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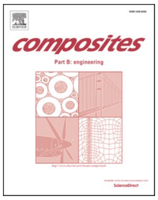

A critical review on mechanical micro-drilling of glass and carbon fibre reinforced polymer (GFRP and CFRP) composites

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ABSTRACT

Recent trends in miniaturisation and high-strength fibrous composites encourage the use of mechanical micro-drilling technology of fibre-reinforced polymer composites (FRPs). Although severe expertise has been gained through the past few decades on the machinability of FRPs, this information cannot be directly adapted to the micro-drilling mainly due to the size effect. Therefore, the main aim of the present study is to comprehensively review challenges, recent experience, and future aspects of mechanical micro-drilling of glass and carbon fibre reinforced polymer (GFRP, CFRP) composites. The chip removal mechanisms of micro-drilling of FRPs are reviewed and compared to conventional-sized technologies. Furthermore, the micro-drilling-induced geometrical defects (delamination, burrs, fibre pull-outs *etc.*) and the cutting energetics are also discussed. Moreover, the future aspects and research directions are highlighted in this growing research area.

1. Introduction

Fibre-reinforced polymer (FRP) composites are widely applied compound materials in the high-end industries mainly due to their excellent specific mechanical properties, dimensional and chemical stability, good damage tolerance and easy-to-shape manufacturability [1]. Their application can reach a significant weight reduction and cost-saving compared to metallic structures; therefore, they are widely used in the automobile, sport, microelectronics, and aerospace sectors [2,3]. FRPs are often manufactured ready to shape; however, further processing is often required to manufacture geometrical features (*e.g.* holes, edges, pockets) with complex shapes and strict tolerances [4]. Although most of the holes are needed for assembly, and FRP parts are joined through macro-sized holes (diameter is ~3 mm and larger) [5]; micro-sized holes (diameter is less than ~1 mm) in FRPs are also the focus of the interest. Micro-holes in FRPs are used in (i) miniaturised polymeric composites in microelectronic systems *e.g.* in printed circuit boards (PCB) [6], (ii) polymeric biomedical filters [7], (iii) micro-perforated composite panel absorbers [8]; (iv) composite engine nacelles to improve aerodynamic properties [9–12], (v) fibre optic sensor placing into FRPs for monitoring and diagnostics mechanical, thermodynamical and aerodynamical conditions [13,14], (vi)

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micro-perforated panels in FRPs to improve acoustic absorption and noise control [15], and (vii) micro-robot flight components such as bending actuator and hinge locking components [16].

Mechanical machining and non-conventional technologies can manufacture micro-holes in FRPs. Although non-conventional technologies like laser drilling (LD) [17–20], abrasive water-jet machining (AWJM) [21], electro-discharge machining (EDM) [22–24], and electrochemical discharge machining (ECDM) [25,26] are wear-less and do not result in large working forces and torques that could significantly deform the composite structures; these technologies have low material removal rates (MRR), are often difficult-to-apply and have remarkable limitations and challenges [27]. For example, the proper set of taper angle and heat affected zone (HAZ) (thermal damages like matrix melting and fibre swelling [10]) is difficult-to-control in LD technology [28–32]; the abrasive particle size and taper angle limit the applicability of the AWJM technology [21], the elliptical hole formation due to the anisotropy of the composites is a big challenge in the LD and EDM technologies [33], the electrical conductivity of the CFRP composite is often required to be improved by the application of conductive fillers that reduces the resultant strength of the composite [34], the frequent electrode replacement in EDM increase operation time and decrease machining efficiency [22].

In mechanical micro-drilling, the tool makes direct contact with the composite; therefore, the tool wear and machining force-induced geometrical damages (*e.g.* delamination, fibre pull-out) and potential tool breakage make mechanical micro-drilling of fibrous composites challenging [10]. However, the reachable hole quality is excellent (*i.e.* conventional delamination factor below 1.20 [35–37], average surface roughness under 3 μm [38,39], burr-free edges with optimal conditions), the material removal rate is good (*i.e.* over 5 g/min in optimal conditions [40]), and the applicability of this technology is more independent of the composite properties than other advanced technologies like EDM and ECDM [37,41]. As mechanical micro-drilling of FRPs is getting huge attention due to the growing industrial need for micro-holes in FRPs, the main objective of the present review paper is to overview and discuss recent expertise, lack of knowledge and future trends in mechanical micro-drilling of glass and carbon fibre reinforced polymer (GFRP and CFRP) composites. First, the review methodology is presented in Section 2. Second, the difficulties and challenges of micro-drilling of FRPs are presented in Section 3. Then, recent expertise, solutions and innovations are reviewed and discussed in Section 4, including the chip formation mechanisms, cutting energetics (cutting force, torque and temperature), micro-drilling-induced geometrical damages (delamination, burrs), surface microstructure, and tool wear. Finally, the future trends are highlighted and discussed in Section 5.

2. Review methodology

In this section, the review methodology is presented to ensure a transparent review process. Although there is no strict standard for conducting a semi-methodological review [42], the general aims, methods, key ideas and relationships are presented below.

Scientific papers were searched in the ScienceDirect, Springer and Google databases using the keywords of “micro-drilling”, “CFRP” and “GFRP” in the time period of 1997–2022. Considering that some keywords have another form having the same meaning (*e.g.* “CFRP” and “carbon fibre reinforced polymer”), the original keywords were replaced by them, and the search was repeated. Then, the titles of the searched papers were scanned and decided whether is it suitable (*i.e.* present experience in micro-drilling of fibrous composites). After the first filtering step, the titles of each reference of each title-filtered paper were scanned and repeated many times until relevant titles were still found. Since some duplicated titles occurred; these were removed from our database. Finally, the abstracts and conclusions of each paper were carefully screened, and irrelevant papers were excluded from the database of this review project. This data collection process was conducted by the corresponding authors and checked by two independent co-authors. Nevertheless, it has to be highlighted that this review paper also includes a discussion of that key papers in the machining of fibrous composites, which cannot be found by this data collection method. The inclusion of these additional papers was needed to support the narrative of the critical review and future scopes. The distribution of the year of publication of the selected papers is illustrated in Fig. 1.

3. Difficulties in micro-drilling of fibrous polymeric composites

Mechanical micro-drilling of FRPs combines the difficulties of fibrous composite machining (non-homogeneity, anisotropy, abrasive nature of fibres *etc.*) and downscaled machining (size effect, tool breakage *etc.*) [6,43]. The schematic of mechanical conventional-sized drilling versus micro-drilling of FRPs is illustrated in Fig. 2.

In mechanical micro-drilling, the uncut chip thickness is small and often comparable to the cutting edge radius [44]; therefore, ploughing will dominate the chip removal mechanisms [45]. Therefore, the downscaling of the macro-sized tools and technologies to the micro-scale does not result in a proportional reduction of process characteristics. This is called as size-effect [6]. Low feeds are often applied in micro-drilling because the slim and weak micro-drills often break due to larger cutting forces caused by higher feeds and accelerated tool wear [46,47]. However, low feeds result in a small uncut chip thickness that may be close to the minimum chip thickness and result in ploughing and elastic recovery, not chip removal. It is a tendency that a chip is not formed at each pass of the cutting edge, making understanding, and controlling the process even more difficult [48].

Despite numerous mechanical drilling technologies being developed in the previous decades to machine conventional-sized holes in FRPs effectively [4], these are not directly adaptable to the micro-scale. Researchers showed that helical milling (also known as orbital drilling [49]), tilted helical milling and wobble milling technologies produce less machining-induced geometrical damages in FRPs than conventional drilling [50–52]. However, these multi-axis (3D, 4D, 5D) advanced technologies need a more complex tool movement which would be difficult to accurately implement in micro-scales due to the precision limitations of machine tools and industrial robotics; and the slender and weak stiffness of micro-mills [53]. Conventional-sized drilling technologies using pilot holes are also advantageous because the axial cutting force of the second drilling operation is significantly lower, and the hole quality is therefore expected to be better [54,55]. Nevertheless, in micro-scales, considering that the diameter of the pilot hole drill is smaller than the final drill’s diameter, it is often not possible to select a smaller diameter tool than the nominal hole diameter.

Although advanced cutting tool geometries (*e.g.* double point angle twist drill, brad and spur, step drill, one-shot) are advantageous in FRPs from the point of view of drilling-induced geometrical defect formations

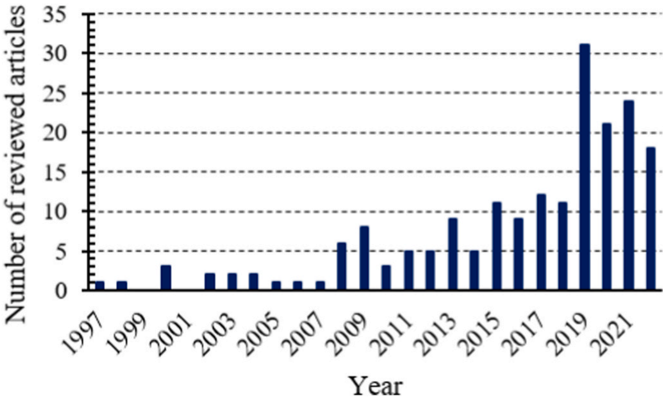

Fig. 1. Publication year distribution of the reviewed papers.

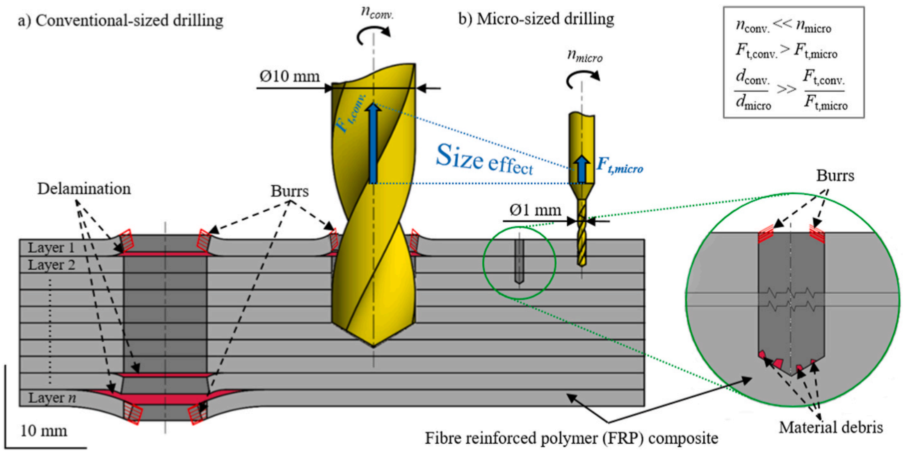

Fig. 2. A schematic illustration of macro and micro-drilling of fibrous polymeric composites: (a) conventional-sized and (b) micro-sized drilling, where n denotes the spindle speed, F_t is the thrust force, and d denotes the hole diameter.

(*e.g.* delamination, burrs) [4], these tools are usually not available in micro-sizes. Therefore, the drawbacks of twist drills having conventional geometry make the micro-drilling of FRPs even more challenging. The ratio of the chisel edge to the tool diameter is larger than in macro drilling; therefore, the drill's chisel edge dominates the drilling process. It is well-known that the cutting mechanism at the chisel edge is not advantageous, mainly due to the close to zero effective cutting speed and negative rake angle; therefore, the considerable dominance of the chisel edge will disproportionately increase the axial cutting force and thus increase the probability of drilling-induced push-out delamination [56]. The chip removal from the hole is also problematic due to the small specific drill flute space [57]. Another drawback of the slender tool used for micro-drilling is the considerable tool run-out, which often results in inappropriate hole shape, rapid tool wear and tool breakage [58]; and the often extremely high spindle speeds (up to 160 000 rpm) required to ensure appropriate cutting speed [59].

Similarly to the conventional-sized drilling of FRPs, the typical drilling-induced geometrical damages in the micro-scale are delamination, burrs, matrix cracking and smearing, fibre pull-out and breakage, fibre/matrix debonding, thermal degradation, fuzzing and spalling, matrix burning and subsurface damage [60–63]. However, their measurement and qualification are more complicated and require more expensive devices and cumbersome technologies, mainly due to the microscopic sizes of the damages. For example, a commercial digital camera is often preferable for burr measurement around conventional-sized holes; in micro-scales, a digital microscope is required [64]. Applying back-up support plates reduces the probability of delamination formation; therefore, it is widely investigated in the literature [35,65,66]. In micro-scales, only a solid supporting element (*e.g.* aluminium, phenol, brass, wood [35,65,67]) can be used, and hollow support plates (*i.e.* the support plate is not machined during the drilling operation [68]) would be difficult-to-implement in micro sizes. The mechanisms for clamping FRP composites for micro-drilling operation are also difficult, mainly due to the relatively flexible polymeric composites [69]. Considering the difficult-to-cut nature of the FRPs and the challenges of micro-drilling, preliminary experiments and optimisation are often required before serial manufacturing. The recent expertise in micro-drilling of FRPs is presented in the next section.

4. Recent expertise in micro-drilling of GFRP and CFRP composites

4.1. *Chip formation mechanisms in micro-drilling of FRPs*

In conventional machining of FRPs, the chip formation mechanism is highly influenced by the fibre orientation. The effects of fibre orientation on chip formation for conventional machining are illustrated in Fig. 3a–d. For the fibre orientation angle of $\theta = 0^\circ \pm \delta$ (where δ denotes a region where the discussed phenomena dominate the chip removal mechanisms), as shown in Fig. 3a, the cutting mechanisms are buckling and peeling with advancing cracks forming in front of the cutting edge [70]. For fibre orientation angle of $\theta = 45^\circ \pm \delta$, the fibre fracture is induced by compression shear, then by interlaminar shear. The machined surface displays more damage, as shown in Fig. 3b, due to microcracks generated on the fibres above and below the cutting plane. As shown in Fig. 3c, the chip removal mechanisms are bending and compression for fibre orientation angle $\theta = 90^\circ \pm \delta$. This leads to severe tool wear and poor work piece surface quality. When $\theta = 135^\circ \pm \delta$, the chip removal mechanism of FRPs is dominated by macro fracture. The rake face of the cutting tool pushes and bends the fibres, as can be seen in Fig. 3d, and, as a result, out-of-plane displacements are observable due to elastic bending caused by the compression of the rake face.

There is a paradigm shift in the chip formation mechanism of micromachining of FRPs from conventional machining, as explained in Fig. 3e–g. In all these figures, chip formation of micro-machining of FRP has a fibre orientation angle of $\theta = 45^\circ$. The fibre orientation is expected to have similar effects on micro-drilling chip formation to that of macro-machining chip formation [44]. However, as the feed value in micro-drilling of FRPs is now comparable to the edge radius of the tool (r_β), the size effect will largely influence the chip formation process. In such conditions, the effective rake angle during chip formation becomes highly negative, and the specific cutting force of the mechanical micromachining increases [71]. Additionally, chip formation may not take place when the feed is below a minimum chip thickness (h_{min}) where material plastically deforms under the edge of the tool. The rest elastically recovers, as shown by Fig. 3e. Although the number of studies on the chip removal mechanisms of FRPs in micro-sizes is few, and there is a lack of information, we suppose that dominant mechanisms of chip formation in micro-sizes are similar to that of macro-machining with a cutting tool having large cutting edge radius. This results in micro chip removal mechanisms possibly being analysed in the future through macro setup with a tool having accelerated tool wear *i.e.* larger cutting edge rounding.

When undeformed chip thickness (UCT) is equal to the minimum chip thickness shown in Fig. 3f, the chip starts forming with a portion of elastic deformation and recovery. Finally, the material is removed and formed as a chip when the unformed chip thickness is larger than the minimum chip thickness as shown in Fig. 3g. Determination of the ratio of minimum chip thickness to the cutting edge radius is essential in micromachining in order to avoid or minimize the ploughing effect and achieve the desired material removal. However, the authors found no relevant studies on the analysis of this ratio in the micro-machining of

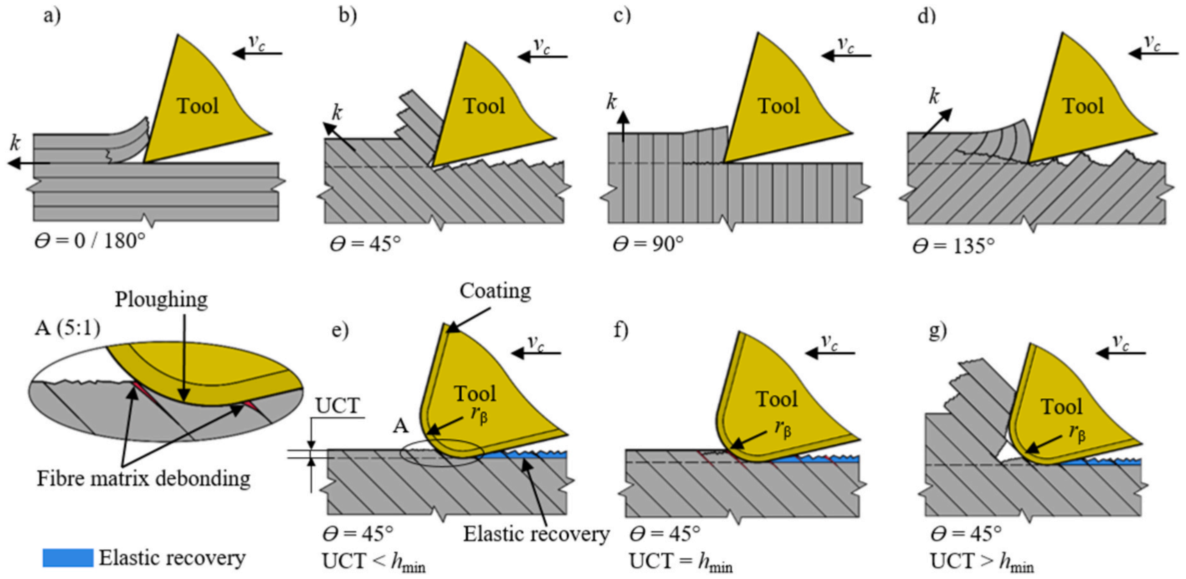

Fig. 3. Schematic drawings on chip formation mechanisms in unidirectional FRPs: conventional-sized orthogonal cutting of FRPs at fibre cutting angle of (a) $\theta \approx 0°$, (b) $\theta \approx 45°$, (c) $\theta \approx 90°$, (d) $\theta \approx 135°$, and micro-sized orthogonal cutting of unidirectional FRPs at fibre cutting angle of $\theta \approx 45°$ when the (e) uncut chip thickness (UCT) is smaller than the minimal chip thickness (h_{min}), (f), UCT $\approx h_{min}$, and (g) UCT $>> h_{min}$, where k denotes the direction of fibre reinforcements, and v_c is the cutting speed.

fibrous composites; thus, investigation of h_{min}/r_β is recommended in the future.

In several types of FRPs, there may be an absence of definite orientation of fibres in the plastic matrix, as it is illustrated in Fig. 4. The fibres can be orientated randomly. As a result, the orientation angle of the fibre with respect to the cutting edge varies during the machining operation, as can be seen from Fig. 4b and c. The chip formation for randomly oriented fibres (milled and chopped fibres) can be occurred by the combined action of micro-fracture of the fibre, in-plane shear and compression induced shear [72]. The chip formation process for micro-machining can be more complex where three zones (ploughing, transient and chip removal) are to be considered depending upon the undeformed chip thickness value [71]. Further, as the undeformed chip thickness is comparable to the milled fibre or chopped fibre, the assumption of equivalent homogeneous materials [63] for FRPs can be held in micromachining, as can be seen from Fig. 4f and g. Fibres and

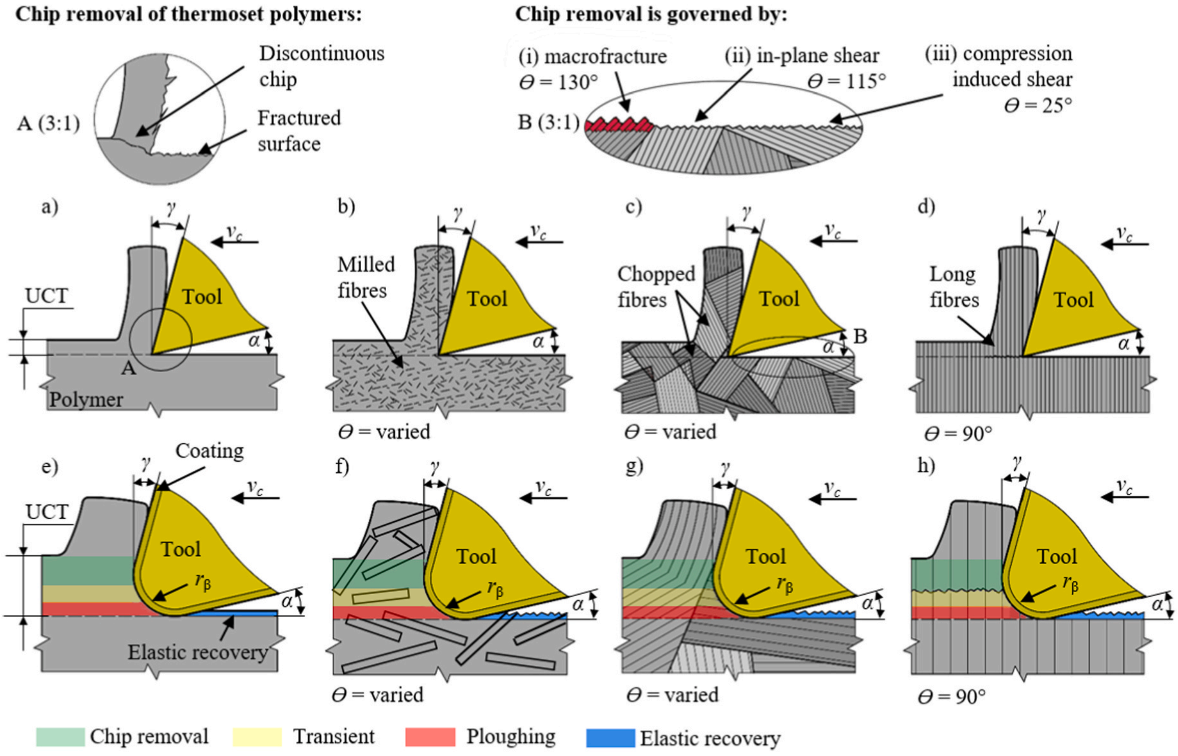

Fig. 4. A schematic illustration of the influence of reinforcement type on the chip formation in conventional-sized and micro-sized machining of FRPs: conventional-sized machining of (a) a quasi-homogeneous thermoset polymer, (b) milled FRP, (c) chopped FRP, (d) long unidirectional FRP; and micro-sized machining of (e) a quasi-homogeneous thermoset polymer, (f) milled FRP, (g) chopped FRP, (h) long unidirectional FRP, where α denotes the clearance angle and γ is the rake angle.

matrix are to be considered as a different phase for the chip formation [44].

4.2. Energetics of micro-drilling of FRPs

The basic principles of the micro-drilling process are similar to the conventional macro-drilling process, as both tool geometry and material removal process parameters are similar [71]. Nevertheless, in the micro-drilling process, the tool sizes are reduced in the micro range, creating different characteristics that are not so significant in the macro-drilling process. Foremost is the tool edge radius effect which changes the chip formation process and the trends of the specific cutting forces to the undeformed chip thickness in the micro-drilling process [6]. The specific cutting force is defined as the cutting force per unit area of chip cross-section [71]. In the macro-cutting processes, the trend of specific cutting force is linear in reducing the undeformed chip thickness because the material is sheared more than ploughed. The tool edge radius is neglected because the undeformed chip thickness is too large compared to the tool edge radius. On the other hand, the undeformed chip thickness is comparable to the tool edge radius, and it cannot be neglected in micro-drilling. The workpiece material is ploughed rather than sheared, which increases the work hardening and specific cutting forces [44,71]. Fig. 5 shows that until the undeformed chip thickness is larger than the cutting edge radius, the ratio of undeformed chip thickness to tool edge radius (r_β) is greater than one, and specific cutting forces do not vary significantly. Specific cutting forces increase significantly when the ratio r_β is less than one. The non-linear trend of the specific cutting force to the undeformed chip thickness is known as the size effect phenomenon [6,45].

The tool aspect ratio of tool diameter and length is also an essential factor affecting the micro-drilling process [74]. The effect of the tool buckling and deflection produced by thrust and unbalanced radial forces are often ignored at a low rotation speed in the macro-drilling process. However, the effect of the tool deflection and buckling are significant in the micro-drilling process as specific tool stiffness decreases due to the high depth-to-diameter ratio or aspect ratio. The tool deflection effect is amplified at a high tool rotation speed in micro-drilling [75]. Watanabe et al. [73] showed that even a small tool run-out could cause severe tool deflection due to dynamic instability. It could result in deviation of drill centre in the micro-drilling of printed circuit boards, as shown in Fig. 6.

In addition to size effect and aspect ratio, the microstructure of the workpiece also affects the micro-drilling process because the nominal diameter of fibre reinforcements of the composite is comparable to the tool edge radius. In the micro-drilling process, the work piece material cannot be considered isotropic and homogeneous, as considered in the macro-drilling process [76]. Fig. 7a shows a schematic representation of the macro-drilling process of quasi-homogeneous thermoset polymer. Fig. 7b shows a schematic representation of the FRP workpiece to show the alternate layers of FRP layers in macro-drilling process. A clear shift of the behaviour of cutting force for FRP workpiece from that of the homogeneous polymer can be observed. This difference is mainly due to the different chip removal mechanisms associated with fibre cutting angles [70]. Fig. 7d shows the location of the drill point (consisting of cutting edges and chisel edge) contact at a different layer in micro-drilling. It can be seen that either the whole drill point is located in one layer or spread in both layers depending on the drilling time. However, the width of the cutting element is sufficiently small so that the element may be located only in one layer during drilling, and cutting forces fluctuate in nature, as shown in Fig. 7c and d. Therefore, its alternate fibre and matrix layered structure fibres and matrix are considered as separate phases rather than as an equivalent homogenous material (EHM) [44].

Therefore, the conventional-sized drilling force analysis process, which does not consider the downscaling effect, cannot be applied directly to predict the trend of the cutting forces in the micro-drilling of FRP composites. Moreover, in the micro-drilling process, cutting force values are also comparatively low compared to the cutting force of the macro-drilling. The measurement of the low-value cutting force signal is most important to determine the tool breakage force. The signal of micro-drilling cutting forces is captured by a micro dynamometer and finally displayed on the screen after amplification [59]. The cutting force models for CFRP composites reported in the literature are primarily statistical in the micro-drilling process. These models were obtained using linear regression analysis to correlate thrust force with input variables such as feed, speed and drill bit geometrical parameters [10,37,77]. In addition to experimental statistical methods, analytical methods based on linear elastic fracture mechanics, composite mechanics or energy methods theory were proposed to predict the thrust forces in the composite layers. Single fibre is considered as a beam, and cutting forces are determined separately according to the fibre orientation range from 0° to 90° and the range from 90° to 180° [78]. In the last decade, mechanistic cutting force model for fibre-reinforced composites drilling were reported by many others [79].

The mechanistic modelling approach combines comprehensive cutting mechanics and tool geometries to relate the process inputs to outputs parameters, and complex material behaviour is characterized

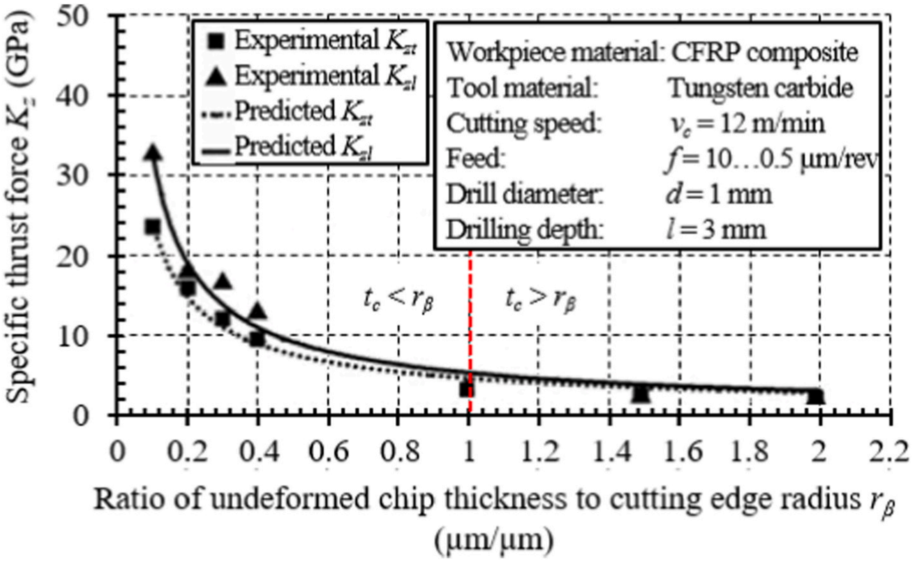

Fig. 5. Downscaling effect in micro-drilling on specific cutting force [6].

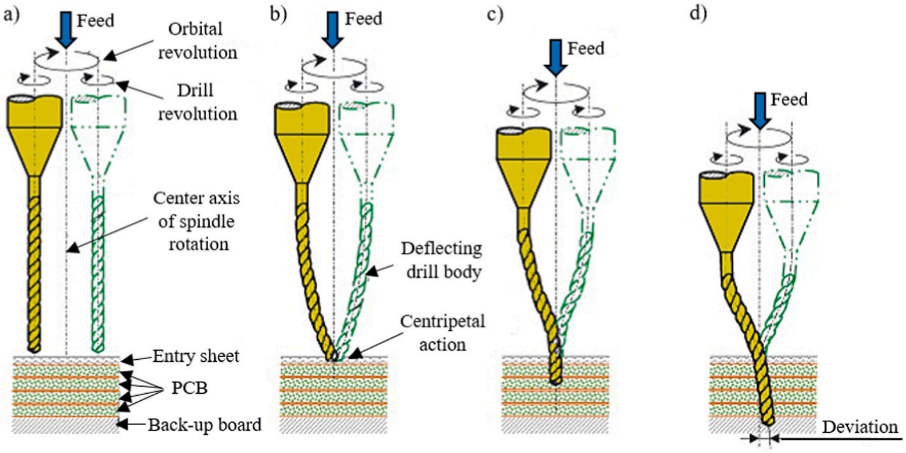

Fig. 6. Downscaling effect in micro-drilling on aspect ratio [73].

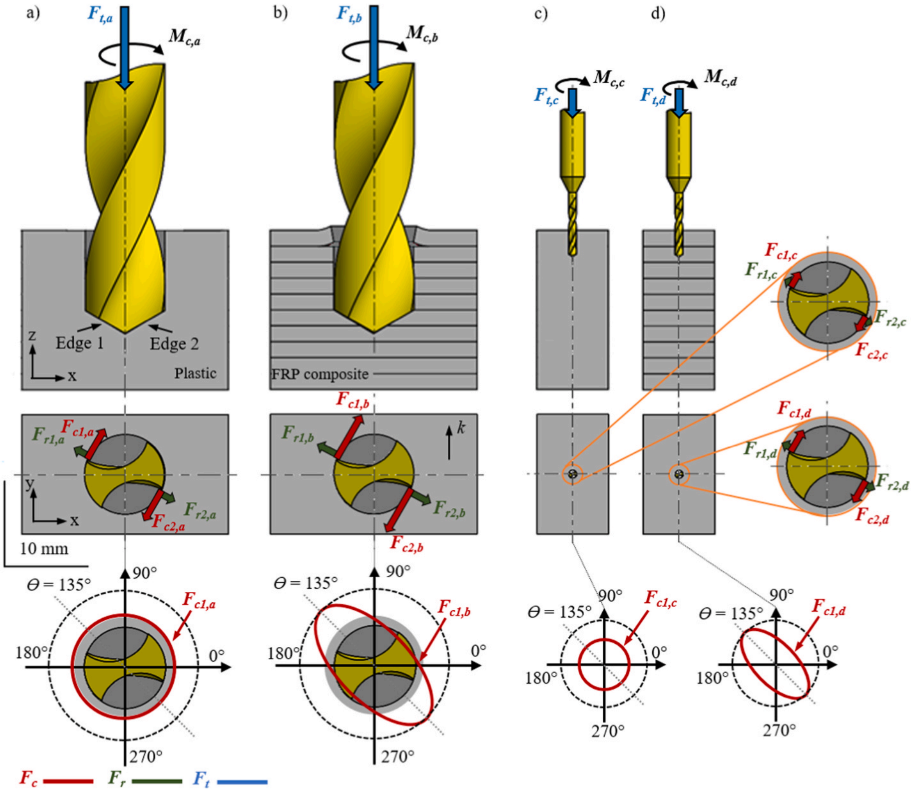

Fig. 7. A schematic illustration of the key differences in the cutting force and its fluctuation in macro vs micro-sized drilling of FRPs: macro-sized drilling of (a) quasi-homogeneous thermoset polymer and (b) unidirectional FRP, and micro-sized drilling of (c) quasi-homogeneous thermoset polymer, and (d) unidirectional FRP, where F_c denotes the main cutting force component, F_r is the radial cutting force component, F_t is the axial cutting force component *i.e.* thrust force, and M_c denotes the torque.

through an empirical relation between chip area and cutting forces calibrated with a small number of experiments. These forces are assumed to be proportional to the undeformed chip area of the cutting edge. The proportionality constant is called as specific cutting force or specific cutting energy. Specific cutting forces are determined by a calibration process requiring experimental cutting force data at different cutting conditions. Generally, the Victor-Kienzle power law model is used to develop the empirical model for nonlinear machining force characteristics in the macro-domain, as shown by Eq. (1).

$$F_i = K_i b t_c^{(1-m_i)} \tag{1}$$

Where K_i and m_i are empirical parameters depending on the cutting condition (feed, material type and tool geometry). The exponent m_i may vary from 0 to 1, and the width of cut b is also constant. The parameter K_i is the specific cutting force. Klocke et al. [45] modified this Victor-Kienzle power law, as shown in Eq. (2), to relate specific feed force K_f with uncut chip thickness t_c for micro-drilling tests.

$$K_f = K_{f1.1} t_c^{-m_f} \tag{2}$$

Where $K_{f1.1}$ is the force needed to cut a chip of 1-by-1 μm and m_f is an empirical parameter. Anand et al. [6] extended the Victor-Kienzle power law in the term ratio of tool edge radius and undeformed chip thickness as given by Eq. (3), and the trend of the specific cutting forces to the tool edge radius is shown in Fig. 5.

$$K_i = C_i r_r^{-m_i} \tag{3}$$

Where $i=\{x,y,z\}$ directional cutting forces; the empirical constants, C_i and m_i are determined by mathematical regression analysis of the experimental data. Rahamathullah and Shunmugam [80] developed a mechanistic model for predicting thrust and torque in the micro-drilling of glass fibre-reinforced epoxy sheets. Their work considered material removal in cutting lip, chisel edge, and indentation zones without considering the tool edge radius effect.

Anand et al. [44] proposed the mechanistic models considering tool edge radius effects and fibre-reinforced plastic material as an EHM of each layer to predict average thrust force and torque. A specific cutting force for each phase is determined separately, and the location of the cutting edge is to be determined to identify the phase or phases in contact with the cutting edge. Depending on the type of phase in contact with an element of the cutting edge, the specific cutting force of that particular phase will be used to determine elemental cutting forces. The high-frequency variations of thrust and torque signals are inherent characteristics of the fibre-reinforced composite due to repeated fibre and matrix failure to form chips, as shown in Fig. 8. The average absolute deviations in thrust force and torque predictions in micro-drilling on fibre regions of the composite laminate are determined to be 3.99% and 6.29%, respectively. On the other hand, average absolute deviations of thrust force and torque predictions in matrix regions of the composite laminate are 6.30% and 14.81%, respectively. The fluctuation of cutting forces and torque produces vibration in the tool. The vibration in the tool affects the hole quality, which can be measured by roundness error [37]. However, the proposed mechanistic model predicts only the average values of thrust forces and torque in different regions (matrix, fibre and transition) using separate specific cutting forces for each layer.

Hence, the modelling of cutting forces is still in a progressive stage. Finite element and multi-scale modelling will be applied in various micro-machining processes, such as micro-milling and micro-turning to predict the fluctuation of cutting forces on each layer in CFRP material [79]. It may be further extended to predict the cutting force and temperature in the micro-drilling process to enhance the micro-hole performance in CFRP and GFRP materials. Relevant studies on the cutting energetics on micro-drilling of GFRPs and CFRPs are summarized in Table 1 and Table 2, respectively. Furthermore, these tables indicate the existing research gaps and possible future research directions.

Table 1

Relevant studies on the cutting energetics in micro-drilling of GFRPs (NA denotes not available).

Factors	Response parameters		
	Cutting force	Cutting torque	Cutting temperature
Feed	[43,77,80–82]	[77,80]	[83]
Cutting speed	[43,77,80]	[77,80]	[83]
Tool geometry	NA	NA	NA
Cooling	NA	NA	[83]
Strategies	[77]	[77]	NA
No. of holes	NA	NA	[83]

Table 2

Relevant studies on the cutting energetics in micro-drilling of CFRPs (NA denotes not available).

Factors	Response parameters		
	Cutting force	Cutting torque	Cutting temperature
Feed	[6,10,12,37,44,76,81, 84–89]	[10,44,77]	[89]
Cutting speed	[10,12,37,76,87,89–91]	[10,77]	[89]
Tool geometry	[12,44,76,84–86,90]	[44]	NA
Cooling	NA	NA	NA
Strategies	[76]	NA	NA
No. of holes	[91–93]	[92,93]	[92,93]

4.3. *Micro-drilling-induced geometrical defects in FRPs*

Micro-drilling-induced geometrical defects are mainly influenced by the feed, fibre orientation and tool geometry [94]. Although the delamination is the most severe defect in the macro-drilling of FRPs often resulting in the rejection of composite parts [61], the delamination is not as frequent and not as accelerated in size in the case of micro-drilling [37]. The reason for this lies in the fact that the delamination (*i.e.* layer separation or deformation, crack propagation *etc.*) formation is primarily governed by the cutting force [95]. In the case of micro-drilling, the size of the drilling tool and the often-low feeds result in small uncut chip thickness; thus, the axial force is also small compared to macro-sized drilling [71]. Therefore, this relatively low cutting force often does not even approach the critical thrust force and keeps the probability of delamination formation in micro-drilling at a very low level. Researchers often highlight that (i) the ratio of the chisel edge to the tool diameter is larger than in macro-sized drilling; therefore, the chisel edge of the drill dominates better the drilling process, and (ii) the small undeformed chip thickness often results in ploughing-dominated chip removal mechanism. Nevertheless, the change of the mechanism's dominance does not directly cause a significantly larger probability of delamination formation in the micro-drilling of FRPs.

Shyha et al. [12] analysed the effect of drill geometry and drilling conditions on hole quality in the micro-drilling of CFRPs through Taguchi orthogonal arrays. They observed that the feed and the drill geometry influenced the most significant internal hole damages. Nevertheless, the helix angle between 24° and 30° had no significant influence on the machining-induced geometrical errors. They achieved conventional delamination factors (F_d) below 1.3 at the entry and exit sides. They observed various types of defects on the hole wall, such as internal cracks, porosity, fibre/matrix debonding and resin loss. Pliusys and Mativenga [90] conducted micro-drilling experiments in CFRPs

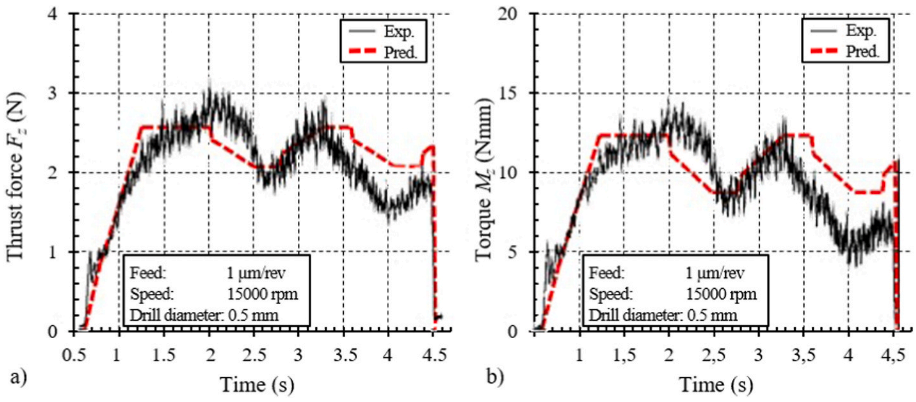

Fig. 8. Comparison of experimental (a) thrust force, (b) torque with simulated results [44].

through Taguchi orthogonal arrays. They found that the spindle speed and drill point angle have the most significant factors influencing the peel-up and push-down delamination. They also highlighted, that the mechanical supporting of the last layers of the composite helps in the reduction of the thrust force and thus in the reduction of the probability of drilling-induced delamination formation. Rahamathullah and Shunmugam [10] analysed the hole quality in micro-drilling of CFRPs using a drilling strategy with a peck cycle. They calculated the conventional delamination factor at the entry and exit sides also and found them in the range of 1.15–1.40 and 1.30–1.51, respectively. Their results prove that the larger the feed, the larger the delamination formation. In addition, the spindle speed did not significantly affect either the delamination or the diameter of the holes. Therefore, they recommend drilling micro-holes in CFRP using low feeds, large spindle speeds and a partial withdrawal of drill during the drilling cycle. Kim et al. [39] conducted micro-drilling experiments in CFRPs using different lubrications. They could improve the machinability of CFRPs by using nano-solid lubrication (*i.e.* graphene nanoplatelets and multiwall carbon nanotubes), resulted in smaller drilling-induced delamination and burrs, as it is shown in Fig. 9. The conventional delamination factor was measured in the range of 1.2 and 1.55, while the burr area was between 10 000 and 150 000 μm^2. Then, Kim et al. [38] continued their investigations and concluded that the larger graphene nanoplatelets are superior to the smaller ones and thus have a more advantageous effect on the tribological properties of CFRP machining. Pallapothu et al. [7] conducted micro-drilling experiments in GFRPs through Taguchi orthogonal arrays and analysed the influences of feed, cutting speed and lubrication on the delamination. They found that the lubrication influences delamination most significantly, followed by the feed and speed, respectively. The conventional delamination factor was found between 1.009 and 1.0125, which indicates that delamination is moderate at each analysed parameter combination. Although researchers calculated similar values of conventional delamination factors to characterise the micro-hole qualities to the expected ones based on the experience collected through the analysis of conventional-sized drilling FRPs, the areas of these delaminated/wrecked areas are significantly smaller. Therefore, the micro-drilling-induced delamination is not severe as to the resultant strength of the composite as it is usual in conventional-sized holes.

Dougrusadik and Kentli [35] micro-drilled CFRPs using different mechanical supporting circumstances (supported and unsupported cases). They found that the application of support plates is advantageous from the point of view of delamination formation; however, these plates slightly damaged the surface of the composites. They observed that the delamination damage in micro-drilling differs significantly from the conventional-sized, as the drilling process exhibits unusual behaviours as process size decreases. It can be explained by the larger dominance of the random error in reduced sizes. James and Sonate [96] experimentally studied the micro-machinability of CFRP/Ti stacks using ultrasonic vibration-assisted technology. They observed almost zero drilling-induced entry delamination, which is different and unexpected based on the gained experiences in the conventional-sized machining of CFRP/Ti stacks. Anand and Patra analysed hole quality in micro-drilling of CFRPs and found that the hole quality is the best if the feed is almost equal to the cutting edge radius rather than at the lowest feed value.

Unlike the delamination, the drilling-induced burr formation is primarily governed by the type of mechanical supporting circumstances (*i.e.* whether the material is supported against buckling) and not by the feed-governed cutting force. Therefore, drilling-induced burr formation is prevalent in both conventional and micro cases. Considering that the severity of the drilling-induced burrs directly affects the assembly process (*i.e.* the larger the burrs, the more difficult the assembly is), the micro-drilling-induced burrs are at least as severe as those used in conventional-sized drilling FRPs.

In high-tech applications, the matrix materials are generally thermosets, and the reinforcement is usually fibre-like. The fibre-matrix interfacial interaction should be maximised to reach better mechanical performances. In fibrous composite materials, the fracture does not usually occur suddenly. The type of fracture can be identified with different techniques (*e.g.* scanning electron microscopy) and classified into five groups (Fig. 10). The surface structure of the machined composites usually depends on the type of breaking.

Xu et al. [100] analysed the propagation of fibre-matrix interface debonding during the machining of CFRPs. Based on the beam bending theorem, they modelled the edge milling process. They proved that the feed and cutting edge radius presented the linear and non-linear proportional relations to the degree of debonding. Still, cutting edge radius had a more significant impact on variation in debonding degree than feed rate. Gao et al. [101] investigated the damage mechanism of carbon fibre reinforced polymer in micro-drilling (Fig. 11). Their results showed that the entrance delamination is mainly caused by the incomplete fibre cut-off of the top layer. They determined that the delamination damage can be limited using support plates placed on the front and rear sides of the CFRP laminate. Materials of support plates also influence the delamination reduction.

Grilo et al. [102] and Sakai et al. [103] analysed the effect of drill geometries and cutting factors on composite breaking. Both observed the surface of composites with a scanning electron microscope and identified the CFRP cutting mechanism. Wang and Zhang [104] proved that the subsurface damage and the mechanisms of a machined component are greatly influenced by fibre orientation (Fig. 12). They also found that the curing conditions during composite production do not have an obvious effect on machinability. Several researchers [105–107] confirmed that the fibre cutting angle has the most significant influence on surface quality. The analysis of the composite surface microstructure is an intensively investigated field. Contrarily, in the point of micro-drilling, only a few articles are available, as it can be seen in Table 3 and Table 4.

Although avoiding drilling-induced macro geometrical damage is challenging, researchers developed drilling practices and technologies to minimize the probability of damage formation. The techniques and solutions available in macro-sized hole machining (*e.g.* drilling by a brad and spur drill, hole machining by tilted helical milling or wobble milling) often cannot be directly adapted to micro-scales, mainly due to the slender cutting tools and limits of micro-scaled tool geometry generation. However, some technologies can be successfully adapted into micro-scales, such as feed rate control [36,77,88,116], pilot hole machining [76], application of support plate(s) [35,65,67] and cryogenic cooling [117,118]. Feed rate control and pilot hole machining are beneficial because the thrust force can be significantly reduced, primarily responsible for delamination formation. The application of support plates supports the FRP material against buckling; therefore,

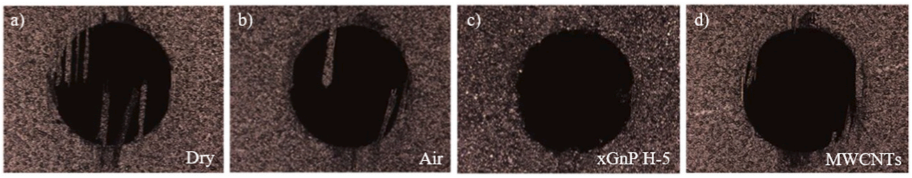

Fig. 9. Images of the hole entries in cases of four different lubrication conditions: (a) dry, (b) air, (c) xGnP H-5, (d) MWCNTs [39].

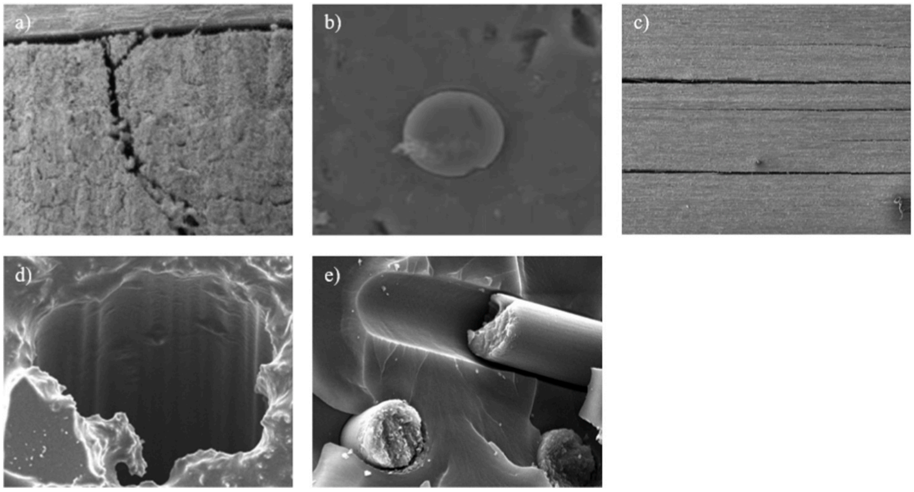

Fig. 10. Types of composite breakings a) matrix cracking [97], b) fibre-matrix debonding [98], c) delamination [99], d) fibre pull-out [72] and e) fibre breakage.

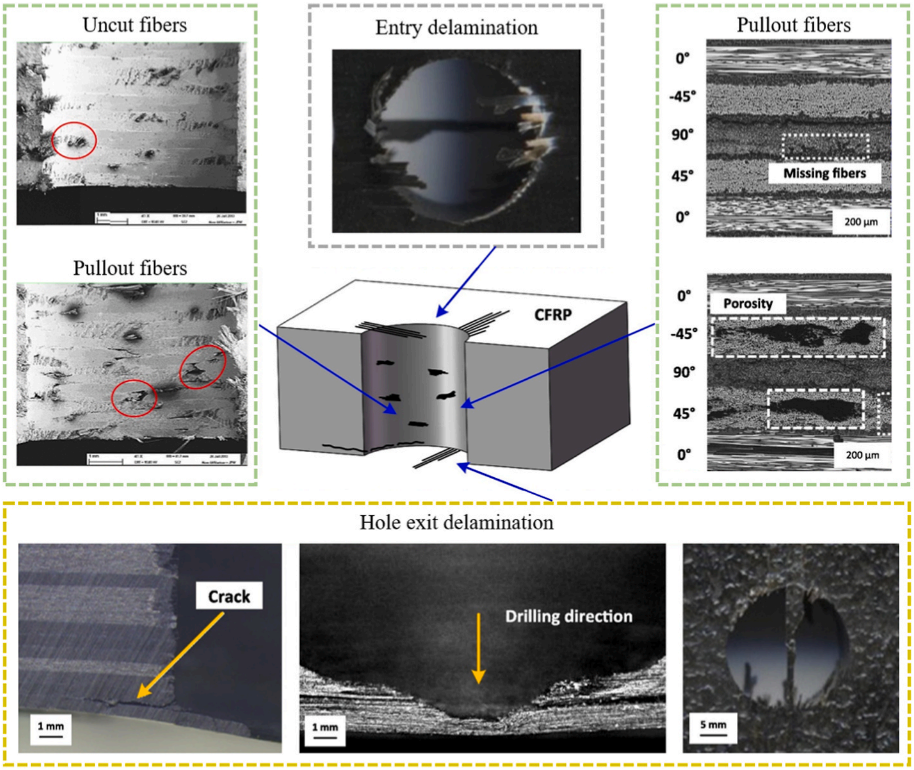

Fig. 11. Different damage forms in CFRP drilling [101].

delamination and burrs are fewer expected. In contrast, cryogenic cooling significantly increases the brittleness of FRPs, thus reducing the probability of bending-induced burr formation. Considering, that the application of pilot holes and hollow support plates has a trivial size limit, implementing feed rate control and cryogenic cooling seems relevant on even smaller micro-scales; thus, these technologies require further research and development in the coming future.

4.4. Tool wear and monitoring in micro-drilling FRPs

Excessive tool wear and catastrophic failures are critical concerns when dealing with the micro-drilling of fibrous composites. Unlike conventional-sized drilling, the micro-drilling operation entails a very poor ability for composite chip ejection and cutting heat dissipation during the material removal process. Consequently, a large amount of cutting heat can be easily accumulated at the tool-chip and tool-work interface to exacerbate the temperature-related degradation of the tool edges. Additionally, the highly abrasive reinforcing fibres can cause serious abrasion and erosion of the fresh drill edges while the soft matrix rubs against the tool surfaces, leading to the blunting and dulling of drill bits. Progressive abrasion wear in the form of edge blunting or dulling has been extensively confirmed as the dominant wear mode governing the machining of fibrous composites [47,119–123]. Specially, three tool edge regions exist during the FRP machining that undergo intensive wear, as shown schematically in Fig. 13 [124].

The first tool region responsible for the composite chip separation is located at the tool rake face. The wear progression in tool region 1 is mainly governed by the sliding and rubbing of resected fibres. The wear

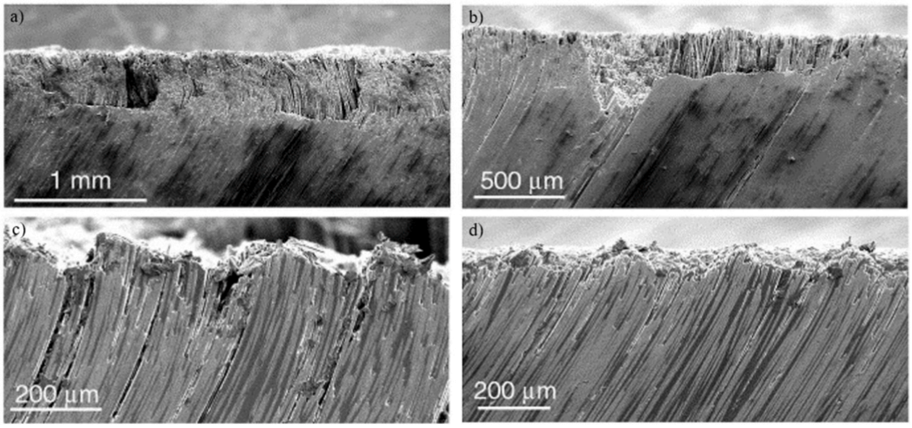

Fig. 12. Subsurface microstructure at fibre orientation of 120°, depth of cut of 0.1 mm and rake angle of [104] (a) −20°, (b) 0°, (c) 20°, (d) 40°.

Table 3
Relevant studies on the micro-drilling-induced burrs, delamination and micro-geometry in GFRPs (NA denotes not available).

Factors	Response parameters			
	Burrs	Delamination	Microgeometry	Diameter
Feed	[43]	[7,108]	[43]	[7]
Cutting speed	[43]	[7,108]	[43]	[7]
Fibre orientation	NA	NA	[109]	NA
Depth of cut	NA	NA	[109]	NA
Tool geometry	NA	NA	NA	NA
Cooling	NA	[7]	NA	[7]
No. of holes	NA	[108]	NA	NA
Strategy	NA	NA	NA	NA
Supporting properties	NA	NA	NA	NA

Table 4
Relevant studies on the micro-drilling-induced burrs, delamination and micro-geometry in CFRPs (NA denotes not available).

Factors	Response parameters			
	Burrs	Delamination	Microgeometry	Diameter
Feed	[12,110]	[10,12,36,37,40,65,87,111]	[10,12,37,67,76,84]	[36,67,76,110,112–114]
Cutting speed	[12,110]	[10,12,36,37,40,65,87,90,111]	[10,12,37,67,76]	[36,67,76,110,112–114]
Fibre orientation	NA	NA	NA	NA
Depth of cut	NA	NA	NA	NA
Tool geometry	[12]	[12,36,40,90,96,111,115]	[12,76,84,96]	[36,76,96,112,115]
Cooling	[38,39]	[38,39]	[38,39]	[39]
No. of holes	[39]	[39]	[39]	[39,114]
Strategy	NA	NA	[76]	[76]
Supporting properties	NA	[65]	[67]	[67]

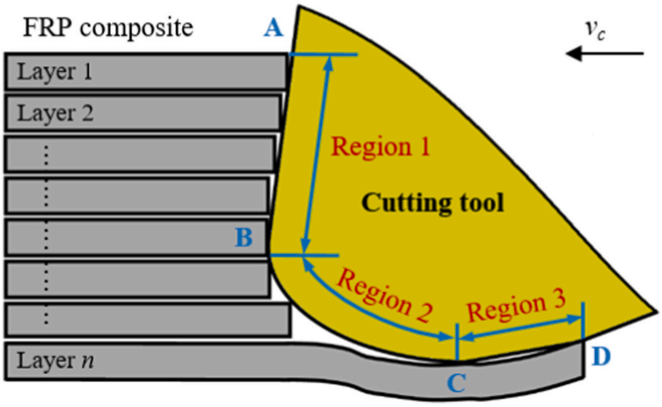

Fig. 13. Schematic illustration of the tool wear regions in fibrous composite machining (redrawn based on Ref. [124]).

length is mainly equal to the tool-chip contact length but may vary when the fibre cutting angle changes. Tool region 2 is located at the tip radius zone, which entails the severe abrasion of fibres leading to the formation of edge rounding wear. Therefore, such a region tends to undergo the enlargement of the edge tip radius, which signifies the blunting of edge sharpness during the machining operation. Additionally, it is also worth mentioning that the size effect is likely to take place in this region during the micro-drilling of fibrous composites. The phenomenon depends significantly on the comparative difference between the feed rate and the actual edge radius. For instance, if the actual edge radius of region 2 is larger than the feed rate, a size effect may take place, and severe ploughing actions will dominate the chip separation instead of shearing, leading to rather difficult chip removal. Then rapid tool wear progression and poor surface finish will be promoted during the micro-drilling process. While tool region 3 denotes the cutting edge at the tool flank surface that experiences severe tool-work interaction and bouncing-back effects. Therefore, severe erosion becomes prevalent within this region as the severely-bent fibres elastically recover across the tool flank surface. Moreover, during the micro-drilling operation, the chip separation is carried out within the primary drill edge zone, so the drill edge wear is a key concern when dealing with the machining of composites. Since the instantaneous cutting speed of each drill edge segment varies with its position relative to the drill tip, the edge segment far away from the drill tip involves the highest speed. In contrast, the drill tip entails zero cutting speed. Therefore, the wear extents exerted onto the drill edge segments are different [122].

Many scholars have stated that abrasion wear and flank wear are the main wear mechanisms of cutting tools governing the micro-drilling of FRP composites [38,65,67,84,108,125]. Abrasion wear is mainly arising from the severe mechanical abrasion and erosion of hard reinforcing fibres onto the fresh tool edges, which leaves various grooves or marks on the tool surface. Flank wear is often noted as a characteristic wear mode for quantifying the severity of drill bits following the composite micro-drilling. As shown in Fig. 14 [65], signatures of flank wear and corner rounding were identified for the micro drills after the drilling of CFRP laminates. Sakuma et al. [96] pointed out that the tool wear mechanisms in CFRP machining are the dislodging of hard tool particles from the tool surface, while Rawat and Attia [119] attributed the

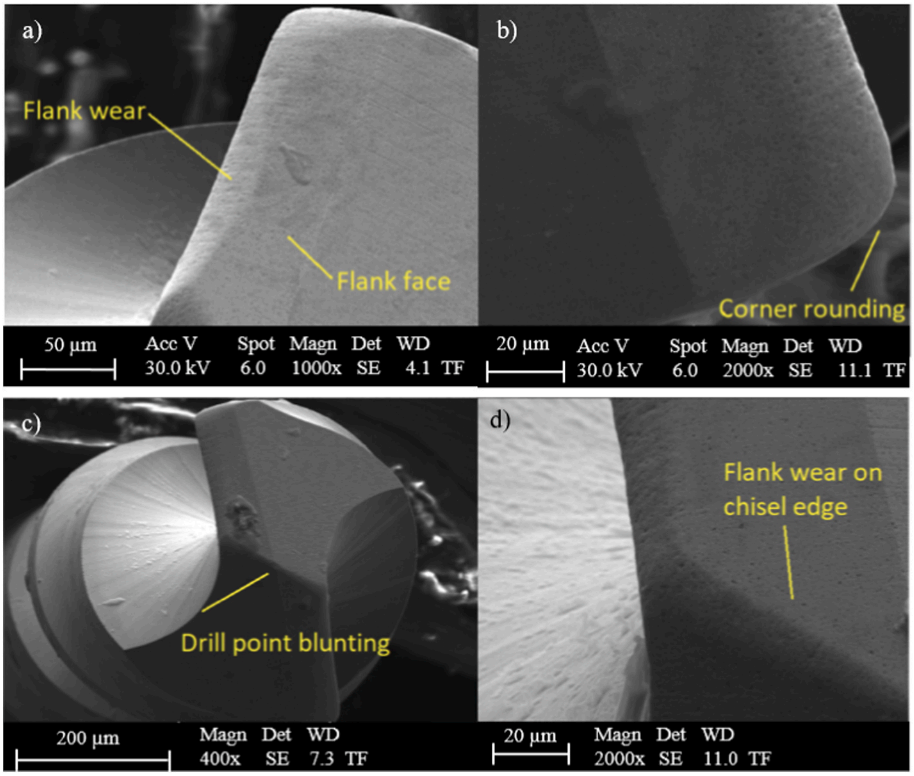

Fig. 14. Wear morphologies of micro drills during the drilling of CFRPs [65].

abrasive wear of WC drills to the results of both hard and soft abrasion modes when drilling woven CFRPs. Huang et al. [125] stated that abrasive wear of the chisel edge and the main cutting edge were the main wear modes occurring in the micro-drilling of multi-layer PCBs. Kim et al. [38] also found that abrasive wear occurring at the tool flank surface was the key wear mechanism during the micro-drilling of multi-directional CFRPs.

Due to the small dimeter of drills used in the drilling operations, the amount of tool wear when micromachining FRPs is very small compared with conventional-sized drilling. However, the micro-drilling process entails very poor ability of chip evacuation and heat dissipation; therefore, it is more likely to induce highly localised temperatures focusing on the tool-workpiece interface, which can trigger the occurrence of adhesion wear for the cutting tools [84]. Since brittle fracture dominates the chip separation of fibrous composites, the actual tool-chip contact interface becomes rather small, which makes it impossible for the occurrence of crater wears as frequently encountered in the cutting of metallic alloys [126]. Regarding the failure of micro drills, fracture and chipping of cutting edges are noted as the key failure modes governing the micro-drilling of fibrous composites [125]. The phenomena are attributed to the cumulative abrasion wear that modifies the edge shapes and results in stress concentration, thereby inducing the catastrophic failures of tool edges. While for the coated micro-tool, the fundamental failure modes are mainly coating peeling or delamination, as reported by Fu et al. [84] when micro-drilling epoxy/graphene nano platelet nanocomposites.

To quantify the severity of tool wear during the micro-drilling of fibrous composites, measuring either the cutting edge rounding (CER) or the flank wear width are becoming preferred. As abrasion wear acts as the key wear mode governing the drilling of fibrous composites, the CER has become the most notable indicator for the assessment of tool wear, which can provide a more accurate quantification than conventionally-used indicators (*e.g.* the flank wear width). According to Faraz et al. [47], the CER was found more effective in quantifying the tool wear progression as it correlates well with the composite drilling outputs. As shown in Fig. 15, the wear phenomenon of CER becomes very evident during the drilling of CFRP composites, which can accurately quantify the extent of drill wear for fibrous composites. However, in some cases, measuring the CER is not easy and may be constrained by the existing equipment; therefore, inspecting the flank wear zone seems to be a more convenient means which has been extensively used in the open literature [38,39,65,67,84,92,93,96,108,125]. However, since the flank wear land around drill edges is often non-uniform, measuring the flank wear may not yield accurate quantification of actual drill wear during the micro-drilling of fibrous composites. Additionally, due to the small-size features of the drill tip zone, it also presents difficulty and challenges for manual wear assessment. Therefore, more research works need to be conducted to develop special indicators and automated systems suitable for micro drill wear evaluation.

There is no doubt that tool wear affects the micro drilling responses of fibrous composites, such as the cutting forces/temperatures, hole quality, and surface morphologies, as the wear alters the conditions for the tool-chip and tool-work interactions during the material removal. Progression of tool wear will cause an increase in cutting forces and temperatures since the chip separation conditions are exacerbated [119,120,122]. It can also lead to deteriorated hole quality and increased extents of surface damage such as delamination, burrs, cavities, *etc.* There are many process conditions that affect the progression of tool wear during the micro-drilling of FRP composites. In general, drilling parameters, cutting environments, composite types and tool geometries/materials are critical factors influencing the development of drill wear. Dogrusadik and Kentli [65] stated that the feed was more effective on flank wear than spindle speed for both unsupported and supported cases. The materials of the support plates were found to have an influence on the flank wear, and cutting parameters were more effective on flank wear for the supported cases. Huang et al. [125] highlighted the effect of a cold air-cooling condition on the tool wear for the micro drilling of multi-layer PCB consisting of copper foil and ceramic particle filled GFRPs. Results indicated that the cold air was more effective in reducing the tool wear during the micro drilling of

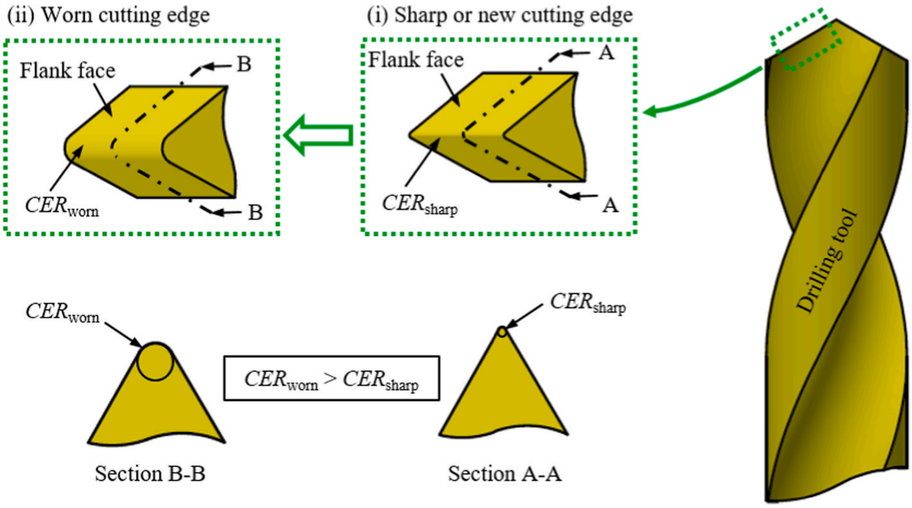

Fig. 15. Cutting-edge rounding (CER): (a) sharp cutting edge; (b) rounded cutting edge (redrawn based on Ref. [47]).

multi-layer PCBs due to its easy penetration into the cutting area to form a lubricating film that could alleviate the stress between the drill and the material. The authors also pointed out that increasing the feed rate or the spindle speed could effectively reduce tool wear. Additionally, increasing the resin content in GFRP could reduce the fracture in the main cutting edge of micro drills. Fu et al. [84] claimed that the uncoated tool underwent a progressive edge rounding, and the tool edges did not show the corner fracture, while the diamond-like carbon (DLC) and diamond-coated tools experienced almost negligible wear compared with the uncoated counterpart. These coated tools suffered from chip adhesion on the flank face and coating delamination due to the consequence of machining stress. Kim et al. [38] studied the tool wear behaviours of micro drills in the drilling of multi-direction (MD)-CFRPs using graphene nanoplatelets. It was found that larger graphene nanoplatelets could effectively reduce the friction between the MD-CFRP composite and the tool, and the enhanced lubrication using air spray with nanoparticles of xGnP nano-solid lubrication could lead to reduced tool wear. Moreover, Ogawa et al. [93] found that micro drills often underwent more rapid wear in drilling CFRP than in drilling GFRPs. As a consequence, the tool life of CFRP plate drilling was much shorter than that of GFRP machining. Moreover, Ogawa et al. [92] further highlighted the effectiveness of superior tool diamond coatings in reducing the wear progression in micro-drilling CFRPs and found that the diamond-coated tool showed a much longer tool life than the non-coated tool.

To control wear progression and prevent catastrophic tool failures in micro-drilling of fibrous composites, tool condition monitoring has become a promising technique in recent years. The methods of tool wear monitoring may involve direct mode and indirect mode [127]. The direct mode lies in measuring the quantities of tool wear directly by optical instruments such as a CCD camera, scanning electron microscope [128], confocal microscopy [129,130] and white-light interferometer [131,132]. While the indirect mode [38,108] aims to predict the tool state by monitoring the signals related to the machining process. The tool wear state can be monitored via a variety of signals, such as cutting forces, vibration, current, acoustic emission, surface finish attributes, *etc.* [96]. With the development of artificial intelligence, various algorithms (*e.g.* artificial neural network, hidden Markov model, support vector machine, *etc.*) have been successfully applied to monitor the tool wear state during the micro-drilling of FRPs. However, to yield high-accuracy monitoring of tool wear, more endeavours are required to develop high-reliable equipment and algorithms. Finally, to improve the wear resistance of micro drills, more attention must be paid to optimizing tool geometries/process parameters and developing high-performance tool materials for the fibrous composites.

5. Future trends and outlook

Research into micro-drilling of CFRP and GFRP has increased significantly over the past ten years, as shown in Fig. 16. This is in part due to the miniaturisation effect, where more applications look to benefit from the improved specific strength to weight ratios that composites can offer [133]. If this research interest correlates to industrial application, understanding the current and future trends is imperative to high quality, high production rate manufacturing.

Whilst laser cutting of holes is the predominant method for multiple hole generation [10], the higher quality of drilled holes, which can avoid HAZ, using defined tool geometry, may become more relevant. In such a case, more effort needs to be extended to understanding the future direction of machine tools, tooling, tool coating and the effects of hole quality on mechanical performance. This becomes even more relevant when applications are extended to safety-critical components, for example, aerospace flight control components utilising micro-holes [9]. The technologies required for accurate, cost-effective machining of today's GFRP and CFRP materials also need to be extended to meet tomorrow's material choices, which may include more natural fibre materials combined with carbon or glass materials to make hybrid fibre reinforced polymers (HFRP) [134]. In addition to the greener credentials of HFRP due to the lower energy-intensive manufacturing requirements [135], tool material [136] and testing requirements also need to be considered to reduce the carbon footprint of CFRP/GFRP

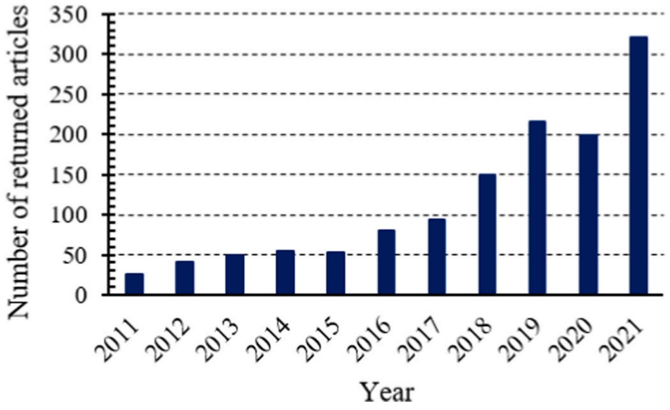

Fig. 16. A 10-year trend in research towards GFRP and CFRP micro-drilling (compiled from June 2022 online literature search terms "micro-drilling CFRP" and "micro-drilling GFRP").

manufacturing.

5.1. Requirements for micro-drilling machine tools

Whilst machines such as laser cutters and abrasive waterjet machines [20,21] are used extensively for micro-drilling in FRP materials, conventional machine tools such as 3 or 5-axis milling machines are common within manufacturing facilities [137]. Given the widespread access to these machines and their suitability for micro-drilling, the future manufacturing industry needs to consider several factors when selecting the correct micro-drilling machine tool.

Whilst the resolution of machines needs to be high to place several holes next to each other, a further requirement of these machines is a high stiffness. This is required for both tool and hole quality considerations. A high rigidity, combined with good alignment, keeps bending moments in the tool low to reduce the chances of tool breaking. Reduced stability can be detrimental to the hole cylindricity which can be exacerbated by the heat conduction along the fibre direction [10]. Some researchers prefer the use of miniaturised machine tools (MMT) which are designed specifically for high spindle speeds of up to 100 000 rpm [138] or even as high as 300 000 rpm [125] and up to 0.1 μm resolution.

High speeds are required [76] to prove suitable cutting speeds, and relatively large feeds have to be applied to overcome the issue of size effect to ensure the uncut chip thickness is greater than the cutting edge radius, which is seen in the majority of micro-drilling papers [10,12,76,80]. Whilst specific machine tools have been designed for micro-hole drilling, the use of “spindle speeders” is common in micro-machining to adapt standard spindles which may have maximum speeds of up to 10 000 rpm [43]. Whilst these offer the chance to use “standard” machine tools, the additional mass on the spindle is likely to alter the dynamic cutting behaviour of the tool. Several sources note that the dynamics of a machine tool alter the stability of the cutter and overall quality of the machined surface [139,140] which should be considered a factor when micro-drilling in CFRP/GFRP.

Machine tools should also be capable of peck cycles which are found to suppress the formation of delamination in micro-drilled composites [10]. Whilst this capability is present on most machines through simple G83 (full retraction) or G73 (partial retraction) CNC inputs, little work has been completed to fully understand the benefits and drawbacks of each. Rahamathullah and Shunmugam [10] highlighted that abrupt changes in cutting force occur in contact with fibrous material compared to polymer matrix, suggesting that peck cycles need to be used with caution. An alternative to peck drilling is an adaptive machining approach, also termed by Teti as “sensorial perception” [141,142]. This may take the form of a passive or active machine learning-based system which can adapt cutting parameters based on material type and current cutting conditions, which will vary, dependant on the amount of fibre or resin the cutting edges are engaged with. This would take a similar form to stack machining, whereby different feeds and speeds are used depending on the material engaged [143]; however, this is typically pre-determined based on the thickness of the stacks. Therefore, a novel process [144,145] which uses an in-process algorithm for feed drive motors to detect material type to detect and change feed speed within 0.25s, may be required to dynamically change the feed and speed of the machine tool during micro-drilling. Whilst other methods have employed several indirect measurement methods such as acoustic emissions (AE) to determine the material being cut [146–148] as well as dynamometer-based methods [148] in stack machining, there is no reason why the lower feed rate of the micro-drilling process would not allow this method to be successful. Whist useful for purely CFRP and GRFP micro-drilling, this would also be effective for machining PCBs where copper forms part of the laminate and requires separate feeds and speeds.

Hybrid machining centres which utilise ultrasonic effects to oscillate the tool in an axial direction may also be an area of exploration in future machine tool selection. Ultrasonic drilling can take the form of rotary ultrasonic assisted drilling (RUAD), where a tool has an axial amplitude induced by an ultrasonic frequency generator which assists the normal rotation of a tool. This has been found to aid chip breaking and ejection in metallic micro-drilling [149] and benefited macro [150–152] and micro [96] machining processes in terms of increased hole quality and superior tool life through reduced thrust forces for FRP materials.

Machine tools should also be capable of cooling the process. It is noted that cryogenic cooling appears to offer improved benefits in macro cutting compared to minimum quantity lubrication (MQL) or flood coolant in CFRP machining [153], in addition to being a more environmentally friendly coolant type [154]. It is widely reported that cooling of CFRP cutting on the macro scale is beneficial to tool wear and machined quality [155–158]. GFRP studies showed an increased in cutting force but improvements in some metrics of hole quality, including cylindricity, circularity [159] and surface roughness metrics [154]. In one of the few coolant studies concerning micro-drilling of FRP materials, Huang et al. [125] note that cooling by blowing cold air (5.2 °C) externally across the cutting face/tool interface, tool wear was reduced. The resultant improved quality is a result of a change from some fibres being broken by a bending mechanism changing into a shearing mechanism. However, mixed results in delamination increase/decrease have been reported [160]. Nano-solid-lubrication has also shown promise in the micro-drilling of CFRP [39]. This successful trial, which reduced tool wear and improved hole quality, utilised graphene nanoplatelets and multiwall carbon nanotubes applied via an external nozzle in a similar way to traditional MQL application. The effects of using external or through tool coolant in micro-drilling of FRP have not been fully explored and may provide benefits, especially where the size of the tool may allow rapid cooling based on the macro findings. The use of dry coolants such as LN_2 or $scCO_2$ offer the advantages of being more environmentally friendly than flood coolants, in addition to reduced clean-up and drying compared to other methods.

5.2. Requirements for micro-drilling tools

Design requirements for micro-drilling tools include; an adequate hardness to withstand cutting forces at the cutting edge, good wear properties in order to cut material for longer without replacement or regrinding of the cutting edges, and rigidity and toughness to prevent tool breaks along the tool shaft [161]. A requirement of more productive tools for the outlook of micro-drilling must therefore cover; tooling substrate, tooling coating and tooling geometry balancing the life of the tool with hole quality.

One aspect of machining that must be considered for the future sustainability of the conventional cutting process to remain relevant and not be replaced by non-contact methods, such as laser machining, are the green credentials of machining. This is because carbide-based tooling is difficult to recycle. Perhaps one strategy for micro-drilling is to regrind used macro-drills into micro-drills. Potentially, this could improve the 40% recycled material available in typical cutting tools [162].

At present, little exploration of tools other than solid carbide has been completed. Whilst the future of tool substrates is likely to be carbide-based, due to the shock instability of ceramics and polycrystalline cubic boron nitride (PCBN) materials [70], inserts are frequently used to improve the base material cutting characteristics. For micro-drilling tools, polycrystalline diamond (PCD) cutting edge inserts or PCD twist drill inserts in a carbide shaft may allow a more robust cutting tool due to their efficacy in retaining a sharp cutting edge which allows high-quality FRP cutting. PCD has shown to be highly effective in macro-scale FRP machining due to high hardness and resistance to wear, but this comes at a high price [70] which may be unwanted for experimentation purposes due to the potential for snapping a small diameter shaft.

In-lieu of self-healing coatings of tools which are in their infancy [163,164], and may be unsuitable for the abrasive nature of carbon fibres, the future of micro-drilling may utilise coated carbides. These have superior wear properties compared to uncoated tools, allowing them to produce high-quality machined components for longer than their uncoated counterparts [165]. One issue with the coating may be the thickness of the applied physical or chemical vapour deposition (PVD and CVD, respectively) coating, which may become difficult at the micro-scale due to a very sharp cutting edge which makes adhesion of the coating difficult. However, due to the limited literature on FRP cutting with TiC, TiN, TiCN, AL_2O_3 or diamond-like coatings, a significant opportunity for exploring coatings exists. To expedite the understanding of wear during cutting processes, tribology testing making use of micro pins may be appropriate prior to cutting trials [163,166,167]. Whilst coatings offer improved wear resistance, larger changes to the cutting performance can be attained through geometry changes in macro-drilling [72], which is likely to be true for micro-drilling.

Hasan et al. [161] note that common micro-drilling geometries include twist, spade, d-shaped, single flute and compound type micro-drills, as shown in Figs. 17 and 18. However, most micro-drilling in CFRP [10,36,39,65,76,80] and GFRP [77,80] materials utilise twist drills with minor variations such as steps [12]. The use of specialised geometries such as saw, candlestick, core and stepped geometries produce less delamination than twist counterparts in macro-drilling, suggesting an area of future exploration where lessons can be learnt from significant research in macro-drilling [168,168].

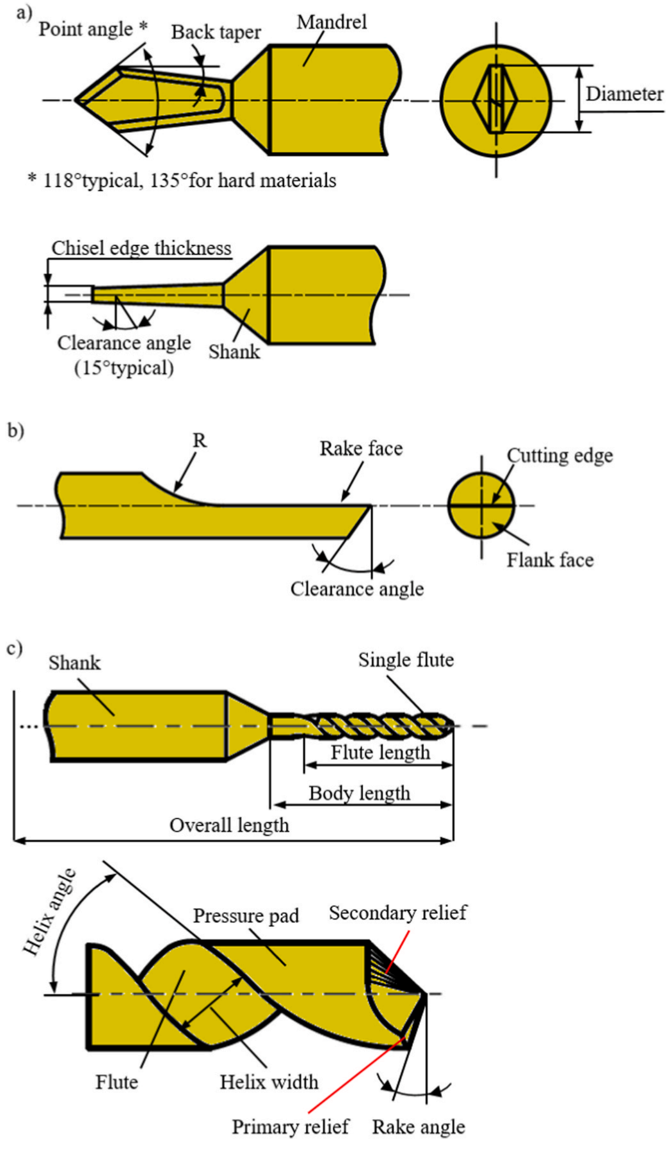

Fig. 17. Micro drill geometries: (a) spade, (b) d-shaped, (c) single flute micro drills (redrawn based on Ref. [161]).

In addition to RUAD where conventional twist drills can be used, rotary ultrasonic machining (RUM) offers an alternative process which utilises grinding style core tools which have embedded abrasives to grind holes in surfaces. As per RUAD, results for RUM were positive, with reported benefits of using core drills compared to twist drills [143,169,170], albeit on the macro-scale. Micro-drilling utilising only ultrasonic motion, without a rotating spindle, has also been used successfully with reported improvements in delamination and holes sizes for a range of grit sizes to form the abrasive slurry [96] but at the cost of slow feed rates of 5 μm/s. Whilst could be deemed an unproductive solution; the tool geometry is a simple pin without any machined geometry, which could offset the costs of highly specialised tooling geometries.

As previously noted, coolant has been shown to have benefits to the micro-drilling process [39], but more direct delivery methods to the cutting interface are suggested to improve the cutting further due to localised heat partition ratio changes where abrasion with fibres occurs [43,155]. It is also likely that the delivery of coolant to the tip of the tool would aid in removal of chips through the flutes of the tool.

In-tool wear monitoring, in a similar way to the aforementioned in-process adaptive machine tool (see chapter 4.1), may be more critical for micro-drilling than macro-drilling due to the general difficulty in measuring wear [171]. Literature for tool condition estimation using a range of indirect methods, such as dynamometer readings (suggested resolution 0.002 N for micro-drilling [10]), on machine readings such as spindle power and torque, tool measurements such as vibrometer and AE measurements exist for a range of materials [141,171–174] and have potential use for micro-drilling of GFRP/CFRP materials. Some sources in the micro-machining of metallic materials have used multiple sensor/data sources to increase the predictability of tool wear which could be applied to FRPs [171,175]. It is apparent that tool wear monitoring employs several types of artificial intelligence models such as adaptive network-based fuzzy inference systems (ANFIS) [172,176], artificial neural networks (ANN) [141], convolution neural networks (CNN) [177], which should also be incorporated into micro-drilling applications and potentially real-time adaptive machining.

5.3. *Mechanical requirements*

Whilst some applications of products with micro-holes are not intended for structural applications, future applications or aerospace applications will require rigorous testing to ensure holes to not cause detrimental mechanical effects beyond their intended design. Typical aerospace material qualification programs involve a pyramid scheme of testing from single coupons to full assemblies. Strict guidelines apply to the spacing of holes for mechanical strength reasons with specific tests for open and filled hole coupons. The effect of introducing micro-sized defects inside the bore is likely to be detrimental to the overall strength; however, tolerance levels have not been set, which needs research from certifying bodies.

Whilst not completed using conventional cutting, in one of the few investigations into mechanical strength changes due to the inclusion of micro-holes, Young and O'Driscoll [20] used laser hole perforations of 50 μm, and 500 μm apart to show a significant reduction in tensile (up to 48%) and compression strength (up to 54%). This suggests that for load-bearing micro-drilled parts, mechanical testing is essential. Several investigations into the effect of hole defects have been completed for macro-testing, with open hole compression or tensile fatigue testing shown to be the most effective means of mechanical testing [178]. Whilst strength decreases with increasing hole size [179] or increasing bore defect [178], the effects of multiple micro-holes on mechanical performance remains relatively unexplored, and no specific FRP testing regime exists for micro-drilled holes, something which needs regulatory exploration. Since variables in macro machining: machine tool [139,

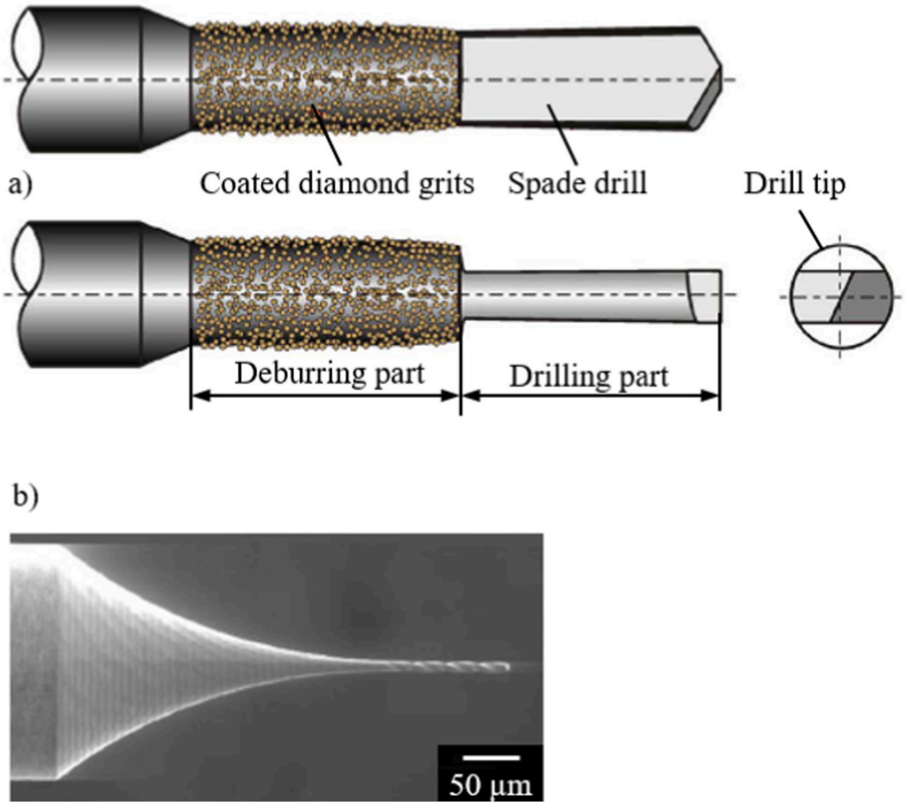

Fig. 18. (a) 2 flute twist and (b) compound type micro-drills [161].

180], tool geometry [139,181,182], tool coating [165], cutting parameters [183] and cooling [155] all alter the machined quality of machined composites, and links between surface quality and mechanical performance have been observed [139,155,165,180,184–187], these factors, noted in Fig. 19, all require further exploration in micro-drilling.

Since the effect of micro-drilling FRPs does not follow metallic conventions [76], it is recommended that FRP-specific testing be completed. Whilst typical testing of aerostructure parts, for example,

Fig. 19. Variables for exploration and data capture in micro-drilling and mechanical testing.

relies on a testing pyramid [188], it is suggested that this can be expedited with the use of finite element analysis (FEA), where high correlation between experimental and analytical results are now being observed for macro and micro-machining, with further advancements on the near horizon [189]. The change to a more FEA-based approach may require a change in current test methods [190,191] which needs to be assessed at a regulatory level [192] but would work well with micro-level defects where individual fibre tows can be modelled. FEA of micro-drilling of FRPs is also well suited to analyse the increased use of nano-particulates dispersed in a matrix material to increase the toughness and mechanical properties of composite materials [193]. A future trend of FEA, as well as the machine tool, is the ability to create a database of materials which could be employed for micro-drilling operations. Such "digital shadows" could be used to provide details like surface quality, delamination, and force metrics [144], allowing material selection based on criteria such as high throughput or minimum delamination or tool selection.

5.4. Micro-drilling inspection techniques

To observe and quantify the damage caused by micro-drilling, inspection techniques need to be applied. Hole drilling can be characterized by entry and exit delamination, hole size, cylindricity and bore defects such as fibre pull-out or matrix smearing. Whilst methods exist for macro hole inspection, this needs some development for micro-hole applications, for example, bore defects, where current methods cannot be scaled as easily.

Whilst some inspection techniques, such as delamination of micro-drilled entry and exits, can be highly automated to provide delamination factors [10,76] which is useful for large quantities of micro-holes, the future of inspection may lie in other areas. A less well-developed technique to assess the cutting quality is to analyse the chips, as completed by Ashworth et al. [155], to determine the effects of heat, from which material degradation through HAZ could be observed, an important factor in a micro-hole generation [20].

Another inspection technique of the future may be the capture and automation of micro x-ray computed tomography (xCT) data for some or all micro-holes if required to meet structural needs. Whilst completed for macro-machining with a voxel size of 2.5 μm [194], even higher resolution can be achieved using x-ray synchrotron (XS) sources with voxel sizes down to 1.1 μm for CFRP materials under going in-situ experiments [195]. To date, no literature has investigated an in-situ micro-drilling process using either xCT or XS methods. As a pre-cursor to this, inspection using epi-fluorescent dyes may be effective due to their success in replicating xCT at a much lower cost for macro CFRP milling [196]. A benefit of xCT analysis is the non-destructive nature of the test but with the drawback of the high computational time required to process images.

A full understanding of wear in micro drill is required to reduce unnecessary tool changes in production environments [197]. To do this, the inspection methodology for micro-drills needs further analysis. Current observation of micro-drilling tool wear for GFRP shows flank, and chisel edge wear [125] are used as metrics. Further analysis should determine if the phenomenon of CER, noted by authors as a useful metric for predicting cutting force and surface quality [47,165] in macro-machining, is suitable for micro-tooling.

The effect of the resin cure state may become more critical prior to the micro-drilling of composites. Merino-Perez et al. [198,199] thermally aged samples to understand how heat build-up during macro-drilling can alter the resin state. It was found that for thermally aged samples, representing areas where HAZ occurs and the matrix is locally aged, the elastic modulus and hardness can increase by 16% and 12%, respectively. The nanoindentation results will become more relevant for micro-drilling as the tool cutting face could be in contact with pure resin, whilst for macro tools, the complete composite must be considered. As such, it is recommended that any investigation into the effects of different materials should utilise nano-indentation methods to correlate tool wear to the material.

The future outlook of micro-drilling of CFRP and GFRP requires significant experimental and analytical focus on the requirements of machine tools, cutting tools, mechanical performance and inspection techniques.

6. Conclusions

In the present review study, the micro-drilling of fibre reinforced polymer (FRP) composites is critically reviewed, discussed and compared to conventional-sized drilling. The key differences between conventional and micro-sized drilling of FRPs, main challenges, experiences, technical solutions and future trends are discussed and highlighted. According to the present study, the following conclusions can be drawn:

- Mechanical micro-drilling of FRPs combines the difficulties of fibrous composite machining (non-homogeneity, anisotropy, abrasive nature of fibres *etc.*) and downscaled machining (size effect, tool breakage, ploughing effect *etc.*). Considering the difficult-to-cut nature of the FRPs and the challenges of micro-drilling, preliminary experiments and optimisation are often required before serial manufacturing.
- Measurement and qualification of micro-drilling induced geometrical defects (*e.g.* burrs, delamination, fibre-matrix debonding) and process features (*e.g.* cutting force, torque, tool vibrations, cutting temperature, tool wear) are more complicated and require more expensive devices and cumbersome technologies than in conventional-sized technologies, mainly due to the microscopic sizes of the damages.
- Micro-drilling-induced delamination is less severe than it is used in conventional-sized holes. This is because the lower axial cutting force is often smaller than the critical thrust force responsible for layer separation and destruction in FRPs. Nevertheless, the relative amount of micro-drilling-induced burrs is as significant as in the case of conventional-sized machining of FRPs.
- Excessive tool wear and catastrophic failures are critical concerns when dealing with the micro-drilling of fibrous composites. Unlike conventional-sized drilling, the micro-drilling operation entails a very poor ability for composite chip ejection and cutting heat dissipation during the material removal process. Consequently, a large amount of cutting heat can be easily accumulated at the tool-chip and tool-work interface to exacerbate the temperature-related degradation of the tool edges. Additionally, the highly abrasive reinforcing fibres can cause serious abrasion and erosion of the fresh drill edges. At the same time, the soft matrix rubs against the tool surfaces, leading to the blunting and dulling of drill bits.
- Considering the growing trend of miniaturisation and spread of fibrous composite applications, the micro-drilling of FRPs will be a determining research direction in the future: (i) the machine tools and equipment need to be further developed to implement precision, peck cycles, cooling, chip removal and ultrasonic vibration assistance; (ii) advanced cutting tool geometries should be implemented in micro-scales; (iii) develop specific FRP testing regime for micro-drilled holes to analyse effects of multiple micro-holes on mechanical performance; and (iv) further exploration of machine tool, tool geometry, tool coating, cutting parameters and cooling is required in micro-drilling.

CRediT authorship contribution statement

Norbert Geier: Conceptualization, Writing – original draft, Writing – review & editing, Project administration. **Karali Patra:** Conceptualization, Writing – original draft. **Ravi Shankar Anand:** Conceptualization, Writing – original draft. **Sam Ashworth:** Conceptualization, Writing –

original draft. **Barnabás Zoltán Balázs:** Visualization, Writing – review & editing. **Tamás Lukács:** Writing – review & editing. **Gergely Magyar:** Writing – review & editing. **Péter Tamás-Bényei:** Conceptualization, Writing – original draft. **Jinyang Xu:** Conceptualization, Writing – original draft, Writing – review & editing. **J Paulo Davim:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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