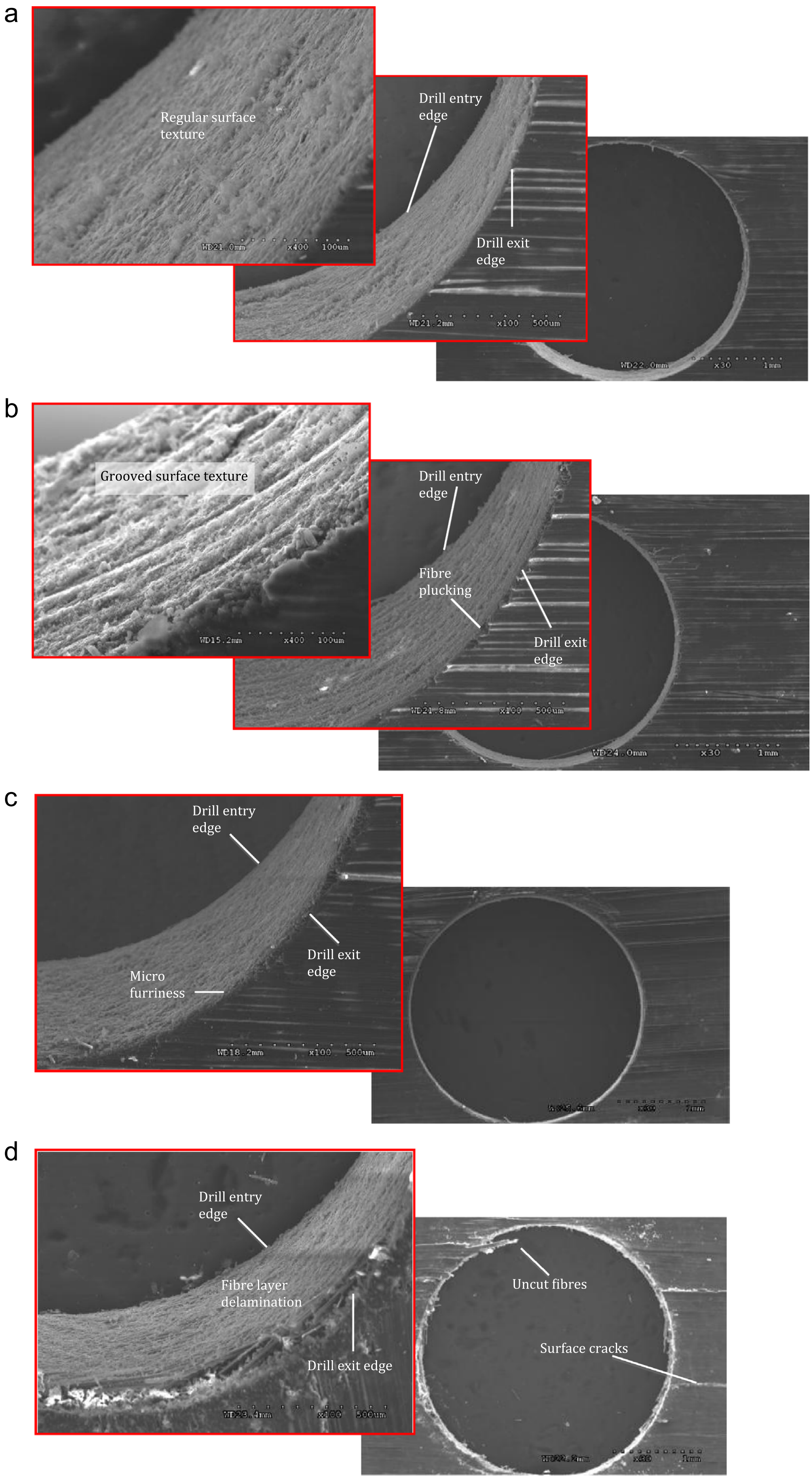

Fig. 5. SEM micrographs of micro-core drilled holes in composite plate showing (a) the first hole –PCD drill, (b) the first hole – electroplated diamond drill, (c) the 216th hole – PCD drill and (d) 216 hole – electroplated diamond drill.

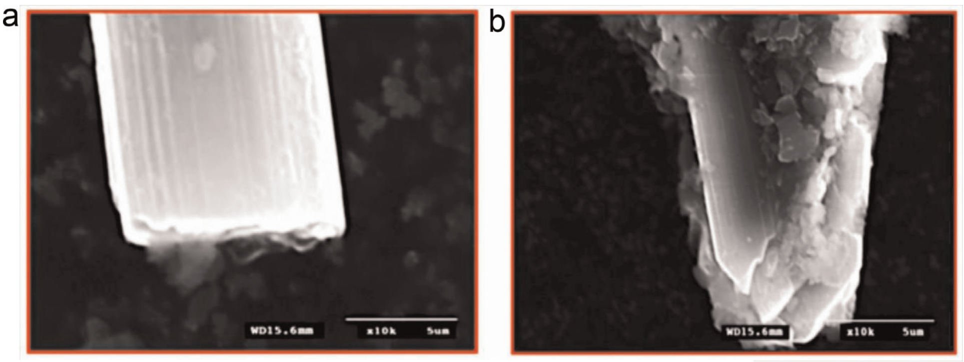

Fig. 6. Fractured ends of single carbon fibre strands resulting from (a) drilling with laser generated PCD drill – shearing, (b) drilling with electroplated diamond drill – abrasion/rubbing.

the drill intercepting the fibres at the different angles around the hole periphery [10], the fractured fibres produced from the laser-generated PCD tool (unworn and worn tools) generally showed well defined cleaved ends (Fig. 6a) as would be expected from shear fracture. However, fibres in the debris from the electroplated diamond tools in the two wear conditions generally showed a more complex fracture pattern (Fig. 6b) which could have been produced as a result of contact with several abrasives which progressively machine away the fibres, causing a stepped fracture pattern. These images point to the distinct differences in the cutting action of the drills between the teeth on the laser generated PCD drill compared with the electroplated diamond abrasive drill.

The recorded drilling forces for the 1st, the 108th and the 216th hole, which were processed using a Gaussian filter in Matlab to reduce the signal noise, are presented for the two micro-core drills: PCD with defined edges (Fig. 7a) and electroplated diamond (Fig. 7b) designs. While the peak drilling force is generally encountered towards the exit of the hole, in most cases it has been observed that there is a significant increase in the force during drilling from the initial to the latter part of the hole prior to exit; on average 1.8–1.9 times increase. As this was observed with both drill types, the mechanism causing this phenomenon for both cases is likely to be the same. The load increase is expected to be due to the contact of the inner circular wall of the drill with the softened resin granulate debris liberated during the drilling action which becomes trapped between the drill surfaces and the hole/core. This effect becomes more pronounced as the composite core expands with elevating temperature.

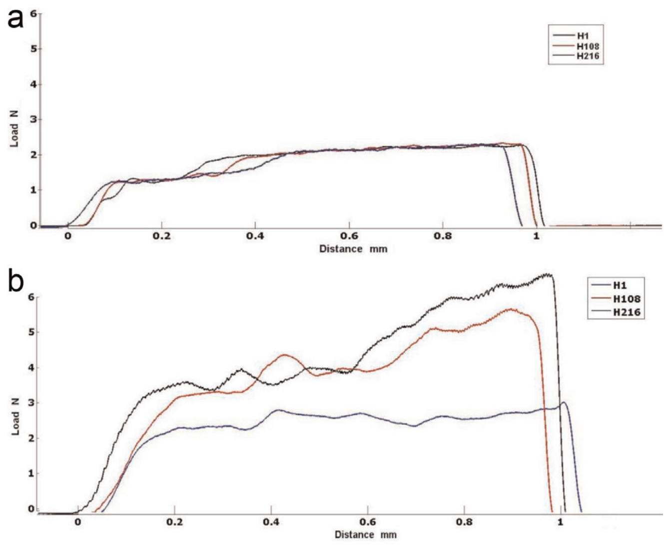

Fig. 7. Graphs of loads in drilling through a 1mm thick composite plate for (a) the laser generated polycrystalline diamond (PCD) micro-drill and (b) the electroplated diamond (EPD) micro-drill for hole 1, hole 108 and hole 216.

While the peak drilling forces for the laser-generated PCD micro-core bit were consistent for increasing number of holes, the peak forces increased significantly for the electroplated diamond tool as the tests progressed, resulting in a cutting force that was ca. 3 times higher than for the PCD core bit. Referring to the wear observed on both tools discussed earlier, these trends can be explained firstly by the durability of the cutting edges on the PCD drill and their ability to remain sharp (see Fig. 4c). Secondly for the case of the electroplated diamond tool, increased rubbing as a result of the progressive fracture and ensuing reduction in protrusion of the diamond abrasives and the clogging of the cutting surface yielded increased drilling forces (Fig. 4d),

Thermal images were captured for the 1st and 216th hole drilled for both drill types using the test arrangement described in Fig. 3. The maximum recorded temperatures for the 1st hole drilled with the PCD and electroplated tools were 81° C and 90° C respectively, as shown in Fig. 8a and b. The central core area was the hottest recorded region of the drilling site as the drill penetrated through the material for both the fresh and worn PCD and electroplated diamond micro-core drills; however, the temperature gradients exhibited a greater latitudinal spread (i.e. along the 0° ply direction) in all cases.

From the graphs it can also be observed that the PCD drill produced less heat in the composite material surrounding the hole compared with the electroplated diamond drill. This phenomenon is most likely due to the significantly higher thermal diffusivity of the PCD drill (nominal thermal diffusivity=0.12 $m^2\,s^{-1}$; thermal conductivity=550 $W\,m^{-1}\,K^{-1}$) [18] which is able to conduct heat away far more rapidly than the predominantly nickel-based matrix of the electroplated core drill (nominal thermal diffusivity=0.01 $m^2\,s^{-1}$; thermal conductivity=91 $W\,m^{-1}\,K^{-1}$) in the environment of the relatively low thermally conductive carbon composite (Carbon epoxy composite in-plane nominal thermal diffusivity=0.008 $m^2\,s^{-1}$; thermal conductivity=25 $W\,m^{-1}\,K^{-1}$) [19].

Fig. 8c and d show the thermal gradients at the maximum recorded drilling temperature captured while drilling the 216th hole with the PCD and electroplated drills respectively. While an increase in drilling temperature from the first hole was observed, the difference in the maximum measured temperatures between the two drills is more pronounced (PCD drill 100° C, EP drill 125° C). This is certainly due to the reduced cutting ability of the electroplated core drill resulting from the wear characteristics reported earlier, (max. drilling force: PCD tool=2.2 N; electroplated diamond tool=6.4 N). As a result, the electroplated drill produced significantly more heat in the surrounding material than the PCD drill.

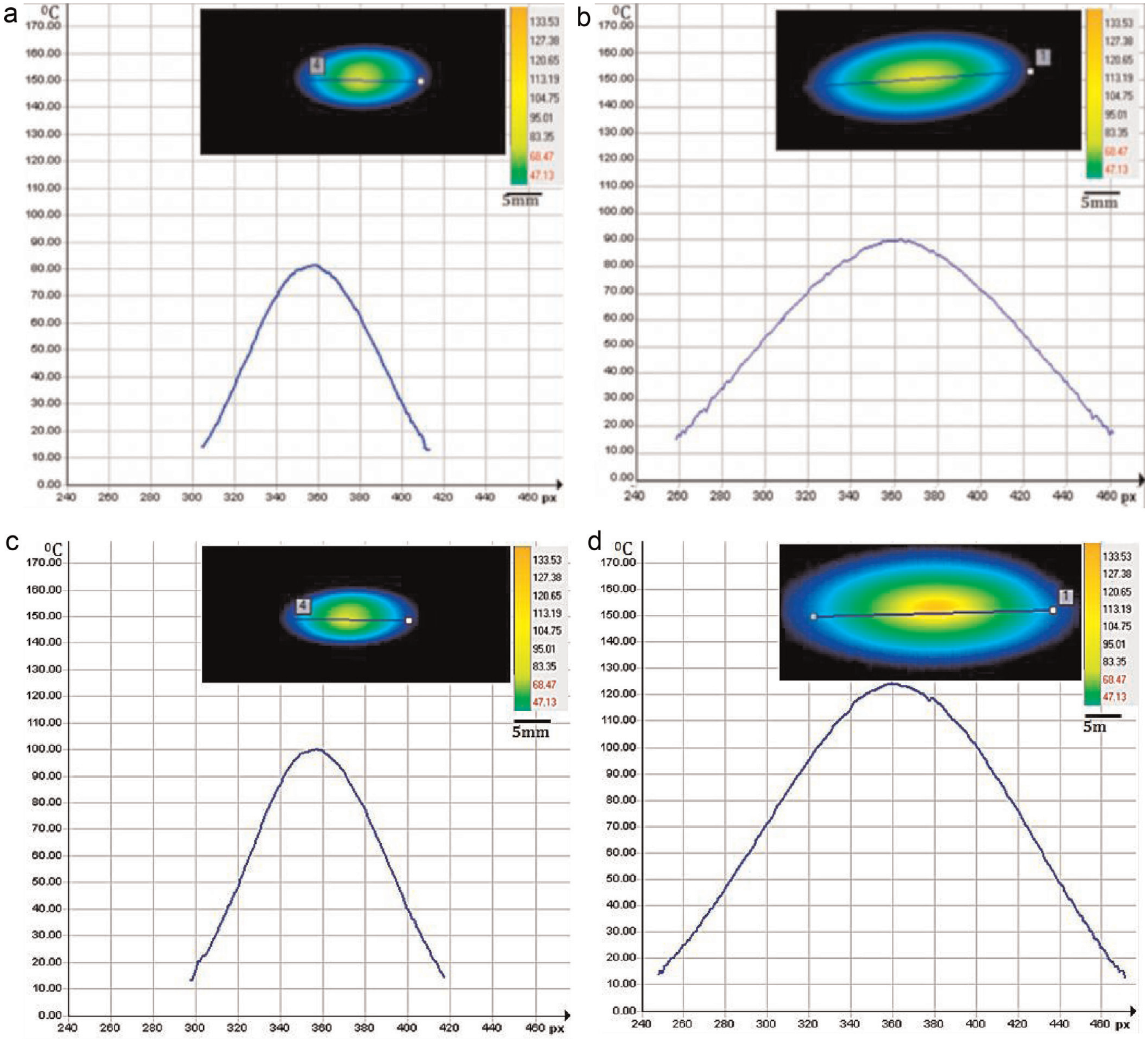

Fig. 8. Thermal gradients during the drilling of 1 mm carbon composite plate (a) hole 1 with PCD, (b) hole 1 with electroplated diamond, (c) hole 216 with PCD and (d) hole 216 with electroplated diamond micro-core drills.

For more aggressive operating parameters, e.g. higher drill feed rates, the differences in drilling temperatures would be expected to be more pronounced between the two drills. Elevated drilling temperatures could occur with the electroplated core drill if the space between the tool's bond surface and workpiece surface was inadequate to cater for the quantity of debris generated in the drilling operation. This situation will be worsened with tool wear (i.e. diamond fracture or loss, surface clogging) which reduces the tool's cutting effectiveness and clearance for debris evacuation, increasing the likelihood of tool rubbing. Conversely, the laser produced tool has a significantly larger allowance for chip flow due to its individual teeth which are separated by gullets.

From the results presented in these comparative tests, it has been shown that the PCD micro-core drill, with defined cutting teeth, exhibited superior drilling performance compared with the electroplated diamond core drill having stochastically distributed abrasives. The novel design of the PCD tool allows for ample chip clearance resulting in minimal clogging of the cutting teeth compared with the electroplated diamond tool.

The durability of the solid polycrystalline diamond tool in this application results in good hole integrity even after 216 holes which is well beyond the point at which the electroplated diamond tool fails due to a combination of abrasive fracture, surface clogging and increasing drilling force resulting in delamination of the composite ply.

6. Conclusions

The drilling mechanism of a novel laser produced micro-core drill from a solid PCD structure incorporating defined edge cutting teeth-and has been compared against a conventional micro-core drill utilising diamond abrasives in an electrolytically applied

Nickel matrix. Evidence has been presented to show that the drilling mechanisms of the two drills are significantly different:

- The PCD core drill predominantly exhibits a shearing action of the carbon fibres during drilling. The defined edges of the cutting teeth produce well-defined hole surfaces, exit edges and fibre fractures showing clean cleaved ends.
- A more complex mechanism takes place during micro-core drilling using the electroplated diamond tool. Abrasive traces on the hole surface and reduced exit edge definitions are shown, with exposed fibre ends exhibiting irregular fractures caused by progressive/multiple contact with abrasives.
- The cutting forces of the electroplated micro-core drill was ca. 36% higher than for the PCD core drill when the tool was new and ca. 190% higher after 216 holes due to the pronounced abrasive fracture and surface clogging of the electroplated tool causing catastrophic delamination of the composite.
- The electroplated diamond micro-core drill produced 11% higher drilling temperatures than the PCD drill when new, which increased to 25% after 216 holes. The electroplated drill also produced a greater thermal spread (1.8 times greater along the 0° direction of fibre lay at 40° C for the 216th hole) than the PCD core drill.

These results have not only enhanced the understanding of the different mechanisms of diamond micro-core drilling, but have highlighted the benefits that can be realised in the drilling of abrasive composite structures with laser generated tools. This will provide enabling manufacturing capabilities in current and emerging applications of these high strength to weight materials.

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