Review

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Advanced cutting tools and technologies for drilling carbon fibre reinforced polymer (CFRP) composites: a review

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Abstract Carbon fibre reinforced polymer (CFRP) composites have excellent specific mechanical properties, these materials are therefore widely used in high-tech industries like the automobile and aerospace sectors. The mechanical machining of CFRP composites is often necessary to meet dimensional or assembly-related requirements; however, the machining of these materials is difficult. In an attempt to explore this issue, the main objective of the present paper is to review those advanced cutting tools and technologies that are used for drilling carbon fibre reinforced polymer composites. In this context, this paper gives a detailed review and discussion of the following: (i) the machinability of CFRP including chip removal mechanisms, cutting force, tool wear, surface roughness, delamination and the characteristics of uncut fibres; (ii) cutting tool requirements for CFRP machining; and (iii) recent industrial solutions: advanced edge geometries of cutting tools, coatings and technologies. In conclusion, it can be stated that advanced geometry cutting tools are often necessary in order to effectively and appropriately machine required quality features when working with CFRP composites.

Keywords CFRP, machinability, advanced cutting tools, uncut fibres

Nomenclature

k (1) – Direction of fibres
n (rpm) – Spindle speed
r_β (mm) – Cutting edge radius
v_c (m/min) – Cutting speed
v_f (mm/min) – Feed rate

α (°) – Clearance angle
β (°) – Lip angle
γ (°) – Rake angle
θ (°) – Fibre-cutting angle
σ (°) – Point angle
ϕ (°) – Fibre orientation angle

CFRP – Carbon fibre reinforced polymer
MD – Multidirectional
PCD – Polycrystalline diamond
UD – Unidirectional

1. Introduction

Carbon fibre reinforced polymer (CFRP) is an excellent structural composite material, which has two main components: (i) high-strength carbon fibres with a diameter of ~8μm and (ii) the flexible and tough matrix material. The manufacturing costs of carbon fibres and of CFRP composites are extremely high; even so, CFRPs are widely used in high-tech industries, where high strength-to-weight ratio (specific strength) and stiffness constitute important requirements. This is especially true to the following areas and products: automobile, aerospace, marine industries and civil engineering, wind-turbines, sport equipment and robotics. In addition to their favourable qualities of specific strength and stiffness, CFRP composites also exhibit relatively low density, high damping ability, good dimensional stability and good corrosion resistance [1–8].

Manufacturers are trying to produce CFRP parts in a ready-to-shape manner by way of moulding, vacuum bagging, compression moulding, filament winding or using hand-lay-up laminating techniques. Nevertheless, the machining of these materials is still necessary in order to: (i) meet dimensional tolerances, (ii) manufacture difficult-to-mould features like pockets or advanced surfaces, (iii) finish the edges of laminated composites or (iv) drill holes for reasons of assembly [1–6]. Therefore, hole drilling and edge trimming are the most commonly demanded machining operations, which are to be analysed and optimised for the industry in question.

Even if the machining of CFRPs is often required, they are a difficult-to-cut material due to: (i) the high abrasive wear effect of the carbon fibres on the cutting tool, (ii) their non-homogenous and (iii) anisotropic properties [1–6, 9]. Numerous machining-related problems can occur when improper machining technology is applied. The most frequent feature-related geometrical damages are delamination (separation of laminated layers), fibre pull-out and uncut fibres, micro-cracking, inappropriate surface roughness and matrix burning. Such damage can mainly be influenced by the geometry of the applied cutting tools [10–22], process parameters [19, 23–26], the tool path [27–29] and the application of back-up support plates [16, 23, 30–34].

The use of conventional cutting tools is usually not the best solution from the point of view of cost and with respect to machining good quality features in CFRPs. Nonetheless, many researchers [27, 35–37] have tried to develop special technologies for these conventional tools using diverse methods. It is true to say that, with the application of these special technologies (and using conventional tools), in the majority of cases good quality features can be machined in CFRPs. Yet, the use of these technologies usually causes an increase in both machining time and cost. Recently, cutting tool producers and researchers have developed a wide range of cutting tools with special geometries for CFRP manufacturers, which situation necessitates that a review of these advanced cutting tools and their applications be included in the present paper.

In light of the above, the main objective of this study is to review those advanced cutting tools and technologies that are used for drilling carbon fibre reinforced polymer composites. Therefore, this paper offers a detailed discussion of (i) the chip formation mechanisms and machinability of CFRPs including cutting force, tool wear, surface roughness, delamination and the characteristics of uncut fibres; (ii) cutting tool requirements; and (iii) recent industrial solutions including advanced tool edge geometries, tool coatings and technologies. The focus of the present discussion falls on cutting tools and technologies related to drilling operations.

2. Machinability of CFRP composites

The machinability of CFRPs is examined mainly through the analysis of: (i) cutting force acting on the cutting tool and on laminated layers, (ii) cutting torque, (iii) machined surface roughness parameters, (iv) the delamination of laminated layers, (v) the characteristics of uncut fibres and (vi) tool wear. To a significant extent, the above-listed optimisation parameters are influenced by conventional factors like cutting speed, feed rate, depth of cut, the material of the workpiece, the geometry of the cutting tool, cooling, etc. However, the inhomogeneity and anisotropy of CFRPs cannot be analysed using these conventional factors. For this reason, new parameters have been defined by researchers in order to analyse the effect of fibres' directions in the materials used. These new factors are fibre-cutting angle and fibre orientation angle.

In the case of the orthogonal cutting of unidirectional fibre reinforced polymer (UD-CFRP) composite materials, fibre-cutting angle (θ) can be defined as the angle between the vector of the cutting speed (v_c) and the direction of fibre reinforcements (k), as shown in **Fig. 1 (a)**. This factor is constant during orthogonal cutting; however, in the case of drilling (**Fig. 1 (b)**) or milling (**Fig. 1 (c)**) operations, the same factor alternates in line with the function of the rotation of the cutting tool. To take this into account, researchers have introduced fibre orientation angle (ϕ): the value of this angle is equal to the angle between the vector of the feed rate (v_f) and the direction of fibre reinforcements, as depicted in **Fig. 1 (c)**. With the application of θ and ϕ, it becomes feasible to analyse chip removal mechanisms of fibre reinforced composite materials. This topic is discussed in Section 2.1.

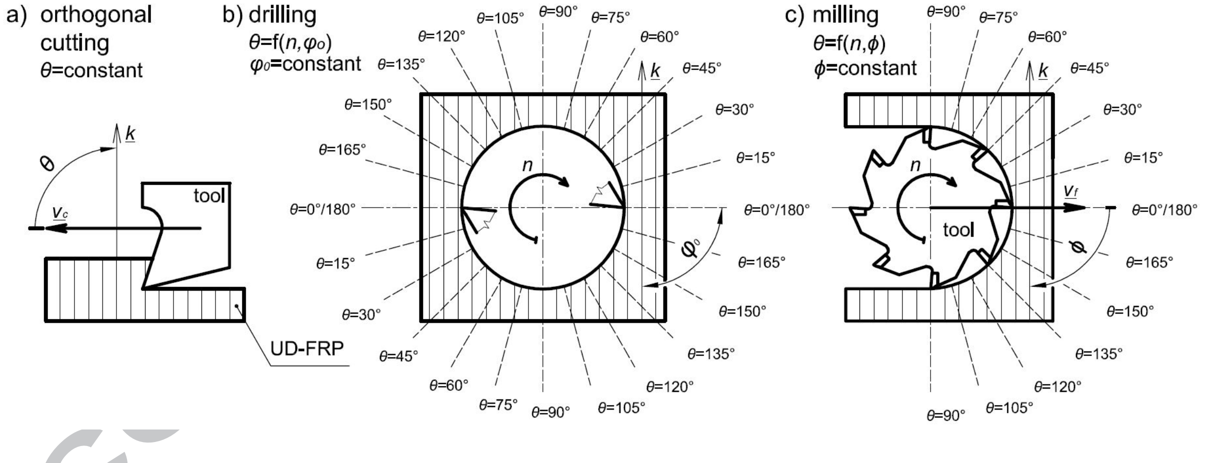
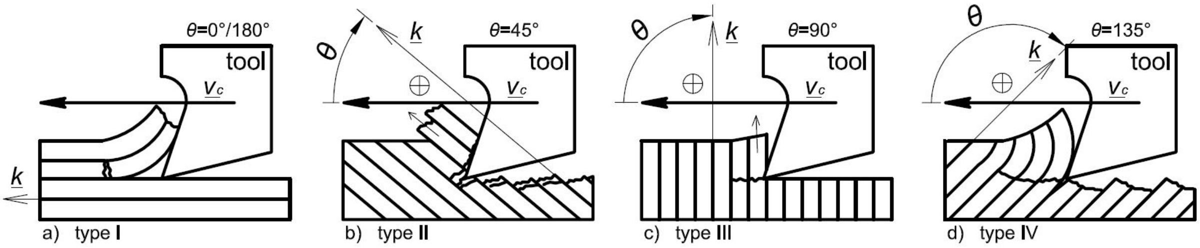


Fig. 1 Schematic drawings of **(a)** orthogonal cutting, **(b)** drilling and **(c)** milling of fibre reinforced polymers (FRPs). In the figure, θ is the fibre-cutting angle, ϕ shows the fibre orientation angle, φ_o is the starting orientation of tool edge with respect to the direction of fibres, k is the direction of fibres, n is the spindle speed, v_c is the cutting speed and v_f is the feed rate.

2.1 Chip removal mechanisms of unidirectional FRPs

Chip removal mechanisms were analysed by many researchers [4, 12, 23, 38–52] in order to understand and describe the surface characteristics (surface roughness, uncut fibres, delamination, fibre pull-out, etc.) of machined unidirectional carbon fibre reinforced polymer (UD-CFRP) composites. Based on the results of such research, it can be established that fibre-cutting angle has the most significant effect on chip removal mechanisms of unidirectional FRPs [4, 51]. Furthermore, chip removal mechanisms are independent of cutting speed, as discovered by Lopresto et al. [53]. Li et al. [38] presented a detailed experimental investigation of UD-CFRP orthogonal cutting and chip removal mechanisms in the case of using a solid tungsten carbide tool. They as well as [39, 41, 42, 54] categorized chip formation mechanisms of UD-CFRPs into four different types depending on the fibre-cutting angle: this is shown in **Fig. 2**.



a) type **I** b) type **II** c) type **III** d) type **IV**

Fig. 2 Geometrical model of chip removal mechanisms of UD-CFRPs; this model is to be applied in case the rake angle is positive ($\gamma >> 0°$) and the cutting edge radius is small ($r_\beta = \sim 0$ mm) [4, 23]. **(a)** type I: θ=0°/180°, **(b)** type II: θ=45°, **(c)** type III: θ=90°, and **(d)** type IV: θ=135°. Reprinted/adapted by permission from (Springer Nature Customer Service Centre GmbH): (Springer Nature) (Mechanics of Chip Formation) by (Jamal Y. Sheikh-Ahmad) (COPYRIGHT) (2009).

If the fibre-cutting angle is θ=0°/180° (type I), the rake face of the cutting tool loads the fibres along their axes (fracture mode I: opening, tension), then delaminates the fibres from each other and buckles them on the surface of the composite, as can be seen in **Fig. 2 (a)**. In this case, the fracture generated by delamination and raking causes the fibres to be removed: the resulting chips are usually longer and the machined surface is smoother than in the case of chip removal using type II or IV, as revealed by [4, 38]. If the fibre-cutting angle is θ=45° (type II), the fibre fracture is induced by compression shear, then by interlaminar shear. According to Ahmad [4], during the compression stage, microcracks are generated on the fibres both above and below the cutting plane, and thus the machined surface displays more damage, as can be seen in **Fig. 2 (b)**. Furthermore, in this scenario chips are smaller and surface roughness is worse than in the case of chip removal using operation type I. When the fibre-cutting angle is θ=90° (type III), the resulting chip removal mechanism is crushing-dominated. The edge of the cutting tool compresses the fibres at the transverse direction, then the fibres crush due to the resultant high pressure, as can be seen in **Fig. 2 (c)**. The characteristics of the resulting machined surfaces are usually more favourable due to the crushing effect of the tool. When the fibre-cutting angle is θ=135° (type IV), chip removal mechanism of FRPs is dominated by macrofracture. The rake face of the cutting tool pushes and bends the fibres, as can be seen in **Fig. 2 (d)**, and, as a result, out-of-plane displacements are observable due to elastic bending caused by the compression of the rake face. Moreover, in this case chip thickness is often observed to be greater than theoretical chip thickness (depth of cut) because fracture may occur below the theoretical cutting plane, as discussed by Ahmad [4].

According to Wang et al. [40] and Ahmad [4], rake angle (γ) and cutting edge radius (r_β) also have a significant effect on chip formation mechanisms. However, those factors are not included in the model of chip formation mechanisms that these authors have introduced (**Fig. 2**). According to Ahmad [4], in the case of a greater rake angle, the compressive load of the rake face on fibre reinforcements is higher, and consequently the fracture of the chips is classified as mode II (sliding, shear). In the case of a fibre-cutting angle of θ=0°/180° and a negative rake angle, the resulting behaviour of the fibres can be modelled by a compressed cantilever beam. In addition, the chips are usually smaller and the cutting force is usually higher in the case of a higher rake angle, as pointed out by [4, 55].

The impact of cutting edge radius on fibre fracture mode and on chip removal mechanism is significant, when the fibre-cutting angle is $\theta < 90° + \gamma$, according to Wang et al. [40]. From the point of view of chip removal mechanism, smaller cutting edge radiuses are more preferable, because the resulting fibre removal process will be crushing-dominated, as can be seen in **Fig. 3 (a)**. However, in the case of higher cutting edge radiuses, the nose of the cutting tool bends the fibres rather than crushing them, thus uncut fibres can be observed on the machined surfaces of FRPs. This is shown in **Fig. 3 (b)**.

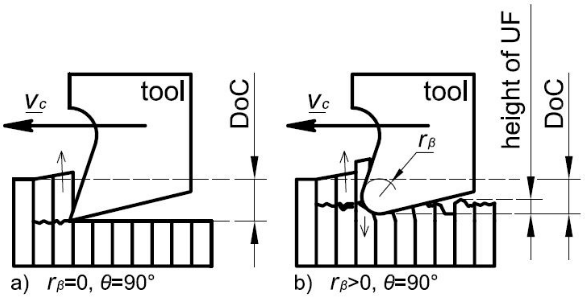


Fig. 3 Effect of cutting edge radius (r_β) on chip formation mechanisms [4, 40]. (a) r_β=0 mm and θ=90°, (b) r_β>0 mm and θ=90°. In the figure, DoC is the depth of cut, UF is uncut fibres and v_c is the cutting speed. Reprinted/adapted by permission from (Springer Nature Customer Service Centre GmbH): (Springer Nature) (Mechanics of Chip Formation) by (Jamal Y. Sheikh-Ahmad) (COPYRIGHT) (2009).

Based on the discussed chip removal mechanisms of FRP composite materials, the following conclusions can be drawn: (i) FRP machining technology should be designed so that fibre-cutting angle falls within a range of $0° < \theta < 90°$ with a view to decreasing the amount of uncut fibres and to improving the quality of the machined surface. (ii) The rake angle of the cutting tool should be as positive as possible to increase the thrust-fracture effect in an attempt to eliminate any potential compressive-bending effect on the fibres. (iii) Cutting edge radius should be as small as possible in order to exclude the emergence of a bending-dominated fibre fracture mode.

2.2 Drilling of CFRP composites

In the first part of this section, research results concerning the most frequent feature-related geometrical damages are reviewed: our discussion extends to (i) delamination, (ii) the characteristics of uncut fibres and (iii) surface roughness related observations and results. Afterwards, cutting tool related research efforts are reviewed including (i) cutting force and tool wear, (ii) the effects of the geometry of the cutting tool and coating. Finally, in the last part of the section, a short review of the cutting environment's cooling is presented.

Delamination

The laminated layers of CFRP composite laminates can separate from each other when they are impacted by unfavourable cutting forces. This phenomenon is called delamination, which has to be minimised in order to keep the mechanical properties of machined parts as adequate as possible. The influence of process parameters on delamination was investigated by many researchers including [7, 10–16, 24, 26, 35, 56–71]. However, there are still many difficulties concerning the application of some of the associated measurements and evaluation-purpose solutions in industrial environments. Delamination can be described by numerous sets of variables composed of one or more dimensional parameters [35, 56, 63, 66, 69, 72–74]. Even so, the conventional delamination factor ($F_d = D_{max}/D_{nom}$) is still the most common optimisation parameter for quality measurements used by researchers. In the case of drilling FRP laminates, peel-up and push-out effects appear at the entry and at the exit points of holes. A schematic figure of delamination can be seen in **Fig. 4**.

Delamination factors can be measured and analysed by (i) conventional images of drilled holes captured by digital image processing [27, 35, 57, 66, 75], (ii) by C-scan of holes [76, 77] and (iii) by using the grinding method [78].

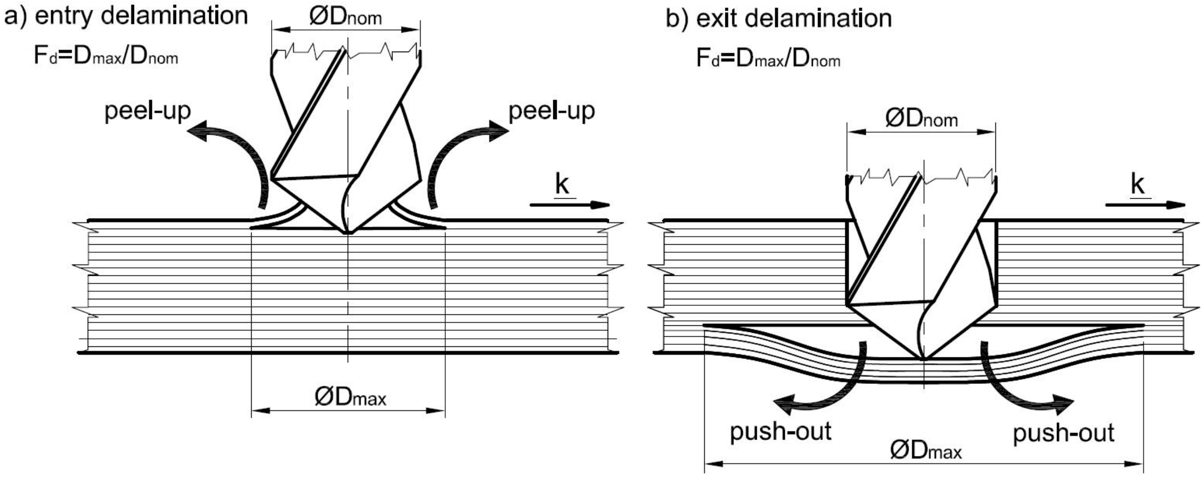


Fig. 4 Schematic figure of **(a)** peel-up and **(b)** push-out delamination effects, when drilling unidirectional fibre reinforced polymer (UD-FRP) laminates

Davim and Reis [57] conducted drilling experiments using brad & spur and straight shank drills. They state that the delamination factor at the exit of the hole is smaller in magnitude than the delamination factor at the entry side. However, Sorrentino et al. [58], as well as Raj and Karunamoorthy [79] observed the opposite: delamination at the exit of the holes is higher than at the entry side. Krishnaraj et al. [24] stated that neither cutting speed nor feed rate has a significant effect on entry delamination. Geier and Szalay [35] conducted drilling experiments in UD-CFRPs using a twist drill with diamond coating and a double point angle, and analysed the influence of cutting speed and feed rate on delamination. They as well as [7, 10, 13, 24, 26, 58, 60–64, 80, 81] observed that feed rate increases exit delamination, but also noted that cutting speed has no significant effect on exit delamination. The researchers also observed that when all process parameters are maintained at constant values, higher feed rates cause higher thrust forces. Higher cutting forces cause more damage to laminated surfaces, and the delamination can therefore be higher, as observed by Davim and Reis [26]. Al-wandi et al. [72] conducted drilling experiments in UD-CFRPs and stated that the delamination factor decreases with an increase of cutting speed.

Sorrentino et al. [58] as well as Li et al. [82] applied feed rate control in order to decrease delamination in CFRPs, and they could achieve decreased push-out delamination. Girot et al. [83] developed a new analytical model for describing the delamination of CFRPs during drilling. With the help of this model, critical thrust force can be estimated for the purpose of achieving delamination-free drilling. In addition, this model takes into account the distribution of pressure along the cutting and chisel edges by mixing delamination modes I and II. Lissek et al. [56] offered an alternative description of delamination by considering the shape and extension of the delaminated area. They found an analogy to the surface metrology and, based on this discovery, suggested new delamination parameters. Their model more accurately describes the delaminated area than other models using the conventional delamination factor. Nonetheless, related calculation can be cumbersome due to possible undercuts in the segmented function of the borders of the delaminated area. In the scope of another research effort, Gaitonde et al. [60] analysed the influence of process parameters (feed rate, cutting speed and point angle) on conventional delamination factors in CFRPs. They applied a cemented carbide (K20) twist drill for the drilling experiments and observed that the peel-up delamination can be reduced when high-speed machining is applied. Furthermore, Grilo et al. [63] analysed the cutting ability of three different cutting tools (brad & spur drill, twist drill and a four-flute drill) concerning CFRPs, and stated that the spur drill produced the best results from the point of view of delamination. Caggiano et al. [73] proved that exit delamination increases with tool wear, and also observed that entry delamination shows a more stable behaviour. Qiu et al. [20] studied the influence of the chisel edge of step drills on delamination when drilling CFRPs. Their results showed that the chisel edge has a significant effect on delamination, especially when the ratio of the step drill's primary diameter to secondary diameter is higher than 0.75. Tsao [84] conducted drilling experiments in CFRPs using compound core-special drills. ANOVA results of Tsao showed that feed rate has the most significant effect on delamination, followed by the ratio of cutting velocity, then by the diameter of the inner drill and finally by the type of inner drill.

Characteristics of uncut fibres

Uncut fibres and fibre pull-out can occur on the machined edges of CFRP composites when inappropriate technology is applied. Uncut fibres usually do not impact negatively the mechanical properties of machined CFRP parts, but they necessitate additional machining operations (which require additional time and cause unnecessary cost) in case their elimination is unavoidable. The appearance of uncut fibres around the edge of the hole shows certain characteristics: usually two burr areas (A_1 and A_2) can be observed at the exit of the hole where uncut fibres occur, as demonstrated by Xu et al. [15]. Such uncut fibres at the exit of holes and their burr areas can be seen in **Fig. 5.**

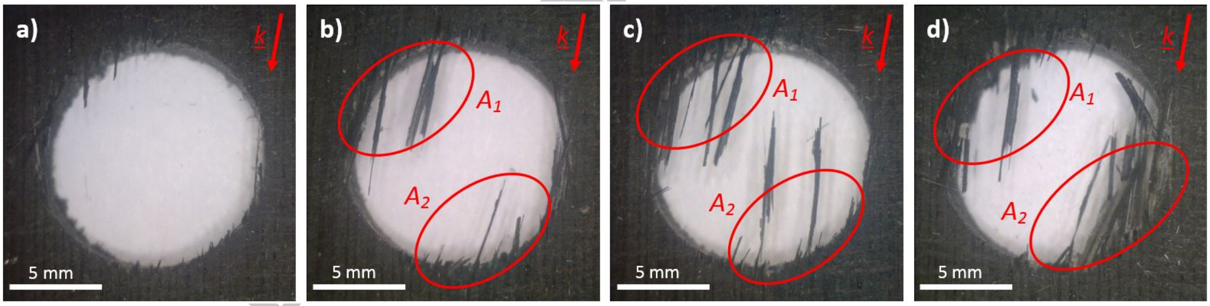


Fig. 5 Uncut fibres at the exit of drilled holes in UD-CFRPs. A_1 and A_2 are the burr areas of drilled holes and *k* shows the direction of fibre reinforcements

The effect of process and technology parameters on the characteristics of uncut fibres was investigated by many researchers [14, 15, 20, 23, 39, 69, 75, 85–89] in order to develop proper technologies for machining CFRPs without leaving uncut fibres behind. Ramirez et at. [85] observed that uncut fibres are localised at θ=135° and proposed a new surface roughness criterion based on the ratio of uncut fibres to the total hole surface. Xu et al. [86] observed that the burr area increases with the increase in thrust force. Heisel and Pfeifroth [14] analysed the effect of feed rate on burr height using conventional twist drills with different point angles in the case of the dry drilling of CFRPs. They observed that feed rate increases burr height at the entry of the hole; however, no clear trend was observed at the exit side of the hole. Xu et al. [88] conducted detailed drilling experiments on CFRPs using different tools (dagger, brad & spur and conventional twist drill) and concluded that feed rate has the most significant influence on the extents of defects. It was also observed that the brad & spur drill produced the best performance on damage reduction. Qiu et al. [20] could minimise the amount of uncut fibres using an optimised step ratio drill. Geier et al. [75] drilled holes in UD-CFRPs and could minimise uncut fibres by applying direct monitoring of uncut fibres through digital image processing. The latter researchers suggested a process monitoring and diagnostics method for drilling

UD-CFRPs, which is based on the characteristics of uncut fibres. Hrechuk et al. [69] proposed a new methodology to evaluate the quality of drilled holes in FRPs. Their model takes into account the visible defects of drilled holes including delamination and uncut fibres. Poulachon et al. [39] drilled holes in CFRPs using uncoated carbide drills, and concluded that as long as tool wear is small, the distribution of uncut fibres is dependent mainly on the angle of fibre orientation. Still, when tool wear increases, distribution is less markedly dependent on the fibre orientation angle. Wang et al. [87] analysed the effect of four different drilling tools (diamond coated and uncoated twist drills and a double point angle drill) on the burr area, and concluded that, in the case of the first five holes, uncoated drills produced a smaller burr area than coated drills.

Characteristics of surface roughness

One-dimensional parameters of surface roughness (*Ra, Rz*) are one of the most common specifications required/used by design engineers, and the analysis of such parameters is therefore vital. Gao et al. [90] analysed the surface characteristics of machined CFRPs, and referent results of ANOVA showed that fibre-cutting angle has the most significant effect on surface roughness, followed by cutting speed, DoC and rake angle. Poulachon et al. [39] analysed the surface topography of drilled surfaces of CFRP composites. They and other researchers [23, 35, 85, 91] observed the emergence of bad-quality surface characteristics in the range of fibre-cutting angles of θ=135°±18°. Furthermore, they concluded that a new surface roughness criterion should be defined, which could incorporate the presence of long lengths of uncut fibres on the analysed surface. Tsao [92] conducted drilling experiments in CFRPs using a core drill with different grit sizes of diamonds (A) as well as with varying thickness (B), feed rate (C) and cutting speed (D). He concluded that feed rate and cutting speed have the most significant effect on surface roughness, and also noted that interaction in terms of AB and BD is significant. Geier and Szalay [35] analysed the surface roughness characteristics of drilled wall surfaces in CFRPs. In the scope of their research, they observed that the ratio of roughness depth to average surface roughness (*Rz/Ra)* is higher than in the case of homogeneous materials, which is due to higher roughness depths caused by uncut fibres and microcracking. Eneyew and Ramulu [91] characterised the surface of drilled holes in UD-CFRPs, and concluded that better surface quality can be machined using higher cutting speeds and lower feed rates. Wang et al. [93] conducted drilling experiments using a one-shot drill and proved that the number of holes significantly increases the following parameters: (i) surface roughness of walls in the case of drilled holes and (ii) the amount of uncut fibres at the entry and at the exit of the holes. In addition, Liu et al. [94] analysed surface characteristics of machined CFRP composites using FEM simulations, and stated that an increase in cutting speed contributes to improved surface quality.

Cutting force and tool wear

With respect to drilling, the analysis of cutting force is essential for predicting tool wear, delamination and surface characteristics [95, 96]. Hintze et al. [41] evaluated total cutting force when drilling unidirectional CFRPs using an uncoated twist drill. They concluded that all components of the cutting force (cutting force, feed force and passive force) are significantly influenced by the fibre-cutting angle. Furthermore, they showed that increasing tool wear results in cutting force components of higher values. Davim and Reis [57] as well as other researchers [15, 91, 97, 98] showed that feed rate has the most significant physical and statistical impact on cutting force. The effect of cutting speed on thrust force is often hyperbolical or insignificant [35]; however, according to Xu et al. [86], high-speed drilling may contribute to the reduction of thrust force and geometrical defects. Anand et al. [99] measured cutting force when micro drilling CFRPs, and extended the cutting model of Victor-Kienzle to also include model-specific cutting force. Tsao and Chiu [77] conducted drilling experiments in CFRPs using core-special drills of different compounds. They observed that cutting velocity ratio (between the inner and outer tools) has the most significant effect on thrust force, followed by feed rate, and finally by the type of the inner drill. Tsao [100] predicted the thrust force of step drills when drilling CFRPs, and used Taguchi and radial basis function networks in order to analyse the effect of the step angle, stage ratio, feed rate and cutting speed. His ANOVA results proved that stage ratio has the most significant influence on thrust force, followed by step angle and feed rate. Specific cutting force is higher when a smaller cutting speed and a smaller depth of cut are applied, as claimed by An et al. [51]. Therefore, high cutting speed and a large depth of cut are suggested to be used in order to ensure stable machining of CFRPs.

Tool wear significantly increases as cutting speed increases, according to Lin and Chen [59]. Ramirez et al. [85] investigated correlations between tool damage, cutting force, cutting temperature and hole surface roughness. They stated that abrasion is the main wear mechanism when machining CFRP composites, and they also noted that flank face wears to the greatest extent, followed by the rake face of the cutting tool. They stated that wear could indirectly be measured by monitoring cutting force or cutting temperature; however, such measurements are difficult to be adopted by industrial environments, as stated by [75]. Raj and Karunamoorthy [9] as well as other researchers [79, 101–103] observed that a higher number of holes results in an increase in the cutting edge radius, which causes the bending of fibre reinforcements instead of crushing them. However, tool wear does not significantly influence the size or on the circularity of drilled holes, as proved by the experimental study of Gaugel et al. [67]. Xu et al. [15] analysed the wear and tool life of two types of polycrystalline diamond drills (a dragger drill and a twist drill) when machining high-strength CFRPs. They found that the PCD dragger drill was capable of producing a higher thrust force than the PCD twist drill; however, the tool life of the dragger drill was found to be longer than that of the twist drill. Merino-Pérez et al. [104] conducted conventional drilling experiments in CFRP composites, and analysed the effects of workpiece constituents and cutting speed on cutting forces. They concluded that the type of resin matrix and the number of holes (~tool wear) have a significant effect on thrust force, but the effect of cutting speed was found negligible. Fernández-Pérez et al. [105] analysed the effect of process parameters on tool wear and on the quality of drilled holes in CFRPs using carbide countersink drills with a diamond coating. They observed that the tool wear mechanism was chipping-dominated, but, concurrently with this, progressive abrasive wear on the main cutting edge was also observable. Furthermore, smooth abrasive wear dominated on the countersink edge of the tool. Wang et al. [93] drilled holes using a one-shot drill, and concluded that cutting edge rounding is the main wear type impacting the secondary cutting edge of the tool, as was observed in [106], too. In [106], three different drills were studied (uncoated, diamond coated and AlTiN coated drills) concerning CFRPs. No significant difference was observed between AlTiN coated and uncoated drills with respect to thrust force. Furthermore, diamond coated drills were capable of causing a lower thrust force than uncoated or AlTiN drills. However, the researchers could identify no significant correlation between diverse wear resistance values of coatings and related results. Kuo et al. [107] analysed the wear behaviour of CVD diamond coated drills (double point and multi-facet drills) with reference to the drilling of CFRPs. They observed that cutting force is not proportionate to tool wear, given the same cutting conditions.

The effects of tool geometry and coating

The geometry of the cutting tool has one of the most significant effects on the above-mentioned geometrical damages, therefore its detailed analysis is of utmost importance. Frank [11] conducted drilling experiments concerning long fibre reinforced thermoplastics. In the scope of this research, uncoated, tungsten carbide helical drills were used, and the effects of cutting edges on the quality of holes were investigated. It was found that the cutting edge has the largest impact on machining results:

larger cutting edge radiuses negatively impact the quality of the hole. In another research, Durao et al. [13] compared five different tool geometries (twist drills with point angles of 120° and of 85°, a brad drill, a dagger drill and a step drill) from the point of view thrust force, surface roughness and delamination. The researchers recommended a low feed rate in order to decrease thrust force and delamination, and noted that thermal degradation may be considerable at low feed rates. For minimising delamination, researchers recommended a twist drill with a point angle of 120°. Heisel and Pfeifroth [14] conducted drilling experiments in CFRPs, and analysed the influence of different point angles (155°, 175°, 185°, 178°) on thrust force and delamination. They discovered that an increase in point angle increases delamination at the exit of the holes. It was also observed that delamination decreases at the entry of the holes concurrently with an increase of the point angle of twist drills. Feito et al. [108] analysed the cutting ability of three different twist drills (point angles of 90°, 118° and 140°) and concluded that a low point angle in the range of 90°-108° is recommendable for reducing delamination. Davim and Reis [57] conducted drilling experiments in CFRPs using a helical flute straight shank K10 drill and a brad & spur K10 drill in order to analyse the effects of such drills on machining power and delamination. They observed that the brad and spur drill produced less delamination and fewer uncut fibres than the straight shank drill. Montoya et al. [109] analysed the performance of coated and uncoated carbide tools in drilling thick CFRP/aluminium alloy stacks. The researchers observed that the analysed uncoated drill had smaller thrust force than the coated one mainly due to cutting edge sharpness. Furthermore, better quality holes were machined using the diamond coated drill thanks to lower flank wear and lower thrust force.

Davim and Reis [26] analysed the influence of process parameters (cutting speed and feed rate) and cutting tools (a helical flute HSS drill, a four-flute K10 drill and a helical flute K10 drill) on delamination damage in CFRPs. As attested by their study, the helical flute K10 drill produced less damage on the CFRP than the four-flute K10 drill; furthermore, the conventional delamination factor was also found to be smaller in this case. The effects of different drills (a polycrystalline diamond (PCD) twist drill and a special diamond coated double point angle drill) on delamination were analysed by Al-wandi et al. [72]. Drilling experiments on CFRPs were conducted and the results were verified by the application of the finite element method (FEM): it was found that the double point angle drill could produce better quality holes than the other tool under scrutiny. Ameur et al. [110] conducted drilling experiments on CFRPs using a WC carbide, high-speed steel (HSS) drill, and a TiN-coated carbide drill. They found that the coated drill produced lower cutting forces than the HSS drill. Furthermore, they showed that the cylindricity error of holes can be decreased by applying a small cutting speed and a high feed rate. Wang et al. [87] highlighted that the diamond coating of the cutting tool can reduce thrust force and delamination. At the same time, they found that the number of uncut fibres increases due to increased edge roundness caused by coating growth. They also discovered that diamond coating increases wear resistance and tool life. Karpat and Bahtiyar [17] analysed the impact of custom-made double point angle PCD drills on thrust force, torque and tool wear. They found that better drilling performance can be achieved by applying those drills that exhibit the shortest primary drilling edge lengths. Furthermore, it was also observed that the helix angle of drilling tools (between a degree of 24°and 30°) has no significant influence on tool life, thrust force or torque, according to Shyha et al. [62]. Durao et al. [111] conducted drilling experiments on CFRPs using five different tools (two twist drills, a brad drill, a dragger and a step drill). Based on their experimental work, the twist drill (with a point angle of 120°) is the best choice for minimising delamination, thrust force and surface roughness. Moreover, Feito et al. [112] compared the cutting ability of a twist drill and a step drill concerning CFRPs, and concluded that the step drill shows lower thrust force and delamination properties especially at low feed rates. In another study, Feito et al. [113] analysed the influence of three special tool geometries (brad, reamer and step drills) on thrust force, torque and delamination. They observed that the reamer drill produces almost delamination-free holes, therefore this tool is recommended to be used in order to decrease delamination. At the same time, the step drill produced higher entry delamination than the brad or the reamer drills.

Karpat et al. [114] analysed the effect of three different double point angle PCD drills on cutting force and delamination. They proposed a smaller chisel edge for the drilling tool in order to decrease thrust force and delamination. However, they have also found that a smaller chisel edge increases the cutting force and the tool wear on the secondary cutting edge. The study of Iliescu et al. [115] pointed out that the tool life of diamond coated carbide drills can be 10-12 times higher than the tool life of uncoated carbide drilling tools. Furthermore, related cutting speed can be 3 times higher when using diamond-coated tools than uncoated ones. The researchers have also suggested certain drilling tool specifications for drilling delamination-free in CFRPs: (i) a point angle of 125°-130°, (ii) a helix angle of 35°-40°, (iii) a clearance angle of 10°-25° and (iv) diamond coating. Qiu et al. [116] designed a novel drill geometry in order to decrease exit defects (concerning delamination and uncut fibres) when drilling CFRPs. They compared the cutting ability of a novel drill with a dagger drill and a conventional drill, and proved that the novel drill could produce better quality holes. Additionally, they stated that the new drill is better at reducing thrust force and exit defects than brad & spur or dagger drills. In their research, Feito et al. [80] analysed the cutting ability of two drilling tools (with point angles of 90° and 118°) for CFRPs: they showed that smaller point angles cause higher delamination, and also concluded that point angle has no significant influence on thrust force. Qiu et al. [19] drilled holes in CFRPs using a twist drill and several step drills in order to analyse the impact of such drills and of related process parameters (feed rate and cutting speed) on thrust force and damage to hole walls. They observed that stepped drills produced smaller thrust force and better hole walls than the twist drill under scrutiny. Furthermore, they also proved that the impacts of feed rate, of cutting speed and of the diameters of different stepped drills on the extent and magnitude of hole damage is significant. Xu et al. [88] studied drilling-induced defects in multidirectional CFRPs using three different tools (brad & spur, twist and dagger drills), and recommended the brad & spur drill for minimising damage and maximising cutting performance. However, the researchers do not recommend the dagger drill for drilling in MD-CFRPs. Hrechuk et al. [117] conducted drilling experiments in CFRPs using an uncoated, a diamond coated and a PCD coated double point angle drilling tool in order to analyse the effect of such drills on tool wear. Their results showed that coated tools performed better in wear resistance, as expected. Furthermore, tool wear of the PCD drill was much less significant than that of the diamond coated drill. Finally, Tsao [118] analysed the effect of diameter ratio, feed rate and cutting speed on thrust force and delamination. In the scope of this study, the core-saw drill was found to be a better choice for delamination-free drilling than the core drill.

Cooling

When machining conventional homogenous materials, cooling is a useful way of reducing cutting force and tool wear, and of removing chips from the cutting area [119, 120]. However, in the case of CFRP laminates, conventional cooling cannot be used so extensively, because carbon chips can damage the guide path of the machine tool if these chips mix into the lubricant fluid. Therefore, a vacuum cleaner is suggested to be used or removing carbon chips from the cutting area [35].

Morkavuk et al. [121] conducted slot milling experiments in CFRPs using cryogenic cooling, and analysed its effect on material damage. It was concluded that cryogenic machining produces less damage, smaller delaminated areas and better surface roughness on machined surfaces. At the same time, it was observed that cutting force increases as compared to the experimental results of dry milling. Kerrigan and Scaife [122] analysed the effect of three different cutting fluids on tool performance during the drilling of CFRPs. They concluded that dry drilling generated lower thrust force and lower torque than all of the fluids tested. Furthermore, coating failure of the cutting tool was found to be lower in the case of dry drilling. Xia et al. [123] compared dry and cryogenic drilling concerning CFRPs, and analysed their effect on thrust force, torque, corner wear of the drill bit, delamination factor and surface characteristics. The researchers concluded that cryogenic cooling not only reduces cutting edge rounding and tool wear, but it also decreases surface roughness. However, in the case of the application of cryogenic cooling, thrust force and torque are higher, and the delamination factor also increases. In the scope of their research, Khairusshima and Sharifah [124] studied tool wear when machining CFRPs in environments of dry and chilled air (at a temperature of minus10 °C, at an air pressure of 0.55 MPa and at a flow velocity of 4.10 m/s). They observed that tool life was 30% higher when chilled air was applied. Furthermore, their ANOVA results showed that feed rate has the most significant impact on tool life.

3. Advanced cutting tools and technologies

This section of the present study is comprised of three parts. Based on the above literature review and on publicly available information provided by tool producers, and relying on the experiences of the authors, the first part of this section offers a structured review of requirements associated with drilling tools used for machining CFRP composites. Then, a structured discussion of cutting tool geometries and coatings used by researchers and the industry follows. Finally, advanced hole machining technologies and future trends in drilling CFRP laminates are reviewed and discussed.

3.1 Requirements concerning drilling tools to be used with CFRPs

As it was stated before, geometrical parameters of drilling tools (point angle, helix angle, cutting edge radius, chisel edge, rake angle, clearance angle, etc.) have a significant impact on the quality of drilled holes (delamination, characteristics of uncut fibres, surface roughness and microstructures) in the case of CFRPs. Therefore, for realising the most effective manufacturing of CFRPs, a collection and listing of special requirements concerning drilling tools are necessary with a view to facilitating the selection of the right tool for the given machining process. Some of these requirements in fact oppose one another, but all of them should be considered when choosing the right tool for a certain drilling operation. In Points i–v below, special requirements concerning drilling tools for CFRPs are elaborated on.

(i) Laminated layers of CFRPs cannot be delaminated by the cutting tool. It is well known that the axial cutting force component (thrust force) of a cutting force has a significant impact on delamination, therefore it has to be decreased. If the value of thrust force reaches a critical thrust force level, laminated layers can separate from each other, therefore the related process has to be controlled. From the point of view of the geometry of the cutting tool, thrust force can be decreased by decreasing the point angle of drilling tools. A smaller point angle ($\sigma<<90°$) decreases axial chip size, which in turn causes the axial force to decrease, too. Furthermore, a sharper cutting edge ($r_\beta=\sim 0$ mm) causes lower thrust force, thus uncoated drills or drills with thin coatings are suggested for use as suited to the above-discussed chip removal mechanisms. Finally, the compression effect of multiple cutting edges can also decrease the sum of axial load, very similarly to compression end mills [27, 125, 126].

(ii) The cutting edge has to cut not only the fibres but also the matrix material properly. As attested by the above-discussed chip removal mechanisms of FRP composites, the cutting edge has to be sharp ($\alpha>>0°$, $\gamma>>0°$ and $r_\beta=\sim 0$ mm) in order to minimise plastic deformation of fibres and of the matrix material. A negative rake angle changes the type of chip mechanism: in this case, chips are usually more segmented, and concurrently passive force also increases due to the appearance of fracture mode

II and interlaminar shearing. In addition, the characteristics of microstructure significantly influence the sharpness of the edge of the tool: in the case of improper tool geometry, the cutting tool bends fibre reinforcements and consequently the fibres get buckled instead of being cut. Thus uncut fibres can appear on machined edges.

(iii) The cutting edge has to have good wear resistance to combat carbon fibre reinforcements. As it is well-known, carbon fibres have a very strong abrasive wear effect on cutting edges. Therefore conventional cutting tool materials (e.g. HSS) are not suggested for use. In this situation, solid carbide (with a higher Co content and a smaller grain size [106]) can be a good choice due to its fine performance, as attested by wear research. In addition, the life span of cutting edges can be further increased by the application of special coatings. In relation to this, the cutting ability of uncoated, AlTiN and diamond coated drills were studied by many researchers, and most of them have found thin diamond coating to be the most effective in increasing tool life.

(iv) The helix angle of drilling tools should be as small as possible in order to minimise the appearance of uncut fibres at the entry and exit edges of the holes. In the case of a lower helix angle, the axial force component of cutting force (during the reaming of the surface of the hole) bends the fibres instead of crushing them, because there is no support for the fibres to be backed up in the axial direction. However, in the radial direction fibres are supported against buckling. Furthermore, proper helix angles of right-hand cuts are more effective in reducing uncut fibres and delamination at the exit side of holes, but helix angles of left-hand cuts constitute a better choice at the entry side of the hole.

(v) It is necessary to minimise the mechanical contact area during machining. The thermal conductivity of CFRPs is much lower than that of metals, and high cutting temperatures can cause matrix or chip burning on machined surfaces. For this reason, the thermal load of matrix materials should be minimised. To this end, the contact area can be minimised by decreasing the shank diameter of the drill: the diameter should be smaller than the nominal, working diameter of the drill. Furthermore, the thermal load of the cutting tool can also be decreased by increasing the clearance angle. While the cutting edge is removing the chips, the resulting machined surface kicks back due to plastic deformation. If the clearance angle is smaller, the leftover material is exposed to more extensive contact with the clearance face of the cutting tool, which causes friction. As it is well-known, higher friction causes a higher thermal load on both the tool and the machined material. Finally, it must also be mentioned that cutting temperature can be decreased either by decreasing the cutting edge radius (a smaller cutting edge radius causes a smaller plastic deformation zone) or by the application of diamond coatings (which causes lower friction).

As a rule, all of the above-listed (i)-(v) requirements cannot be met simultaneously due to the fact that some of these requirements oppose one another (e.g. sharp cutting edge and coatings). However, all of the above-mentioned requirements have to be analysed in detail in order to find the proper technology for the mass production of boring holes in CFRPs, and this is especially true in the case of the aerospace industry.

3.2 Cutting tool geometry and coatings

A wide range of different drilling tools is used by researchers for analysing the cutting ability of such tools and for analysing the machinability of CFRP composites. For CFRPs, the most common drilling tools include the following: (i) conventional twist drills, (ii) double point angle twist drills, (iii) brad & spur drills, (iv) dagger drills (one-shot drill), (v) step drills, (vi) core drills and (vii) special core drills. These types of drills are shown in **Fig. 6**.

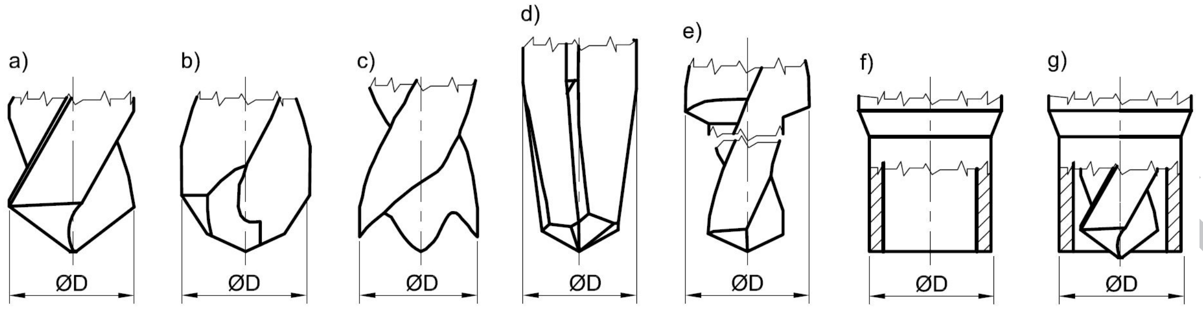


Fig. 6 Schematic drawings of different drilling tools for CFRPs: **(a)** the conventional twist drill, **(b)** the double point angle twist drill, **(c)** the brad & spur drill (candlestick drill), **(d)** the dagger drill (one-shot drill), **(e)** the step drill, **(f)** the core drill and **(g)** the special core drill

As **Tables 1** and **2** reveal, the cutting ability of conventional twist drills (**Fig. 6 (a)**) was analysed by many researchers with respect to CFRPs. Most of the reviewed studies deal with the analysis of cutting force and delamination, fewer studies focus on tool wear, and an even lower number of studies analyse cutting temperature during drilling. Even if conventional twist drill geometries usually do not meet the above-listed requirements of cutting tools for CFRPs, many studies focus on these tools and analyse or optimise related conventional drilling operations rather than addressing the question of the proper tool itself. For machining CFRPs, the point angle and the chisel edge of conventional twist drills are usually not small enough, therefore chip removal mechanism becomes bending-dominated, which causes higher thrust force and delamination, and leaves behind more uncut fibres on machined surfaces. In the case of low feed rates and optimised cutting environments and parameters (cutting speed, cooling, back-up support plate, etc.), it is possible to drill holes with minimised delamination but the operation time of such procedures is too long.

One of the most important objectives of the special drilling tools shown in **Fig. 6** is to reduce operation time. Double point angle twist drills (**Fig. 6 (b)**) usually produce lower thrust force and delamination, compared with conventional twist drills due to their smaller second point angle. The main goal of the second point angle is to decrease axial force, which has a significant effect on delamination and also on the characteristics of uncut fibres. Furthermore, double point angle drills are better at wear resistance compared to conventional twist drills, because the cutting force acting on the secondary cutting edge (which creates the final surface of the hole) is smaller. Double point angle twist drills covered by thin diamond coating can be a good choice for manufacturing good quality holes; however, the optimisation of pertaining drilling process parameters is still often necessary in order to increase productivity and performance as well as to improve the quality of holes [35]. A more detailed explanation of cutting ability of double point angle twist drills can be found in the publications listed in **Tables 1** and **2**.

Table 1 Analyses of cutting tool related phenomena: a review of different drilling tools applied by researchers for drilling CFRPs

Tool category in Figure 6	Type of drilling tool	Analysed optimisation parameters			
		Cutting force	Cutting torque	Tool wear	Cutting temperature
A	conventional twist drill	[14] [15] [19] [20] [23] [24] [31] [57] [58] [59] [62] [68] [78] [80] [81] [83] [85] [87] [89] [92] [99] [101] [106] [107] [109] [110] [111] [112] [115] [122] [123] [127] [128] [129] [130] [131] [132]	[14] [15] [19] [62] [89] [106] [110] [112] [122] [123] [127] [128] [129] [130]	[9] [15] [39] [59] [62] [67] [80] [85] [87] [89] [101] [106] [107] [109] [115] [122] [123] [129]	[68] [85]
B	double point angle twist drill	[17] [35] [72] [79] [82] [87] [91] [97] [98] [104] [114] [115] [117]	[17] [72] [91] [97] [104] [114] [117]	[9] [17] [79] [82] [87] [114] [115] [117]	[98][104]
C	brad & spur drill	[21] [57] [59] [111] [113] [129]	[113] [129]	[9] [59] [129]	
D	dagger drill	[15] [21] [33] [86] [101] [107] [111] [113]	[15] [86] [93] [113]	[15] [93] [101] [107]	
E	step drill	[19] [20] [62] [80] [100] [111] [112] [113] [133]	[19] [62] [112] [113] [133]	[62] [80] [105]	
F	core drill	[92] [134]			
G	special core drill	[77] [118] [135]			

Brad & spur drills (**Fig. 6 (c)**) show excellent performance results as far as the delamination of fibre reinforced materials is concerned. According to Su et al. [21], this is due to the cut-push effect (the drill first cuts the last layer of the composite, then pushes this layer off) of sharp flank cutting edges. As the results of this effect, the number of uncut fibres as well as delamination can be minimised. However, the number of studies on the cutting ability of brad & spur drills is limited, as can be seen in **Tables 1** and **2.** Therefore, further investigations are required to analyse thermal effects, tool wear and the characteristics of uncut fibres when using coated or uncoated brad & spur drills.

Next, the dagger drill (one-shot drill) (**Fig. 6 (d)**) is a special double point angle drill with four straight flutes. The small point angle of the secondary edges reams the final surface of the hole. In the case of these drills, the axial force is low compared to that of other drills, therefore dagger drills show good results concerning push-out delaminations and uncut fibres situated at the exit of the holes. Even so, entrance burrs are easily generated anyway. The cutting ability of such drills was investigated by many researchers, as can be seen in **Tables 1** and **2**; however, the number of studies on cutting temperature and on the machined microstructure is limited. A solid carbide dagger drill can be a good choice when the quality of the hole is significant, but operation time will be longer due to the increased length of the applied tool. Furthermore, to drill holes of large diameters with the help of the dagger drill is often impossible, because such an operation would require too long reaming cutting edges, therefore the cutting tool would also be too long.

Step drills (**Fig. 6 (e)**) are designed on the basis of a step-control scheme: first, a pilot hole is drilled using a smaller diameter drill, then the final surface is reamed by applying a wider diameter tool. In the scope of this process, the goal of the first step is to create a pilot hole quickly and efficiently, whereas the goal of the second step is to ream the final surface of the hole causing minimal geometrical damage. The latter goal is feasible partly due to the low critical thrust force of the second drilling stage, according to Tsao and Hocheng [136]. With the application of step drills, the effect of chisel edge can be minimised on delamination, and, in addition, different diameter holes can be drilled using one single step drill. The step drill is a good choice for minimising both entry and exit delaminations; however, the ratio of the diameters of the first and second drilling steps and process parameters have to be optimised in order to reach high-performance drilling. As can be seen in **Tables 1 and 2**, cutting tool related optimisation parameters were analysed by many researchers, but the number of studies focusing on cutting temperature, uncut fibres and the microstructure of drilled holes is limited.

Table 2 Analyses of material damage related phenomena: a review of different drilling tools applied by researchers for drilling CFRPs

Tool category in Figure 6	Type of drilling tool	Analysed optimisation parameters		
		Delamination	Uncut fibres	Microstructure
A	conventional twist drill	[9] [14] [15] [20] [24] [26] [31] [32] [56] [57] [58] [62] [63] [67] [72] [73] [78] [80] [81] [88] [110] [111] [112] [123] [128] [129] [132] [137]	[14] [15] [20] [23] [35] [39] [69] [75] [85] [87] [88] [89]	[15] [19] [20] [24] [68] [89] [92] [111] [129] [131]
B	double point angle twist drill	[17] [35] [69] [79] [82] [91] [114] [117]	[129]	[35] [69] [82] [91] [98] [104]
C	brad & spur drill	[9] [21] [57] [63] [88] [111] [113] [129]	[88] [129]	[111] [129]
D	dagger drill	[15] [21] [33] [63] [86] [88] [111] [113]	[15] [86] [88]	[15] [93] [111]
E	step drill	[20] [62] [80] [111] [112] [113] [133]	[20]	[19] [20] [111]
F	core drill	[30]		[92]
G	special core drill	[74] [77] [118]		

A core drill is a hollow grinding drill, as can be seen in **Fig. 6 (f)**. It immediately machines the final surface of the hole by abrasive cutting, for which operation usually diamond grains are used. Due to the resulting small chip section during drilling, the thrust force is minimal, and consequently entry and exit delaminations are also minimal. Even so, chip removal is difficult, as chips cannot be removed so easily as with the help of helical flute drills. To overcome this problem, special core drills (**Fig. 6 (g)**) were developed including (i) core-twist drills, (ii) core-saw drills, (iii) core-candlestick drills, (iv) step-core-twist drills, (v) step-core-saw drills and (vi) step-core-candlestick drills, as introduced by Tsao and Chiu [77]. The main problem of special core drills is the kinematic constraint of the inner and the outer drills. As a solution, Tsao and Chiu [77] developed a novel experimental environment to combat the problem of relative motion and chip removal between the inner and outer drills. As can be seen in **Tables 1** and **2**, the number of studies featuring analyses of the cutting ability of core drills and special-core drills is limited.

In fact, most of the above-listed tools can be purchased from tool producers. Yet, for the purpose of reducing drilling-induced geometrical defects, some novel geometries have been developed recently. For example, Su et al. [21] have developed a novel drill bit based on the advantages offered by dagger and by brad & spur drills; Jia et al. [12] have developed a novel drilling tool geometry (based on the dagger drill) in order to decrease the number of uncut fibres at the exit of the drilled holes when machining CFRP composites. The grooves on this newly-developed cutting tool perform upward cutting at the exit of the hole, and thus the last layers of the composite are supported by the material itself, and therefore the cutting edge causes no bending. With a view to this, Tsao and Huang [138] used a hemispherical drill for machining CFRPs.

Tool materials and coatings have a significant effect on tool wear, thus on the micro- and macrostructure of machined holes. As discussed before, the most common wear mechanisms are edge chipping and abrasion, and the primary type of tool wear is edge rounding. Increased cutting edges increase the bending effect of the tool on fibres, therefore the machined surface can be rough and can exhibit a lot of uncut fibres. Concerning the machinability of CFRPs, the impact of the material of the tool (HSS, K10, solid carbide, etc.) and the effects of coatings (AlTiN, diamond, etc.) were analysed by many researchers, and there seems to be an agreement that diamond coating is the most effective solution to combat wear resistance [87, 106]. On the other hand, uncoated carbide drills can produce better quality holes as long as their cutting edge radius is smaller than that of diamond coated edges.

3.3 Advanced hole machining technologies for CFRPs

In addition to the application of special drilling tool geometries with conventional tool paths, special technologies can also be applied for machining high-quality holes in CFRPs. On the one hand, end mills with advanced cutting tool paths can be used including the following processes: conventional helical milling (orbital drilling) [28, 35, 139–148], tilted helical milling [149–151] or wobble milling [37, 152]. On the other hand, non-mechanical machining technologies can also be efficiently applied: these include electrical discharge machining (even for the purpose of deburring) [153–155], laser cutting [156–158] and water jet cutting [159–161] technologies.

Voss et al. [28] compared conventional drilling (**Fig. 7 (a)**) and helical milling (**Fig. 7 (b)**) strategies in order to identify potential differences in tool wear, bore diameter variances and cycle times. They as well as Geier and Szalay [35] could machine better quality holes in CFRPs (with fewer uncut fibres and less delamination) using orbital drilling as compared to the quality of holes achieved by using the conventional drilling strategy. However, the machining time of orbital drilling is about 2-4 times longer than the process time of conventional drilling. Schulze et al. [152] compared conventional drilling, helical and wobble milling (**Fig. 7 (c)**) strategies and concluded that five-axial wobble milling produces less damage to machined holes than helical milling, and they also realised that helical milling could produce better quality holes than conventional drilling. They stated that the industrial implementation of wobble milling is difficult. Even so, there are some industrial environments (e.g. aerospace) where industrial robots do manufacture holes, and it is also true that the implementation of the five-axis wobble milling tool path does not cause too high additional machine tool costs.

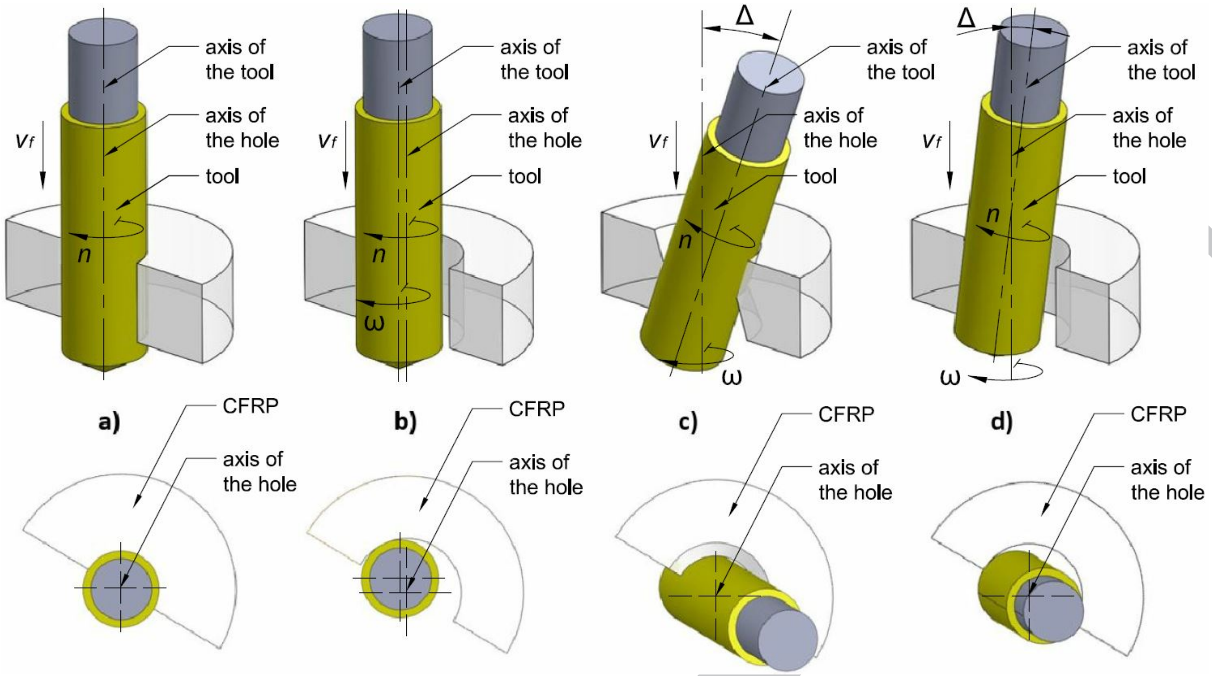


Fig. 7 Schematic drawings of mechanical drilling technologies: **(a)** conventional drilling, **(b)** conventional helical milling (orbital drilling), **(c)** wobble milling and **(d)** tilted helical milling. In the figure, v_f is the feed rate, *n* is the spindle speed and ω is the wobbling speed

The kinematics of conventional helical milling and tilted helical milling (**Fig. 7 (d)**) was analysed by Wang et al. [149]. They showed that effective cutting speed can be zero in the case of conventional helical milling, and also stated that, in the case of tilted helical milling with proper technological parameters, a scenario where effective cutting speed is zero can be avoided. Furthermore, tilted helical milling offers better hole quality and chip removal than conventional helical milling. Wang et al. [36] analysed the influence of pre-drilled pilot holes on thrust force and torque. The researchers could decrease thrust force by applying pre-drilled pilot holes. On the other hand, in the scope of their research, process time and the characteristics of uncut fibres and delamination were not analysed.

Material removal rate (MRR given in cm^3/min) can easily be calculated with respect to conventional drilling and helical milling processes. Nonetheless, the calculation of the same rate for tilted helical milling processes is more difficult, but MRR is constant during these machining processes. However, MRR is not constant during wobble milling due to the complex kinematics of the process, therefore the above-listed technologies could only be compared by using a uniform measure called average material removal rate (AMRR). As attested by previous studies and based on the experiences of the authors, AMRR of conventional drilling is the highest, followed by helical milling, tilted helical milling and wobble milling, respectively (in the case of fixed process parameters).

Even when applying special drilling tools or advanced hole-making technologies, process parameters of CFRP machining have to be optimised in order to develop the quality of holes as well as to improve the efficiency and performance of the process. Researchers optimised process parameters of CFRP drilling by applying (i) response surface methodology [23, 26, 32, 35, 84, 91, 108, 110, 112, 124, 162], (ii) fuzzy logic [163–165], (iii) artificial neural networks [135, 139, 140], (iv) mechanistic models [80, 97, 130, 166], (v) numerical models [72, 80, 112, 167] and (vi) combinations of some of the above methods [128]. For example, Geier and Szalay [35] used multiple optimisation for setting CFRP conventional and orbital drilling process parameters (feed rate, cutting speed and screw pitch of the feeding helix), and applied response surface methodology in order to minimise delamination, surface roughness and thrust force. Abhishek et al. [128] developed a PCA-fuzzy-Taguchi based integrated optimisation method for efficiently minimising (entry and exit) delamination, torque and thrust force when drilling CFRPs.

All in all, the application of the above-discussed technologies offers many advantages. Nevertheless, there is a serious disadvantage to the application of special tool geometries or advanced tool paths when machining CFRPs: more difficult geometries and more difficult tool paths increase the number of factors to be analysed. For example, in the case of using conventional twist drills with conventional tool paths, there are only a few factors that have to be analysed: these include feed rate in the direction of the axis of the hole, cutting speed, the point angle of the cutting tool, the size of chisel edge, etc. However, when helical end mills with helical milling tool paths are used, several additional significant factors have to be analysed, such as the screw pitch of the feeding helix and the feed rate in the direction of the tool path. Additionally, it is also to be considered that the application of advanced cutting tool paths usually increases operation time.

3.4 Future trends in advanced hole machining of CFRPs

Changing industrial environments and environmental protection related political initiatives (EU-level laws, directives, other regulations) prompt researchers to (i) decrease operation times and costs, (ii) to increase the efficiency of manufacturing processes, (iii) to increase sustainability and eco-friendliness and (iv) to develop more flexible and smart processes. For example, thousands of holes have to be drilled in CFRP panels of aeroplanes, therefore drilling efficiency and performance have to be maximised, while the operation time of drilling has to be minimised. In order to meet dimensional requirements (micro- and macrostructures) and, at the same time, to optimise the drilling process (performance, operation time, etc.), advanced drilling technologies have to be developed. A good solution to this is to increase the feed rate, but a higher feed rate causes higher geometrical defects in CFRPs if currently available technologies are used.

Ultrasonic assisted machining (UAM) [168–172] is becoming more popular for drilling CFRPs due to good results associated with this technology with respect to the minimisation of geometrical defects in CFRPs. In light of this interest, most of the current studies deal with the analysis of process parameters of UAM as far as characteristics of machined surfaces and delamination are concerned. During UAM the properties of vibration (frequency, amplitude, etc.) are generated and controlled by researchers; however, there are many other vibrations during machining that should be analysed in the future in more detail. For example, with a proper design of the material and dimensions of back-up support plates, plate-induced vibrations could help minimising drilling induced defects in CFRPs.

On the other hand, sustainable machining is getting more and more attention and importance in order to protect the natural environment. The main goals associated with sustainable drilling are to minimize consumption of cutting fluids and energy [173, 174]. Furthermore, recycling of cutting tools and chips [175, 176] has to be investigated more extensively in order to decrease harmful impacts on the environment. As an alternative, dry cutting (machining without cooling) can be used in the machining of CFRPs, as was discussed before; however, the resulting carbon chips cause many problems to human health and also to the machine tool due to the small size and abrasive wear effect of such chips.

Another alternative, intelligent drilling is characterized by high accuracy and efficiency [177]. Process monitoring and diagnostics as well as the optimisation of process parameters of drilling operations are to be urgently developed if this type of drilling is envisaged to be used in mass production. Smart CNC programs with decision-making algorithms and special tool paths can also be effectively applied in the industry, but these solutions still need a lot of development and design, which scenario results in additional costs and increased operation times. Many researchers suggested the measurement of cutting force when drilling CFRPs in order to monitor the drilling process (by indirectly predicting tool wear, delamination and surface characteristics). However, cutting force measurement entails many difficulties (investment in instrument and equipment, decreases in the machining area, difficulties in the fixturing of the workpiece, etc.), therefore the application of force measurement is limited in the industry. In that situation, monitoring the characteristics of uncut fibres using digital image processing can be a future trend, because this requires less investment, takes up less space from the cutting area, and this method is capable of providing a good quality evaluation of the macrostructure of drilled holes in a direct way [75].

4. Conclusions

In the present paper, current studies dealing with the machinability analysis of carbon fibre reinforced polymer (CFRP) composites were reviewed with particular attention to drilling tools and technologies. Based on the present review, the following conclusions can be drawn:

- The most frequent feature-related geometrical damages in CFRPs are: delamination, fibre pull-out and uncut fibres, micro-cracking, inappropriate surface roughness and matrix burning. These damages can mainly be influenced by the geometry of cutting tools and process parameters (especially feed rate). Less extensive impact is exerted by special tool paths, by the application of back-up support plates and by the application of cooling.

- FRP machining technology should be designed to accommodate a range of fibre-cutting angles of $0° < \theta < 90°$ in order to decrease the number of uncut fibres and to increase the quality of the machined surface. The rake angle of the cutting tool should be as positive as possible to increase the thrust-fracture effect rather than the compressive-bending effect on the fibres. Furthermore, cutting edge radius should be as small as possible to avoid scenarios exhibiting the bending-dominated fibre fracture mode.

- The special requirements concerning drilling tools to be used with CFRPs are the follows: (i) laminated layers of the CFRP cannot be delaminated by the cutting tool. (ii) The cutting edge has to cut the fibres and also the matrix material properly. (iii) The cutting edge must have good wear resistance against carbon fibre reinforcements. (iv) The helix angle of drilling tools should be as small as possible in order to minimise the appearance of uncut fibres on the entry and exit edges of the holes. (v) It is necessary to minimise the mechanical contact impacted area during machining CFRPs.

- The most common drilling tools for CFRPs are the following: (i) the conventional twist drill, (ii) the double point angle twist drill, (iii) the brad & spur drill, (iv) the dagger drill (one-shot drill), (v) the step drill, (vi) the core drill and (vii) the special core drill. It was found that diamond coated double point angle twist drills can be used effectively in drilling CFRPs. In addition, dagger drills are a good solution for drilling small diameter holes, while brad & spur drills are good for minimising defects at the exit of the holes in CFRPs.

- Advanced machining technologies, like conventional helical milling (orbital drilling), tilted helical milling and wobble milling can be applied in order to effectively minimise geometrical defects and tool wear. However, the application of these advanced technologies necessitates additional design and optimisation, which results in increased operation times and costs.

- In the future, more attention is likely to be paid to the analysis and optimisation of ultrasonic assisted, sustainable and intelligent drilling of CFRPs. This solution is envisaged to result in decreased operation times as well as in increased reliability and efficiently.

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