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Review Article

A review on CFRP drilling: fundamental mechanisms, damage issues, and approaches toward high-quality drilling

Jinyang Xu [a,*], *Norbert Geier* [b], *Jiaxin Shen* [a], *Vijayan Krishnaraj* [c], *S. Samsudeensadham* [d]

[a] *State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China*
[b] *Department of Manufacturing Science and Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Budapest 1111, Hungary*
[c] *Department of Production Engineering, PSG College of Technology, Coimbatore 641004, India*
[d] *Department of Mechanical Engineering, PSG College of Technology, Coimbatore 641004, India*

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) composites have become increasingly attractive in modern industrial fields in view of their unique properties and superior functionalities. CFRP composites are extremely tough to drill due to their inherent anisotropy and heterogeneity. The present paper aims to report the state-of-the-art progress in the mechanical drilling of CFRP composites through a rigorous literature survey. It covers the crucial aspects of drilling CFRP laminates, including drilling mechanisms, thermo-mechanical responses, drilling-induced damages, and the effects of various process conditions. The fundamental chip removal and damage formation modes of CFRPs are discussed. Results indicate that high cutting speeds and low feed rates improve the hole quality of CFRPs. Optimizing process parameters, developing suitable tool geometries/materials, and applying proper cutting environments will be an effective means to suppress the drilling damage of cut CFRP holes. More future research endeavors are expected to focus on revealing the mapping mechanisms between tool geometries/materials, cutting environments, process parameters, and CFRP hole-making quality and on proposing a comprehensively optimized hole-making strategy for high-quality drilling of CFRPs.

* Corresponding author.
E-mail address: xujinyang@sjtu.edu.cn (J. Xu).
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1. Introduction

Carbon fiber reinforced polymer (CFRP) represents one type of high-performance composite that has been proved to be a flexible and adaptable engineering material for various engineering applications. This is attributed to its superior mechanical and physical properties, including high specific strength, high specific stiffness, excellent thermal stability, and superior corrosion resistance [1–4]. The CFRP materials are featured by the impregnation of reinforcing carbon fibers with a polymer matrix, yielding superior performances unmatched by individual constituents. Owing to their outstanding advantages, they have been a promising alternative to conventional metallic materials in a wide range of industries, including aerospace, automobile, and defense, which require structural materials with unique properties such as high strength-to-weight and stiffness-to-weight ratios [1,5].

Although CFRPs are often fabricated to near-net shapes by various molding processes, secondary manufacturing operations are still essential to ensure their final product shapes [1–3,6]. In particular, CFRP components are often used in conjunction with other engineering materials by mechanical assembly [7]. Bolt joining and rivet connections are two representative assembly methods depending critically on the quality of machined composite holes. Mechanical drilling has become the most important machining operation to shape the fibrous composites into desired quality and target dimensions for joining purposes [4,8]. Various drilling operations have been applied to make high-quality holes for assembling CFRP laminates. However, these composites exhibit rather poor machinability, which are much tougher to drill than conventional homogeneous materials due to their inherent anisotropy and heterogeneity. The chip removal mechanisms of CFRPs differ significantly from conventional metallic alloys as their two constituents show completely different behaviors. The chip removal of CFRPs depends considerably on the variations of the fiber layup, which makes it rather challenging to control the material separation during the rotary drilling operation as the tool edges periodically cut fibers and polymers following a spiral motion. Additionally, one of the most critical issues associated with drilling CFRPs arises from severe damage induced by chip separation. Since the removal mechanisms of fibers and polymers are totally different and change continuously with the fiber layup, crucial defects involving delamination, burrs, tearing, surface cavities, and glass transition failure are easy to occur, which significantly deteriorates the quality of machined CFRP parts [4]. The aforementioned damages not only drastically reduce the surface finish and assembly tolerance but also degrade the fatigue strength of cut holes, leading to a large proportion of part rejections [6,9–11]. Consequently, drilling CFRPs poses significant challenges to the modern manufacturing community, and numerous efforts have been made to improve their machinability.

To increase the drilling efficiency of CFRPs with desired quality, understanding their drilling mechanisms and behaviors is of utmost importance for the manufacturing community. To date, great endeavors have been made by worldwide scholars to realize the damage-free drilling of CFRPs, covering a variety of essential aspects, including drilling mechanisms, cutting forces, machining temperatures, and hole quality attributes. Moreover, some potential approaches to achieving high-quality drilling of CFRPs have been developed and yielded excellent results for composite machining. Although there are some recent reviews available in the literature to address the drilling progress of CFRPs [12–15], the current research field is still keeping moving, and there is a critical need to summarize the state-of-the-art advances achieved in the field. Additionally, a comprehensive review covering the critical drilling mechanisms and quality issues of CFRPs is still lacking in the open literature. Based on these incentives, the present review aims to report the up-to-date progress in the drilling mechanism and quality studies of CFRP composites through a comprehensive literature survey. In the review, various crucial aspects in drilling CFRP laminates are discussed, including drilling mechanisms, thermo-mechanical responses, drilling-induced damages, and the effects of various process conditions. An emphasis is placed on the discussions of the fundamental chip removal and damage formation modes of CFRP composites. The current review is an extension of the authors' previously published article [4], and its specific points of innovation lie in reviewing the fundamental drilling mechanisms, introducing the drilling force/temperature features, summarizing the process optimization techniques, and overviewing the advanced drilling techniques for CFRP composites. It is hoped that the current work can offer researchers an in-depth understanding of the fundamental drilling characteristics of CFRPs toward high-quality machining.

The logical structure of the review paper is organized as follows. Section 1 provides a brief overview of the fundamental industrial background and research status in drilling CFRP composites. Section 2 elaborates the drilling mechanisms and thermo-mechanical responses of CFRPs following a rigorous literature survey to highlight the key findings achieved in drilling CFRP composites. Then, Section 3 reviews the key characteristics and formation mechanisms of drilling-induced damages in terms of delamination, burrs, tearing and surface cavities, and highlights the critical quality issues faced by the composites manufacturing community. Afterward, Section 4 summarizes the effects of different process conditions on the quality issues of CFRPs through a critical literature survey. The impacts of drilling parameters, cutting tools, and cutting environments on CFRP drilling outputs are carefully addressed. Additionally, Section 5 provides solutions and approaches to solve the quality issues associated with CFRP drilling. Finally, Section 6 draws the key conclusions of the review article and points out the future research perspectives.

2. Drilling mechanisms and thermo-mechanical responses

Although many nontraditional machining operations, such as laser cutting and water-jet machining, have been invented for hole-making of composite materials, mechanical drilling is still considered the most preferred manufacturing technique

Fig. 1 – Photographs showing various drilling-induced damages of CFRP composites [3,16].

for CFRP composites in terms of low costs and high efficiency. The key characteristics of CFRP composites include anisotropy and heterogeneity, making the machining process more challenging compared with other metal cutting processes. Typical defects, such as delamination, fiber frying, spalling, chipping and fuzzing, frequently occur during the machining of CFRPs (Fig. 1 [3,16]) since CFRP is heat insulating and abrasive in nature. Especially, defects such as delamination will influence the accuracy and quality of holes, leading to eventual part rejections during the assembly stage. This failure will ultimately reduce the strength and fatigue life of components, and thus developing high-precision drilling processes and carrying out drilling optimization have been the current research focus [17]. Variables such as machining temperature and cutting force are key operating factors that require optimization to produce a high-quality hole [7]. In the following subsections, the impacts of drilling forces and cutting temperatures in terms of thermo-mechanical aspects are discussed in detail.

2.1. *Drilling mechanisms*

CFRP composites are one of the most popular engineering materials in industrial fields due to their superior properties. They are often constituted by carbon fibers that are strong enough to reinforce the stiffness and strength of the material base and by polymer matrix that distributes the load among fibers and protects fibers from environmental attack. Composite damage tolerance is mainly affected by the direction of fibers because the fibers are more robust along their axial direction. Typical unidirectional (UD) CFRPs have the maximum strength along the direction of the fiber compared with the direction perpendicular to the fiber. Continuous fiber reinforcement is typically utilized in UD or woven configurations to form a thin plate known as a prepreg ply [1]. Proper ply orientation selection is critical for CFRPs to achieve optimum mechanical characteristics for an effective structural design. Therefore, the UD plies require cross-layer in which fiber bundles are aligned at different orientations to form quasi-isotropic laminates [18]. The quasi-isotropic laminates are often made when the orientations of the plies are balanced so that the extensional stiffness of the laminate is the same in each in-plane direction. Typically, quasi-isotropic sheets are created using fiber weaves with layers oriented at 0º, 90º, +45º, and −45º, with at least 12.5% of the layers in each of these four directions. The layers should require 0° plies to respond to axial loads, ±45° plies to react to shear loads, and 90° plies to react to side loads [19]. This sequence simplifies the design of the most fastened joint. On the other hand, fiber orientation also influences the surface of the holes. According to Abrão et al. [20], the worst scenario occurs as the fiber orientation increases from 45° to 135° because of surface irregularities. It is possible to state that the quality of holes can be improved within the range of 0°–90° for the fiber orientation.

As discussed above, the machinability of CFRPs is extremely poor due to the two completely different phases involved [21]. Also, a reliable cutting tool is required to overcome the challenging environments caused by thermal resistance and related wear. Therefore, among all the machining operations, conventional drilling is the most-used method for hole making of composite materials [22]. During the drilling process, the material is removed by a series of fractures of diverse nature and uneven load sharing between the fiber and matrix [23]. The tool edge makes contact with several layers of differently orientated carbon fibers, which causes a dynamic change in the fiber cutting angle, and hence the chip removal modes. Four types of cutting mechanisms are identified: (i) the buckling-dominated mode for the parallel fiber cutting relation; (ii) the shear-dominated mode for the along fiber cutting relation; (iii) the crushing-dominated mode for the vertical fiber cutting relation; and (iv) the bending-dominated mode for the against fiber cutting relation [24–26]. According to Voss et al. [27], the tool-workpiece interaction during the UD-CFRP machining process can be divided into three contact regions, as shown in Fig. 2. In their analytical force model, micro-region 1 refers to the zone that makes the initial mechanical contact with the composite material, and it is in charge of separating composites through the tool rake face. Micro-region 2 refers to the tool tip zone and accounts for the size effects in machining. Micro-region 3 refers to the zone on the tool flank surface that makes mechanical contact with the cut composite surface. Several

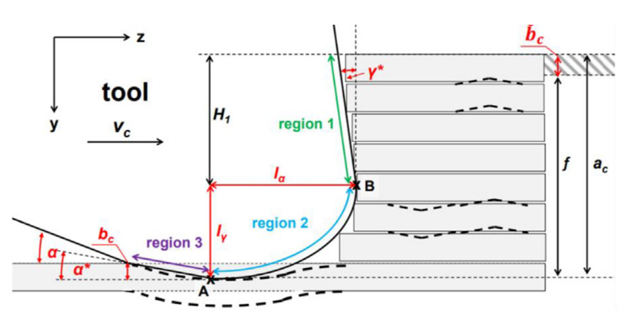


Fig. 2 – Schematic representation of the contact conditions in machining CFRPs [27].

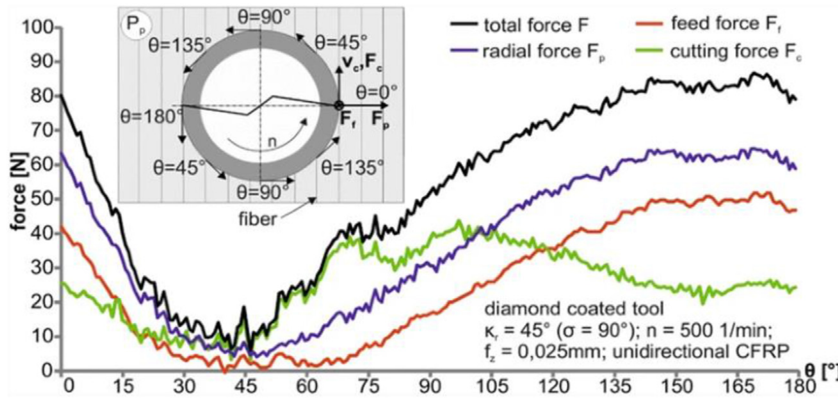


Fig. 3 – The influence of the fiber cutting angle on various drilling force components [34].

parameters need to be taken extra controls, such as feed rate and cutting speed, during the operating stage. Most drilling-induced damages depend strongly on the feed rate [28–30]. Damage-free holes can be achieved in composites by applying a low feed rate and a high speed with a suitable tool geometry [31]. In contrast, low cutting speeds and low feed rates help to minimize tool wear [14]. The influences of key factors are discussed in detail in Section 4. According to Singh et al. [7], drilling dynamics can be captured using mathematical models such as empirical, neural/fuzzy, and classical models.

2.2. Drilling forces

Drilling force plays a vital role in damage occurrence, surface deterioration, and wear progression when drilling CFRPs. It is necessary to analyze its features, which can be decomposed into thrust force (i.e., the axial component of the cutting force) and torque. The drilling force will influence the quality of cut holes, which leads to a further impact on the cutting performance of CFRPs. The polymer matrix is soft and ductile, whereas the fibers are brittle and robust, which will respond to the machining process oppositely and thus influence the cutting force [32–34]. Hintze et al. [34] examined the total cutting force when using an uncoated twist drill to cut UD-CFRPs. The authors concluded that the fiber cutting angle substantially impacts the components of radial force, feed force, and cutting force, as illustrated in Fig. 3. In particular, analyzing the cutting forces in parallel and perpendicular to the fiber direction shows that the respective components are of a similar amount in a cutting angle range between 20° and 90°. In contrast, the force perpendicular to the fiber predominates in the other cutting angle range. The authors also indicated how more tool wear results in larger cutting force components. Furthermore, the most significant statistical and physical influence on cutting forces is exerted by the feed rate, as stated by Davim and Reis [35] and other researchers [36–39]. Specifically, a higher feed rate contributes to the thrust force by the increased chip thickness, which causes machining-induced delamination at the hole entrance and exit sides of CFRP laminates. A high feed rate will lead to a high thrust force. In contrast, a low feed rate will result in a high flank surface temperature. Meanwhile, correlations between factors such as feed rate and delamination extent are obtained by multiple linear regression. It is indicated that the feed rate directly influences the push-down delamination and hole diameter, but unusually it has no apparent effects on the peel-up delamination.

According to Xu et al. [31], high-speed drilling could reduce thrust force and geometrical flaws for CFRPs. Based on their study, the thrust force tends to decrease due to the softening effect of high cutting temperatures on the composite matrix when the spindle speed increases. Due to the increased spindle speed, a large amount of cutting heat will be generated during the drilling operation, resulting in highly-localized temperatures at the cutting zone and the softening of the corresponding work material. Therefore, the drilling process will encounter less force resistance, thus lowering the cutting force, as illustrated in Fig. 4(a). Additionally, the cutting speed often has an overstated or negligible effect on thrust force [40]. Besides, drill bit geometry also dramatically impacts the thrust force. It was discovered that the point angle of the twist drill has an evident impact on the thrust force such that an increased point angle leads to an elevated thrust force. Abrão et al. [20] and Durão et al. [41] conducted experiments to obtain lower thrust force and found that lower thrust forces could be obtained using brad drills and step drills rather than the standard twist drills. Tsao and Chiu [42] employed core-special tools for drilling of CFRPs, as shown in Fig. 4(b). They found that the inner drill type, which has the most negligible impact on thrust force, is followed by the feed rate and the cutting velocity ratio. Furthermore, the compound core-special drills that contain a driven device are more advantageous than the core drills and conventional compound core-special drills in terms of lower thrust force, less delamination, less chip clogging, and higher chip removal. According to An et al. [43], the cutting forces in machining CFRP laminates tend to decrease with the elevation of the cutting speed, as shown in Fig. 4(c). In addition, an increased cutting speed seems to minimize the radial thrust force to a certain extent. Considering that high cutting speed would make the composite separation more efficiently, the high cutting temperature induced by the high-speed cutting would also soften the

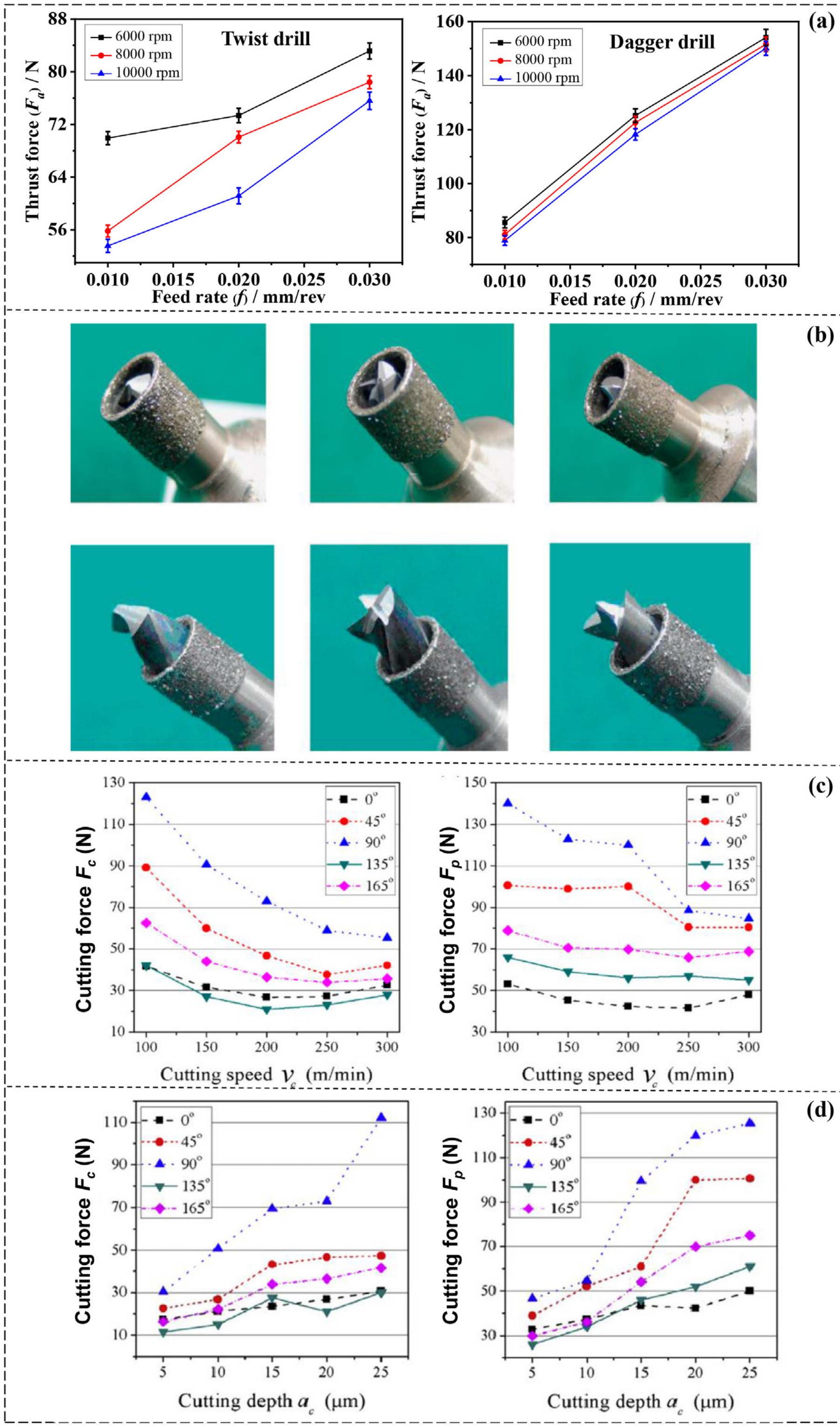


Fig. 4 – (a) Thrust force as a function of the feed rate for twist drills and dagger drills [31]; (b) photographs of various types of the compound core-special drills [42]; (c) the effects of the cutting speed on cutting forces in the horizontal direction (F_c) and the vertical direction (F_p) [43]; (d) the effects of the cutting depth on cutting forces in the horizontal direction (F_c) and the vertical direction (F_p) [43].

matrix base, which helps to weaken the anisotropy of CFRPs. The main cutting force will elevate with increasing the cutting depth as it is directly related to the growth in the volume of cutting material, as illustrated in Fig. 4(d). Therefore, the use of high cutting speed and low cutting depth may benefit the machinability improvement of CFRPs. Table 1 also summarizes the influences of various process parameters on the drilling forces of CFRP laminates.

Additionally, micro holes are commonly used in the latest industry, such as fuel injection nozzles, filters, and printed circuit boards [8]. The most common process applied is mechanical micro-drilling operation due to its large productivity. The process is a micro-scale of the conventional drilling operation to produce micro holes. During mechanical micro-drilling, the chip thickness relative to the cutting edge radius is small [45]. Therefore, plowing will dominate the chip removal process [46]. The downscaling of conventional drilling to micro-drilling presents numerous challenges, including drill size and inhomogeneity effects of composites. Moreover, the size effect is defined as the non-linear increase in specific cutting force with decreasing the chip thickness. Low feed rates are used because the thin and fragile micro-drills frequently break due to larger cutting forces induced by higher feed rates and accelerated tool wear [47,48]. However, low feed rates result in a small uncut chip thickness close to the minimum chip thickness, causing plowing and elastic recovery rather than shearing materials. This phenomenon is known as the minimum chip thickness effect, causing a rise in cutting forces and surface roughness. Moreover, Anand et al. [44] studied the size effects on cutting forces in micro-drilling of CFRP composites. It was found that the size effect was significant when the ratio of undeformed chip thickness to the cutting edge radius was less than unity and non-linear increase of specific cutting force was obtained for the further decrease of the uncut chip thickness. The study also demonstrated that the specific cutting force was influenced by the layered structure of the composite because the cutting tool encountered both carbon fibers and the resin matrix simultaneously.

2.3. *Cutting temperatures*

Thermal behavior is another essential aspect in composites cutting process. The base material of CFRP composites is often made of epoxy resin, phenolic resin, or other polymer materials with low strength but superior durability. The polymer matrix in CFRPs serves the purposes of holding the fibers together, distributing the load, and protecting the fibers from environmental corrosion and wear. However, the polymer matrix has moderate heat resistance, indicating that when the working temperature exceeds a certain threshold, the hard glass state will be transformed into a flexible and highly elastic state, and the physical properties tend to deteriorate sharply [49]. The polymer used in the matrix undergoes chemical degradation with an increased temperature, which takes place directly before the glass transition temperature (T_g). The matrix may be softened at excessive temperatures and thermally decomposed at higher degrees when the CFRP is exposed to temperatures greater than the T_g, resulting in composite failures. Accoding to Xu et al. [50], the dominant

Table 1 – Summary of various process parameters on the drilling forces of CFRP laminates.

Ref.	Workpiece materials	Parameters addressed	Key conclusions
Hintze et al. [34]	UD-CFRP made by IM fibers and a thermosetting matrix	Fiber cutting angle	Fiber cutting angle has a significant impact on cutting force, feed force, and radial force components.
Davim and Reis [35]	CFRP made by epoxy matrix reinforced by carbon fibers	Feed rate	Feed rate is the most crucial cutting parameter that has the most significant physical and statistical influence on the cutting force.
Xu et al. [36]	T800S/250F CFRP	Cutting speed	High-speed drilling reduces the thrust force and geometrical flaws.
Eneyew and Ramulu [37]	UD-CFRP	Feed rate	Thrust force is more influenced by the feed rate than by the cutting speed.
Karpat and Bahtiyar [38]	UD-CFRP	Drill geometry	Thrust force varies as a function of drill geometry relative to the drilling temperature distribution.
Wang et al. [39]	T800/X850 CFRP	Feed rate	Thrust force is nearly proportional to the feed rate for CFRPs.
Geier and Szalay [40]	UD-CFRP	Cutting speed	Cutting speed often has an overstated or negligible effect on the thrust force.
Anand et al. [44]	CFRP with 53.5–54.7% fibers and 46.5–45.3% epoxy resin	Layer structure of composite	Specific cutting forces are influenced by the layered structure of the composite material.
Tsao and Chiu [42]	CFRP with woven WFC200 fabric carbon fibers	Cutting velocity ratio and low rate	A high negative cutting velocity ratio and low feed rate are recommended to produce low thrust forces in drilling CFRP composites.
An et al. [43]	T800/X850 CFRP	Cutting depth	The specific cutting force decreases with the cutting depth.

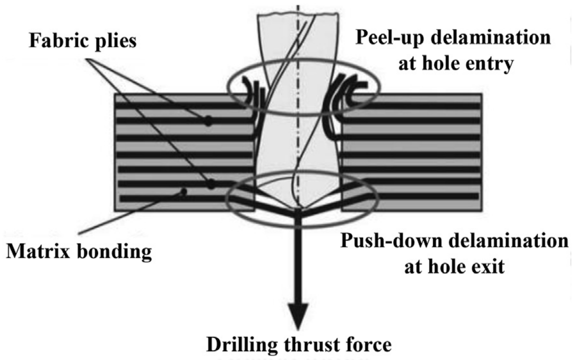


Fig. 5 – Classification of delamination modes in drilling composite laminates [48].

source of heat generation when drilling CFRP composites is the friction taking place at the tool-work interaction zone. To reduce the temperature of the flank tool-work surface, low cutting speeds and high feed rates should be adopted [50,51]. Given more details by Juon et al. [52], the impacts of increasing the temperature can be described in terms of color texture on the laminate surface. This is one of the visual tools used to identify the possible thermal damage, and five color groupings could be observed, including original, brown, red, dark, and charred colors. Meanwhile, the increased temperature tends to degrade the compressive strength of the epoxy, which exposes the composite to thermal loading and thus causes changes in the form of chemical reactions such as oxidation, pyrolysis, and outgassing as the polymer matrix could undergo physical effects such as charring, cracking and delamination. Although the carbon fiber has a higher oxidative resistance, Yang et al. [53] indicated that the weight of CFRP residue decreases with increasing the temperature and oxygen concentration. Zöllner et al. [54] also stated that extreme temperatures or long-term duration of heating could cause fiber damage or even the reduction of fiber diameter.

Foreman et al. [55] examined the thermal properties of epoxy resin and found that the elastic modulus of the material could be predicted at various temperatures. Their results reveal that increasing the temperature boosts the thermal energy, which prevents the system from structural integrity, and hence the modulus is low. The authors also emphasized that the elastic modulus sharply diminishes when the T_g is reached. Compression, tensile, and shear experiments were performed by Plecnik et al. [56] to evaluate the strength of epoxy resin at high temperatures. The T_g was shown to generate a considerable reduction in the compressive strength of epoxy. The temperature during the cutting process indirectly affects the behavior of the cutting force because the softer resin matrix impacts the bonding strength between carbon fibers. The force also affects numerous defects that have already been discussed in the literature [57,58]. When cutting CFRP laminates, it is challenging to distinguish the thermal and mechanical damages. Likewise, flaws like burrs and tearing can be caused by the heat produced on the machined surface due to the cutting process. When heated or cured, thermoset polymers can remain rigid and permanently inflexible, while thermoplastic polymers can be recycled and reused because of their linear molecular structure. The thermoplastic matrix is more prone to severe glass transition failure due to its high susceptibility to cutting heat. However, very few studies [59] are reported to compare the machining properties of the two composite matrices in the scientific literature.

Recently, Xu et al. [59] conducted comparative drilling tests on the carbon/epoxy and carbon/polyimide composites to clarify the different thermal behaviors between the thermoset and thermoplastic composites. It was found that both the spindle speed and the feed rate were critical factors influencing the drilling temperatures of the two composite materials as well as the hole quality attributes. Decreasing the spindle speed or increasing the feed rate tends to reduce the specific drilling energy consumption, decrease the machining temperature and produce more consistent hole diameters. Considering the increased feed rate, the contact distance between the drill edges and the composite material decreases. Thus, the rubbing area and the friction time are reduced, which leads to decreased cutting temperatures. Additionally, the carbon/epoxy composites were found to promote much higher temperatures than the carbon/polyimide ones, especially under the identical cutting conditions. Such phenomena are attributed to the disparate thermal behaviors of the thermoset and thermoplastic matrices. However, more future research works are expected to focus on quantifying the effects of various matrices on the drilling temperature characteristics and the temperature-related cutting damages of CFRPs.

3. Drilling-induced damages

Considering the heterogenous nature of the fiber/matrix system, the anisotropy of the thermo-mechanical contact between the CFRP workpiece and the cutting edges can be divided into three different levels, which are: (i) intraformational anisotropy; (ii) interlayer anisotropy; and (iii) fiber anisotropy. The thermo-mechanical effects, such as anisotropic cutting forces and heat distribution, will be generated along with the chip removal process, thus affecting the quality of cut CFRPs. Numerous machining defects, such as delamination [60–63], burrs [64,65], and subsurface damage [66–69], are expected outcomes of the poor machinability of CFRPs. Apart from the mechanical effects, thermal damage is also formed by high cutting temperatures [70], which influences the quality of the material. Recently, worldwide scholars have paid due attention to the adverse effect of borehole damage as it has a detrimental influence on the quality of machined CFRP surfaces. For instance, based on the experiments done by Yazman [71], a ring tensile test was utilized to observe the damage history of the fiber-reinforced polymers, and it was found that using a backup material in the composite pipe drilling contributed to the improvement of the surface quality. Backup materials prevented the spreading of the interlaminar and intralaminar cracks around the hole at higher feed rates. However, as stated by Gemi et al. [72], the severity of the hole wall damages could vary with the tool geometry and feed rate, mainly formed toward the wind direction when drilling pipe-like composite parts.

3.1. *Delamination*

Delamination is one of the most serious damages promoted in the drilling process. It considerably deteriorates the dimensional accuracy, surface quality, structural integrity, and durable applications of finished parts. It occurs when CFRP laminates are exposed to adverse cutting forces, causing the fiber plies to split from one another due to their poor transverse strength and low interfacial fracture toughness. As mentioned by previous studies [73–75], delamination takes place mainly at the top layer through the peeling of the laminae and near the exit side of the laminate when the instantaneous thrust force exceeds the threshold value. Several non-destructive inspection (NDI) techniques are used to measure the damage form and extent of CFRPs, such as X-Ray technique adopted to detect the damage zone by Velayudham and Krishnamurthy [74], and the optical microscopy method used to inspect the damage morphologies, ultrasound and infrared thermography methodologies used for detection, location, and evaluation of damage in composite materials as proposed by Lai et al. [76,77]. The delamination formation is classified into two categories: peel-up at the entrance and push-down at the exit [76–79]. A schematic diagram showing the two delamination modes is given in Fig. 5 [48]. The formation mechanism of the peel-up delamination is directly related to the geometry of the drill bit and drilling torque. It is formed by the junction point between the cutting edge of the twist drill and the material in which a peeling force is generated along the drill flute. The peeling force detaches the upper laminae from the uncut portion in terms of tearing crack (mode III). Meanwhile, drill vibration may cause the uncut fibers to appear at the top plies where the fiber fringes are pulled up, resulting in mode I delamination with an opening fracture. Therefore, the peel-up delamination can be described as a combination of fracture modes I and III [80].

On the other hand, the push-down delamination forms when the laminae beneath the drill are compressed, and eventually, the thrust force pushes out the laminae from the hole as the shear stress exceeds the interlaminar bonding strength [77]. Thus, delamination occurs at the exit side of the workpiece. Factors such as interface quality, thrust force, and machining parameters, play a vital role in the push-down delamination formation [45,80–82]. Moreover, according to the literature [83,84], it is possible to conclude that increased delamination damage is directly proportional to the elevated drilling temperature. Among all the process parameters, the tool geometry is shown to have the greatest impact on the maximum temperature obtained, which indicates a consistent correlation to research on damage assessment. The push-down delamination is more severe than the peel-up delamination because there is no necessary backup force to counteract the thrust force generated during the drilling operation [85–87].

As derived by Chen [88], to determine the level of delamination damage, the one-dimensional (1D) delamination factor (F_d) is proposed as a ratio of the maximum diameter of the delamination zone to the nominal diameter of the drilled hole, as shown in Fig. 6(a). It is discovered that the delamination factor increases with increasing the drill flank wear since

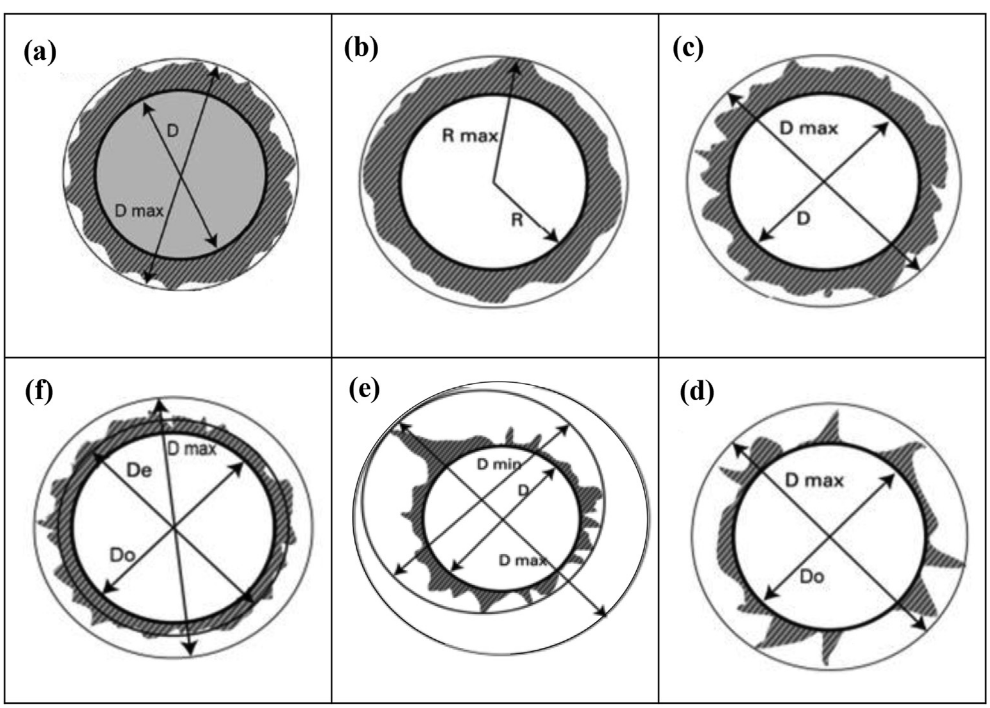


Fig. 6 – Schematic diagrams showing the evaluation of various delamination factors [78]: (a) the conventional delamination factor; (b) the delamination size; (c) the 2D delamination factor; (d) the adjusted delamination factor; (e) the minimum delamination factor; (f) the equivalent delamination factor.

thrust force is elevated with the increased flank wear. Specifically, the effect of drill wear on the delamination factor becomes significant at higher spindle speeds. Additionally, El-Sonbaty et al. [89] proposed the delamination size to quantify the severity of delamination, which signifies the difference between the maximum radius of the damaged area and the radius of the drilled hole, as illustrated in Fig. 6(b). Faraz et al. [48] introduced a two-dimensional (2D) delamination factor denoted as F_a for the sake of completeness, as shown in Fig. 6(c). Nevertheless, the delamination factor is insufficient when a long crack appears simultaneously, which will intensify the fracture strength of the machined hole. Therefore, Davim et al. [90] proposed the adjusted delamination factor (F_{da}) that considers the crack size contribution and damaged area contribution, as shown in Fig. 6(d). It is discovered that both the drilling parameters have an influence on the delamination factor of CFRPs, as illustrated in Fig. 7 [91]. But the feed rate is expected to have a more significant impact than the cutting speed [90].

Moreover, Tsao et al. [92] established an optimized factor, namely the equivalent delamination factor (F_{ed}), as shown in Fig. 6(f). Although it seems to be a better approximation for estimating delamination but it is still not yet sufficient because the effect of the damaged area is considered dominant over the effect of the crack contribution. Based on the previous research on the delamination factor, Nagarajan and Rajadurai [93] established the refined delamination factor (F_{DR}), which includes the effect of severity of damage using Buckingham's theorem. To achieve the accuracy, the total damaged area is divided into three sub-areas, including the heavy damage region (AH), medium damage area (AM), and low damage area (AL). Babu et al. [94] introduced the function of the fine equivalent diameter (D_{re}), *i.e.*, the refined equivalent delamination ratio (F_{ed}), as it takes into account the increase of diameter of the drilled hole at the exit. Especially at a specific cutting speed and feed rate combination, the equivalent and the fine equivalent diameter can differ significantly depending on the relationship between the nominal and the drilled hole diameter. While Durão et al. [95] suggested including the shape of the damaged area by calculating the shape circularity, *i.e.*, the shape of the delamination area has been compared with a circle of an equal perimeter. The comparable evaluation factor model used today does not account for the maximum and

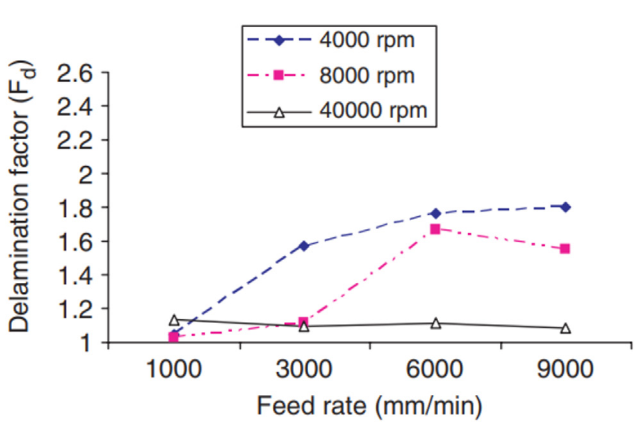


Fig. 7 – Delamination factor as a function of feed rate using 'Brad & Spur' drills at various speeds [91].

minimum delamination area when applied in high-speed drilling. Due to these limitations, Al-Wandi et al. [11] developed an equivalent adjusted delamination factor (F_{eda}) for drilling UD-CFRPs. This factor could discriminate the damage values and the null minimal and maximal delamination values. Silva [96] recently proposed an optimized factor, namely the minimum delamination factor (F_{dmin}), to evaluate the damage extent, as shown in Fig. 6(e). This is done by developing the smallest circle that encloses the delamination damage. Overall, many authors [11,48,88–90,92–97] used different approaches to measure the drilling-induced delamination factor. Most of them used linear regression analysis to obtain an empirical model to derive the delamination factor. The evaluation of drilling-induced delamination in terms of various dimensions is listed in Table 2 [4].

3.2. *Burrs*

Generally, burrs are described as an undesirable projection of material formed by the cutting and shearing processes. The burr formation mechanisms for fibrous composites certainly differ from the quasi-homogeneous materials. For example, the burr types in CFRP drilling may consist of only uncut reinforcing fibers or uncut non-reinforcing fibers or uncut matrix material, or even a combination of the above [15]. The most frequently occurring phenomenon is that the cutting tool peels off the matrix material from the side of fibers due to the high cutting temperature or unfavorable fiber-matrix adhesion. Thus, the burr consists of only uncut reinforcing fibers. Moreover, the interlayer gap may also form burr defects due to several circumstances, such as cavity formation caused by an inappropriate manufacturing process or void formation by chopped rovings due to the reinforcement geometry. CFRP typically forms burrs when the cutting tool is unable to remove all chipping materials up to the nominal depth of cut [15], as depicted in Fig. 8(a) [98]. This will result in the development of delamination [99–101], causing the last layer to peel up, which leads to bypassing the cutting tool and the burr formation at the exit edge of the composite. Moreover, the burr is fundamentally impacted by the cutting edge radius. When the radius is too large, the cutting edge bends the fibers and causes the fibers to get compressed and buckled, resulting in excessive formation of burrs and inappropriate chip removal. Additionally, if the fiber cutting angle is set as illustrated in Fig. 8(b) [102], the cutting tool does not remove the composite material despite deforming the fibers [103,104]. When the fiber cutting angle is $135^\circ \pm \delta$, macro fracture is the primary mode for chip separation. The cutting tool squeezes the fibers and causes substantial cracking propagation, out-of-plane displacement, uncut fibers, and poor surface roughness [105]. Burr formation in fibrous composites can be affected by various factors, including challenging machining kinematics [106], time-varying cutting angles of fibers [102], and complex tool conditions [107]. According to the work done by Xu et al. [36], the severity of burrs significantly depends on the feed rate. The larger the feed rate, the larger the thrust force, and thus the higher possibility of separating the composite layers. Therefore, to yield a low risk of delamination and burr formation, it is always recommended to control the feed rate at a low level to guarantee the quality of drilled holes.

Table 2 – The scientific literature on the most-used hierarchical quantitative criterion of delamination [4].

Ref.	Delamination factor	Associated Formula	Disadvantages
Chen [88]	Conventional 1D delamination factor	$F_d = \frac{D_{max}}{D_0}$ F_d: conventional 1D delamination factor; D_{max}: maximum diameter of the delamination zone; D_0: nominal diameter of the drilled hole.	The material's internal delamination flaw is disregarded.
El-Sonbaty et al. [89]	Delamination size	$R_{max} - R$ R_{max}: maximum radius of the damaged area; R: radius of the drilled hole.	It only considers the size of the delamination.
Faraz et al. [48]	2D delamination factor	$F_a = \left(\frac{A_d}{A_{nom}}\right)\%$ F_a: 2D delamination factor; A_d: total area of the drilled hole; A_{nom}: nominal drilled area.	The possibility of lengthy fractures is not taken into account by the parameter.
Davim et al. [90]	Adjusted delamination factor	$F_{da} = F_d + \frac{A_d(F_d^2 - F_d)}{A_{max} - A_o}$ F_{da}: adjusted delamination factor; F_d: conventional delamination factor; A_d: total area of the drilled hole; A_{max}: area corresponding to D_{max}; A_o: area corresponding to D_o	F_{da} shows null at the hole exit with the maximum and minimal delamination area, and F_{da} and F_d will not be the same.
Tsao et al. [92]	Equivalent delamination factor	$F_{ed} = \frac{D_e}{D_o}$ $D_e = \left[\frac{4(A_d + A_o)}{\pi}\right]^{0.5}$ F_{ed}: equivalent delamination factor; D_e: equivalent diameter; D_o: nominal diameter of the drilled hole. A_d: total area of the drilled hole; A_o: area corresponding to D_o.	It does not reflect the severity of damage.
Nagarajan and Rajadurai [93]	Refined delamination factor	$F_{DR} = \frac{D_{MAX}}{D_o} + 1.783\left(\frac{A_H}{A_o}\right) + 0.7156\left(\frac{A_M}{A_o}\right)^2 + 0.03692\left(\frac{A_L}{A_o}\right)^3$ F_{DR}: refined delamination factor; D_{MAX}: maximum diameter of the delamination zone; D_o: nominal diameter of the drilled hole; A_H: heavy damage area; A_L: low damage area; A_M: medium damage area; A_o: area corresponding to D_o.	The degree of damage must be determined using a specific theorem.

Babu et al. [94]	Refined equivalent diameter	$D_{re} = \sqrt{\frac{4A_e}{\pi}}$ D_{re}: refined equivalent diameter; A_e: damaged area.	The high-speed drilling process has various restrictions.
Durão et al. [95]	Shape circularity	$f = 4\pi\frac{A}{p^2}$ f: Shape's circularity; A: the damaged area around the machined hole; p: the perimeter of the damaged area around the machined hole.	The high-speed drilling is subjected to several restrictions.
Al-Wandi et al. [11]	Equivalent adjusted delamination factor	$F_{eda} = F_{ed} + \frac{A_{max} - A_{nom} - A_d}{A_{max}}$ F_{eda}: equivalent adjusted delamination factor; $A_{\max}$: maximum delamination area; A_{nom}: nominal delamination area; A_d: delaminated area.	Delamination near the hole's outflow cannot be assessed.
Silva [96]	Minimum delamination factor	$F_{dmin} = \frac{D_{min}}{D}$ F_{dmin}: minimum delamination factor; $D_{\min}$: minimum enclosing area; D: pretended drill area.	This factor is restricted to two dimensions.
Xu et al. [97]	3D delamination factor	$F_v = \frac{V_d}{V_{nom}}$ F_v: 3D delamination factor; V_d: cumulative volume of the delaminated CFRP layers; V_{nom}: nominal hole volume of the delaminated CFRP layers.	This factor omits the contribution from the maximum crack length.

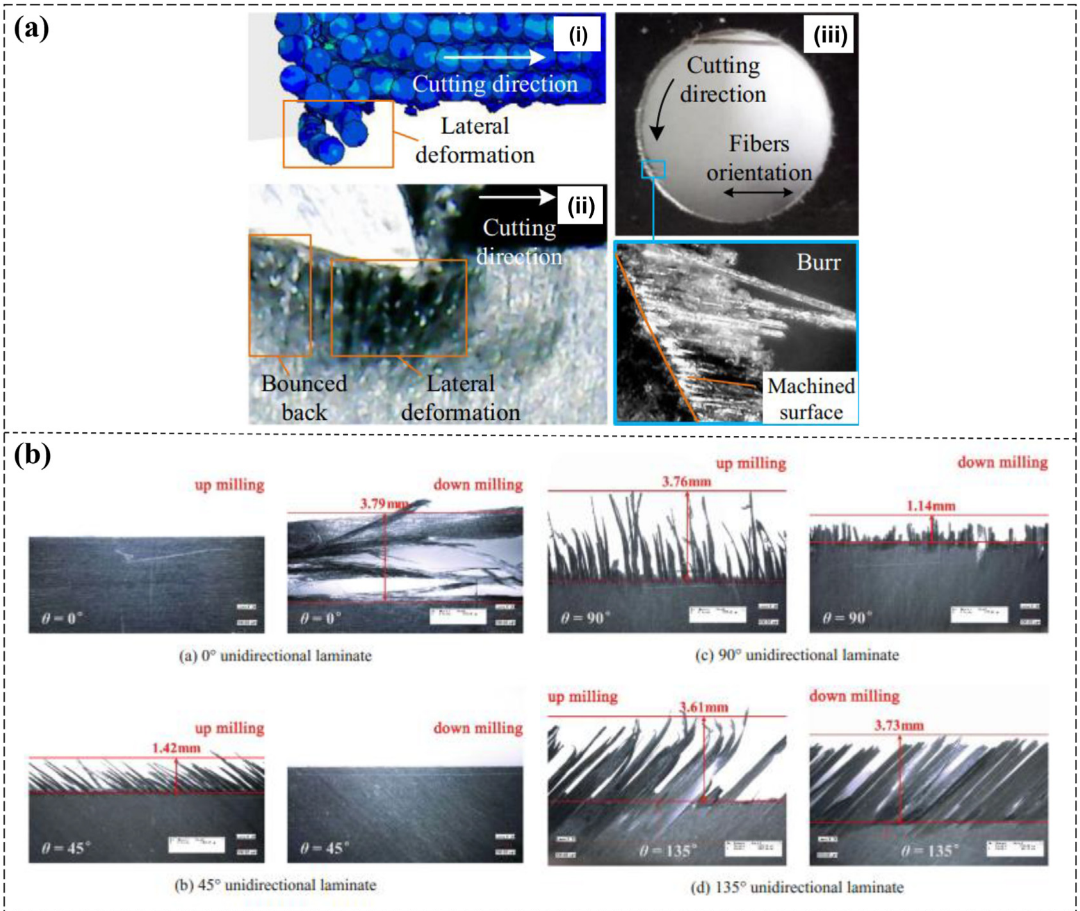


Fig. 8 – (a) Burr formation in CFRP cutting: (i) top view; (ii) side view; (iii) hole exit burr formation in drilling [98]; (b) the images of surface damage of CFRPs at four typical orientations [102].

Following the feed rate, the fiber cutting angle and the depth of cut also have significant impacts on burr size and orientation of UD-CFRPs [102]. Aurich et al. [108] developed a set of theoretical criteria to verify the occurrence of fiber fractures at the hole exit side. It was concluded that drilling-induced burrs mostly depend on the out-of-plane bending deformation of fibers at the hole exit. Other secondary parameters, such as cooling and lubrication conditions as well as the clearance angle of the cutting edge, and the contact area between the tool and the composite, would not have a significant impact on the burr formation, but their interaction with the primary parameters was significant. Xu et al. [109] and Geier et al. [13] concluded that (i) the smaller helix angle decreases the axial cutting force that produces the majority of the delamination and burr formation, (ii) a right-handed helix peels up the composite layer and thus increases burr formation at the entry, and (iii) a left-hand helix pushes the layer outward and increases burr formation at the exit. Based on the burr formation mechanism, a novel step drill [110] with variation step ratios has been designed and the new drill is able to prevent the burr formation at the hole exit side.

Evaluating CFRP burrs is challenging as the burrs appear extremely thin or even minor in length, and thus they can only be measured by non-destructive methods. Therefore, to evaluate the peculiar features of CFRP burrs, the most straightforward measurement is based on quantitative statistics and visual inspection. On the other hand, it is easy to find out the geometric features directly, the amount of burr formation, and the characteristics and orientation of burrs by inspecting the composite. He et al. [111] studied the helical milling process of CFRP/titanium stacks using visual inspection. The findings demonstrated that due to the measuring personnel's subjectivity, accurate measurement and proper identification of machining characteristics could only be achieved by visual evaluation with extensive expertise. By counting burrs, it is possible to quantitatively characterize drilling-induced burrs for CFRPs without requiring additional assessment software. When defining the difference between high-quality and low-quality machined holes, Voß et al. [60] created a unique criterion, namely the damage value, to quantify the number of uncut fibers. The drawback of this method is that it cannot describe the characteristics of burr formation and is fully diameter-dependent. Therefore, another commonly used method, namely the length-based measure, is developed. However, this measure often requires accurate computational algorithms for calculation. On top of that, an area-based burr measure has been developed, which describes the geometries of machined features regarding the quantity of burr formation.

The disadvantage of this measure is that the information about burr characteristics is usually unclear. Lastly, researchers have created more complex evaluation formulas to have an overall characterization of the geometrical feature of burrs. This measurement yields more information not only on the severity of burrs but also on the burr orientation and delamination extension.

3.3. *Tearing*

Tearing is one of the crucial defects affecting the quality of CFRP holes. Unsupported single-layer CFRP materials are easily torn along the fiber direction when the arrangement is hostile to fiber cutting. The interlayer anisotropy of CFRPs, which typically takes place at the outermost surface layer of the drilled hole, is the main contributor to the tearing problem [4]. The fiber-matrix debonding procedure will be initiated when the cutting stress reaches the maximum interfacial strength, which denotes the start of microcracks. As cutting forces are applied, these microcracks will continue to propagate along the fiber direction due to the inadequate support supplied by the polymer matrix in the topmost layer, leading to severe tearing faults. In addition, the fiber cutting angle employed during the material removal process substantially impacts how tearing faults manifest themselves, regardless of the orientation of the fiber ply. Therefore, the most severe tearing defects will form when the main circumferential cutting force acts 90° in the tensile direction. The most-used measures to evaluate the tearing are length-based and area-based methods [15]. The length-based process uses the ratio of the maximum length of the tearing over the nominal diameter, whereas the area-based method uses the total area of the tearing to the theoretical maximum tearing area. The drawback of the length-based method is that it only considers the tearing in 1D and thus cannot describe the defects completely [15]. On the other hand, even though the area-based method represents the tearing in 2D, it still cannot reflect the impact of tearing on the actual holes. A newly proposed method is suggested by Xu et al. [4] to evaluate the tearing by using a ratio of the total tearing area to the nominal area of the hole to achieve better accuracy of assessment.

3.4. *Surface cavities*

Another surface defect that often results in an irregular pattern on the machined surface of CFRPs is surface cavities [66]. The basic morphologies of surface cavities are shown in Fig. 9 [98]. According to Wang et al. [112], surface cavities emerge significantly depending on the angle at which the fibers are shredded. Wang et al. [113] claimed that despite the absence of visible surface damage in the area adjacent to the fiber cutting zone, substantial surface cavities were found in the area in opposition to the fiber cutting zone. Additionally, due to the uneven distribution of cavities in that region, surface cavities only cover a portion of the against fiber cutting zone. The methods for removing composite materials vary depending on the fiber cutting angle [43,66,114,115]. CFRPs use two methods to remove materials: fiber-matrix debonding and fiber fracture. Carbon fibers break with essentially slight plastic deformation, as compared with ductile metallic materials. The different material fracture types show up in the following sequence, depending on the cutting direction: debonding of the fiber/matrix interface, shear fracture, and bending fracture of the fiber. There are five stages involved in the formation of surface cavities. The fiber-matrix debonding takes place firstly in stage 1, and as it develops, the cutting edge extends along the fiber direction. In stage 2, the fiber-matrix debonding stops propagating and the bending-induced fiber fracture initiates. Stage 3 marks the appearance of the secondary fiber-matrix debonding, which spreads until bending-induced fiber fractures take place. The shearing-induced fiber breakdown occurs in stage 4. In stage 5, the fiber-matrix debonding occurs and expands with the movement of the cutting edge once again. The primary causes of surface cavities are fiber-matrix debonding followed by bending-induced and shear-induced fiber fractures. Finally, the depth and width of surface cavities are determined by the occurrence frequency of the shear-induced fiber fracture and the propagation of the fiber-matrix debonding.

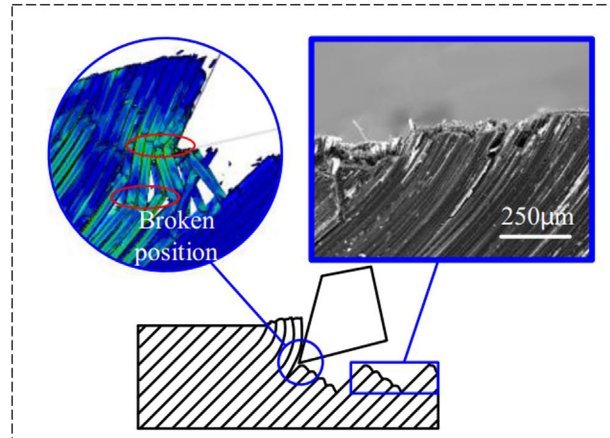


Fig. 9 – Schematic representation of the surface cavities [98].

4. Effects of process conditions

In drilling fibrous composites, process conditions, *e.g.* cutting speed, feed rate, applied tool geometries/coatings, and cutting environments, often pose a significant effect on the drilling mechanisms and responses of CFRP workpieces. This section focuses on discussing the impacts of various process conditions, including drilling parameters, cutting tools, and cutting environments, on the drilling forces, temperatures, hole quality, and tool wear of CFRP composites.

4.1. *Drilling parameters*

The feed rate (f – mm/rev) and cutting speed (v_c – m/min) are critical drilling parameters having the most significant influence on the chip removal of CFRPs [36]. As such, their effects on the drilling forces, machining temperatures and hole quality are considerable. Many scholars worked on determining the influences of drilling parameters through the use of mechanistic [45,80,116–119], experimental [28,35,40,63,90,120] or numerical techniques [114,121–128]. Mechanistic modeling studies attempt to describe the effects of the drilling parameters on the energetics of cutting, using basic mechanical principles and laws, and often require conducting experiments to determine coefficients. The influences of drilling parameters can be analyzed through purely experimental work. In this case, the influences are often modeled through statistical methods, *e.g.* response surface methodology, regression analysis, and analysis of variance, without trying to understand and describe the governing laws and mechanics of cutting. Numerical techniques are discretizing the mathematical equations representing mechanistic laws and behaviors of CFRP composites to solve advanced cutting situations (*i.e.*, drilling and milling).

Although the fiber cutting angle (θ) governs the cutting mechanisms the most [61,129], it is constantly changing during drilling; thus, θ cannot be set. Additonally, the feed has the most significant settable influence on the hole quality and cutting energetics, as it directly affects the size of the chip cross-section [61]. The larger the feed, the larger the chip cross-section, and thus the larger the cutting force [130]. The larger cutting force results in higher friction between the cutting tool and the composite, thus leading to higher cutting temperatures [131]. Considering that the thermal conductivity of polymers is low, the significance of the effect of feed on the cutting temperature is not as dominant as it is observed in metals. As the feed has a direct and significant influence on the cutting force, the probability of drilling-induced delamination formation is also significantly influenced by the feed [132].

Zhang et al. [131] conducted drilling experiments of CFRPs and concluded that the cutting force and hole-exit temperature could be controlled effectively, and the hole-exit damages could be suppressed by the proper set of feed. They proved that the larger the feed, the larger the axial cutting force and the lower the hole-exit temperature, as shown in Fig. 10 [131]. Wang and Jia [133] developed a strong correlation between the feed, thrust force, and drilling-induced delamination in CFRPs. The larger the feed, the larger the thrust force; thus, the delamination formation probability increases significantly. Therefore, a critical thrust force is often defined and calculated to control the delamination formation ability of drilling. Qiu et al. [134] analyzed the influences of drilling parameters on the cutting force and hole wall damages of CFRPs with stepped drills. They found that the larger the feed, the smaller the damaged area is. The possible reason would be that the special cutting force also decreases with the increase of the feed. Therefore, the ratio of the thrust force to the number of fibers is reduced. Wang and Jia [135] reduced the exit delamination and improved the production rate in the drilling of CFRP composites by optimizing the drilling parameters. They found that the larger the feed, the larger the average surface roughness and the conventional delamination factor. The increased feed results in rougher surface structures, as the increased material removal rate leads to larger forces and more significant surface damage.

Researchers agree that the push-down delamination at the hole exit is significantly affected by the feed [136–142]. However, the feed seems to have no significant influence on the entry delamination, according to Krishnaraj et al. [137], as the peel-up effect is primarily affected by the tool geometry. Othman et al. [143] recognized the feed as the factor having the most significant influence on the thrust force, which directly reflects the hole quality and tool wear. In agreement with other researchers, the feed is recommended to be optimized firstly among the other process or environmental parameters. On the other hand, feed control may be a perfect tool for hole damage minimization [139,144]. Yaşar and Günay [145] compared a conventional drilling operation with a feed-controlled one and found that the average surface roughness, conventional delamination factor, and thrust forces were significantly lower than those of a constant feed operation.

The influence of the cutting speed on the drilling responses of CFRPs is not as evident as it is found in the case of the feed. The influence of the cutting speed is often negligible or

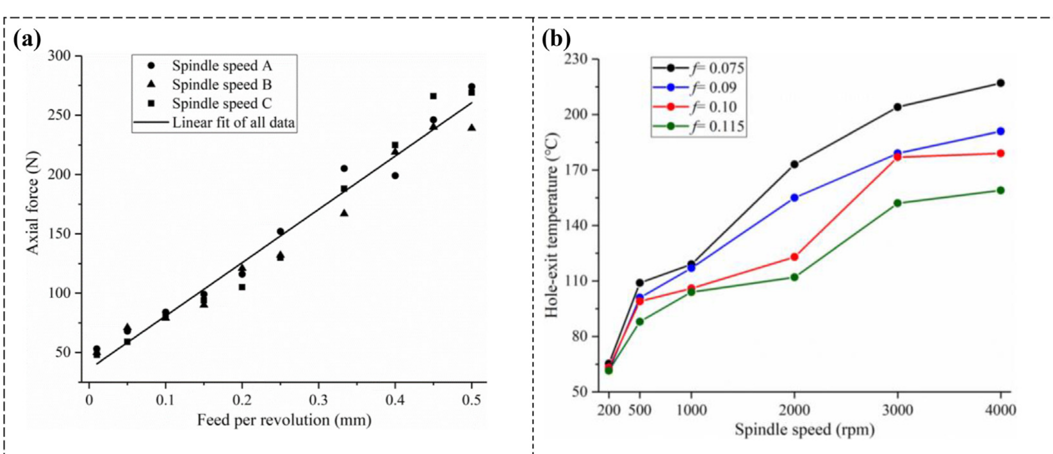


Fig. 10 – The influence of (a) the feed on the axial cutting forces at different spindle speeds and (b) the effect of the spindle speed on the hole-exit temperature [131].

hyperbolical [40,97,146]; thus, much information seems contradictory in the literature, as the analyzed ranges of cutting speed often differ significantly. The cutting speed greatly influences the cutting temperature; thus, the geometrical defects and tool wear rate are also affected [147]. Zhang et al. [131] analyzed the influence of process parameters on the thrust force and hole-exit temperature during the drilling of CFRPs. They found that the larger the cutting speed, the higher the hole-exit temperature is (Fig. 10(b)). This is explained by the fact that the larger the spindle speed, the higher the contact frequency between the cutting edge and abrasive fibers; thus, the heat generation is larger. Qiu et al. [134] conducted step drilling experiments in CFRPs and analyzed the effect of drilling parameters on cutting forces and hole wall damage. They found that the higher the cutting speed, the larger the damaged area is, as the higher cutting speed results in a higher cutting temperature, which is responsible for the accelerated softening of the matrix leading to an increase in the damaged area. The influence of the cutting speed on the thrust force was found to be insignificant. Geier and Szalay [40] showed that the influence of the cutting speed on the thrust force and delamination factor is not monotone if the cutting speed range is large enough, mainly due to the changing of the dominancy of matrix softening effects at higher cutting temperatures and the relatively low significance of the main effect. Merino-Pérez et al. [147] analyzed the cutting temperature in the drilling of CFRPs using uncoated tungsten carbide cutting tools. They observed that the heat dissipation and overall temperatures are significantly influenced by the degree of crystallinity, structure of the carbon fibers and cross-linking density of the polymer matrix. They pointed out that the higher the cutting speed, the larger the concentration of cutting heat in CFRPs. Chen et al. [148] studied the effects of the drilling parameters on the cutting temperatures of CFRP composites. They concluded that with the increase in the spindle speed (n_1 = 1500 rpm to n_2 = 4500 rpm), the thrust force decreased by 13.9%, and the peak cutting temperature decreased by 63.2%. Moreover, Merino-Pérez et al. [149] analyzed the influence of the cutting speed on the drilling forces of CFRPs. They explained the increased effect of the cutting speed on the drilling torque by the negative impact of strain rate on the ability of the matrix to transfer the load to the reinforcement.

4.2. *Cutting tools*

The geometrical properties of cutting tools significantly influence the drilling behaviors of CFRP composites; thus, due attention is paid to their investigation and development [13]. Researchers found that the point angle, helix angle, and length of the chisel edge are the most significant macro-geometrical parameters affecting the composite drilling and resulting hole quality [65,150,151]. The smaller the point angle, the smaller the thrust force, which is advantageous from the viewpoint of delamination suppression. However, a too small point angle results in a huge cutting tool and longer tool path, longer operation time, and cutting instability [13]. The helix of the drilling tool governs whether the radial or axial forces dominate the cutting of the hole surface [107]. The larger the helix angle, the larger the probability of delamination and burr formation because the dominance of the axial cutting force is larger, which is responsible for layer separation and fiber buckling without mechanical support [13,107]. Although the chisel edge length of most of the recent modern twist drills is definitely smaller than a couple of years ago, the chisel edge has a dominant role in the resulting hole quality and tool life, as the chip removal mechanisms at the chisel edge are governed by extrusion rather than shearing [152]. Pardo et al. [152] analyzed the influence of point angle on the machinability of CFRP/titanium stacks and concluded that the point angle strongly correlates to the thrust force. Therefore, smaller point angles are recommended to be applied to reduce the probability of burr formation. Xu and El Mansori [153] studied the drilling mechanisms of CFRP/Ti stacks and highlighted that the point angle directly affects the chip thickness, which significantly influences the chip separation process. Thus, they recommended small point angle drills to promote lower thrust force and delamination factor. Gaitonde et al. [28] observed that a larger point angle results in more extensive delamination at the hole exit. Heisel and Pfeifroth [150] agreed that larger point angles are less preferable from the viewpoint of reducing exit delamination. Additionally, they also concluded that the larger the point angle, the larger the thrust force, and the smaller the delamination at the hole entry. Considering these findings, the point angle is recommended to be large at the hole entry and small at the hole exit. This partly justifies the relevancy of advanced-shaped tool geometries like the double point angle twist drill or dagger drill.

Shyha et al. [154] analyzed the effect of drill geometry in drilling small diameter holes for CFRPs and observed that the helix angle in the range of 24–30° has no significant influence on the thrust force nor on the tool life. Xu and El Mansori [153] highlighted that better chip ejection is in the case of a higher helix angle. They also concluded that the drilling torque is significantly influenced by the helix angle. Considering that the helix angle primarily affects the chip ejection ability of drilling tools, it may directly affect the cutting temperature. However, studies have not proved it yet. Faraz et al. [48] conducted drilling experiments of CFRPs using different cutting tools and found that larger cutting torque is promoted due to a null helix angle. This suggests that the helix angle directly affects the radial cutting force components, thus, affecting the drilling torque and tool performance. Poór et al. [15] reviewed the recent expertise on drilling-induced burr formation and measurement for CFRPs and highlighted that the helix angle and helix direction (whether a right-handed or a left-handed strategy is considered) of the cutting tools directly affect the burr formation ability of CFRPs. Based on their understanding, the larger the helix angle, the lower the probability of burr formation at the hole exit and the larger at the hole entry.

Wang and Jia [133] analyzed the effect of the chisel edge of drills and found that the chisel edge has a significant effect on the thrust force and cutting performance. Qiu et al. [155] and Karpat et al. [156] concluded that the chisel edge has a dominant contribution to the thrust force; thus, it has a significant influence on the drilling-induced delamination. However, Karpat et al. [156] showed that a smaller chisel edge results in a larger cutting force and more accelerated tool wear on the secondary cutting edge. Li et al. [157] developed a thrust force model taking into account the chisel edge and analyzed the

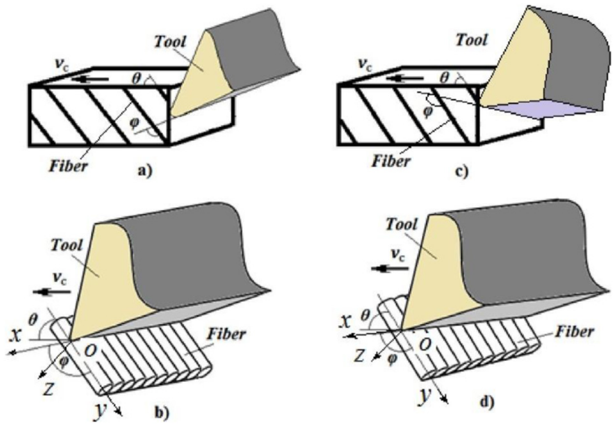


Fig. 11 – A schematic illustration of the azimuth angle (φ) of the cutting edge [158].

influences of drilling parameters on the thrust force of the chisel edge during the drilling of CFRPs. Their results show that the feed has a more significant effect on the thrust force than the cutting speed. Wang et al. [158] analyzed the cutting mechanisms of the chisel edge in the drilling of CFRPs. They introduced the azimuth angle as illustrated in Fig. 11 for a better description of the chip removal mechanisms of the chisel edge. Nevertheless, the avoidance of the cutting of the chisel edge is popular, for example, by using advanced-shaped cutting tools or pilot holes [159–161].

Mechanical drilling of CFRPs can be conducted either using conventional twist drills as illustrated in Fig. 12(a) [14] or advanced drilling tools like step drills, brad and spur drills (often called candlestick drills), dagger drills (often called one-shot drills), core drills, *etc*. The most applied drilling tools are schematically illustrated in Fig. 12 [14]. Although the conventional twist drill is the most applied drilling tool among researchers because its relatively simple geometry can be easily adapted and used for mechanical modeling and calculations, many research works also focus on the analysis of cutting performance and ability of advanced-shaped cutting tools [13].

Advanced-shaped cutting tools illustrated in Fig. 12 attempt to eliminate or reduce the drawbacks of conventional twist drills. Othman et al. [143] conducted drilling experiments of CFRP composites using a twist drill, a brad and spur drill, and a dagger drill. They observed that the brad and spur drill promoted the best hole quality at the exit side, followed by the dagger drill and twist drill. The results of Xu et al. [162] highlight the importance of using functionally-designed tools and optimum cutting conditions for damage-free drilling of CFRPs. They analyzed the cutting performance of twist drills, brad and spur drills, and dagger drills, and it was concluded that the brad and spur drill performed the best in terms of drilling forces, hole quality, and tool wear behavior, followed by the twist drill and the dagger drill. Su et al. [163] studied the cutting performance of brad and spur drills and described their beneficial cutting ability by the cut-push effect (the drill first cuts the last layer of the composite, and then pushes the layer off). By the advantageous phenomena, both the drilling-induced delamination and burrs can be minimized. According to Tsao and Hocheng [160], the main advantage of step drills lies in the fact that the critical thrust force at the second drilling step is significantly reduced compared with the conventional twist drilling. Although the core drills do not have a chisel edge, the cutting forces and probability of drilling-induced delamination formation are

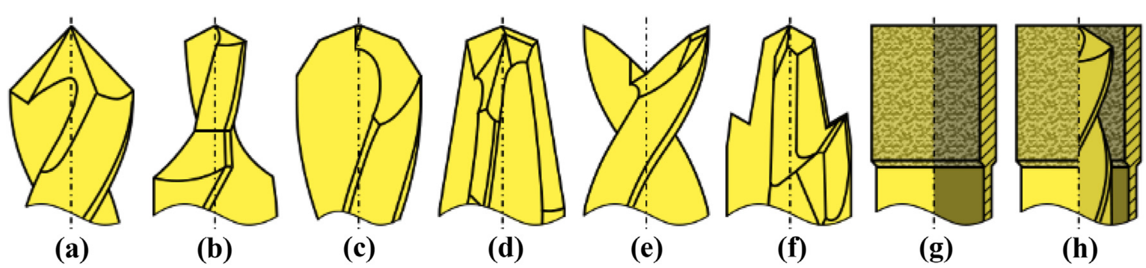


Fig. 12 – Advanced drilling tools for CFRPs [14]: (a) twist drill with a small point angle; (b) step drill; (c) double point angle twist drill; (d) dagger drill; (e) fishtail drill; (f) brad and spur drill with a dagger type center; (g) core drill; (h) core drill with an inner drill.

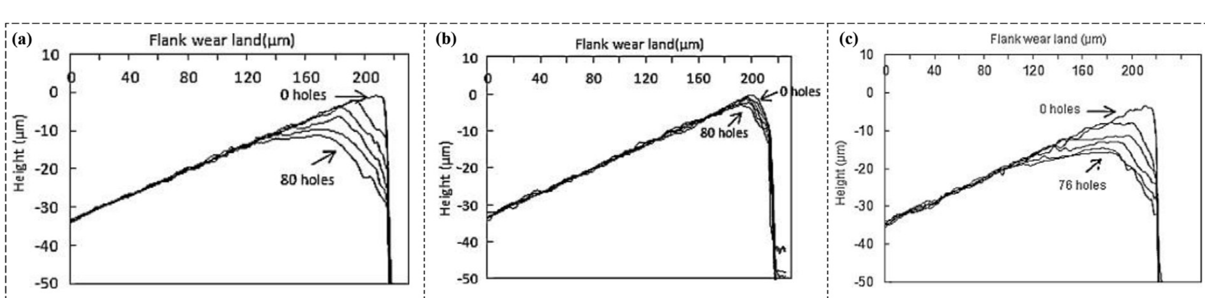


Fig. 13 – The cutting edge profiles of (a) the uncoated carbide drill; (b) the diamond-coated drill; (c) the AlTiN-coated drill [171].

low, but the chip removal is difficult. Therefore, Tsao and Chiu [42] developed novel special drills incorporating the features of core drills and twist drills to combine their advantages.

Considering that carbon fibers exhibit a strong abrasive wear effect on the cutting tools, the discussion of the material issues is essential to select the right one for CFRP drilling in order to yield appropriate tool life and hole quality [164]. Considering that the most common wear mechanism in CFRP machining is abrasion wear in the form of edge rounding [165], high-speed steel (HSS) is not appropriate for CFRP machining, as its wear rate is extremely rapid [166,167]. In contrast, the wear rate of solid carbide tools is often relatively slower, and the sharpness of these tools (*i.e.,* cutting edge radius) can be kept for a quasi-long time [168]. The diamond or diamond-like coated solid carbide tools exhibit the longest tool life [169]. However, the thickness of the coating has a significant effect on machined surface generation, as it directly affects the cutting edge radius, thus the dominance of the crushing versus plowing/bending mechanisms [170].

Although an appropriate selection of cutting tool materials is essential, the experimental results of Xu and El Mansori [153] indicated that the geometrical features of tools exhibit a more significant effect on the drilling behavior of CFRPs than the material composition. Wang et al. [171] studied the wear issues of uncoated, diamond-coated, and AlTiN-coated tools in the drilling of CFRPs, as shown in Fig. 13. They observed similar thrust forces for the uncoated and AlTiN-coated tools, and these thrust forces were significantly higher than those for the diamond-coated ones. Kuo et al. [172] analyzed the wear behavior of chemical vapor deposition (CVD) diamond-coated tools in drilling CFRPs. They found no proportional correlation between the cutting force and the tool wear. Montoya et al. [168] evaluated the cutting performance of coated and uncoated carbide tools in the drilling of CFRP/Al stacks. They observed a smaller thrust force for the uncoated drill; however, the coated drill could produce higher quality holes than the uncoated one, mainly due to the lower flank wear and thrust force. Ameur et al. [173] analyzed the machinability of CFRP composites using WC, HSS, and TiN-coated carbide drills. They found that the thrust force is mainly influenced by the tool materials and the feed rate, which has a strong influence on the exit delamination factor. Furthermore, the thrust force of the coated drill was significantly lower than that of the HSS drill. Wang et al. [169] investigated the cutting performance of diamond-coated drills in drilling CFRPs. Both the thrust force and delamination are reduced by using the diamond-coated tool as the tool has higher wear resistance and longer tool life. The advantage of applying diamond coatings was also confirmed by Iliescu et al. [174]. They could machine 10–12 times longer by the diamond-coated tool than by the uncoated carbide tool. The experimental results of Hrechuk et al. [175] also showed that the CVD diamond-coated drills and polycrystalline diamond (PCD) drills performed better in wear resistance than the uncoated cemented carbide drills.

4.3. *Cutting environments*

Although the drilling of CFRPs can be optimized by the proper set of drilling parameters and careful selection of cutting tools, the appropriate cutting environment also helps to increase productivity and efficiency, decrease tool wear rate, and increase hole quality. Taking the absorbent capacity of polymers into account, conventional cooling methods (*i.e.,* flood cooling, high-pressure flood cooling) cannot be used in CFRP machining. Furthermore, the carbon chips have a severe adverse effect on the machine tool elements; therefore, these chips are recommended to be removed from the cutting space by a vacuum cleaner, or the cutting fluid has to be cleaning-filtrated. These challenges make the application of tool cooling difficult to implement in the drilling of CFRPs. Thus, cooling is often not used in industrial environments (*i.e.,* drilling is performed under a dry condition). However, researchers investigate tirelessly alternative cooling methods, as the coolant not only decreases the cutting temperature but also lubricates surfaces and removes chips. For example, cryogenic cooling is a promising method to decrease drastically the temperature, which has a positive effect on delamination and burr avoidance; nevertheless, its implementation is difficult and expensive [176]. For example, Morkavuk et al. [176] machined CFRPs using cryogenic cooling and found that the cryogenic cooling could produce fewer machining-induced geometrical defects and better surface quality than the dry machining. Khanna et al. [177] applied an indigenously developed cryogenic machining facility for drilling CFRP composites and found that cryogenic machining could improve the surface finish of CFRP holes by 14–38% compared with dry drilling. Xia et al. [178] also recommend applying cryogenic cooling since their results prove that the cryogenic cooling significantly reduces tool wear and increases the quality of machined hole surfaces. However, the cryogenic cooling has a negative impact on the thrust force, drilling torque, and delamination formation. Kerrigan and Scaife [179] conducted the machining tests of CFRPs to assess the performance of isolated cutting fluid chemicals. They found that the dry conditions could yield lower thrust force and torque as well as longer tool life against the best cutting fluid with identical parameters. Khairusshima and Sharifah [180] analyzed the effects of cooling conditions (dry and chilled air) on the tool life during the CFRP drilling and observed a 30% higher tool life under the chilled air condition.

Besides the cooling issues of fibrous composites, the mechanical supporting circumstances also play an essential role in delamination and burr formation abilities of CFRPs [65,86,87]. Researchers often apply back-up support plates to decrease potential material deformation/buckling at the hole exit that could result in accelerated layer separation or burr formation. Tsao and Hocheng [181] modeled the influences of back-up support plates and concluded that drilling with back-up support plates offers a larger critical thrust force than that without back-up. The favorable supporting properties of the metallic part of the FRP/metal are highlighted by Qi et al. [182]. They pointed out that one of the main differences in whether the sandwich structure is drilled from the CFRP or the metal's direction is realized in the change of the supporting properties. Dogrusadik and Kentli analyzed the influences of support plates on the delamination and tool wear in their [101,183] studies, respectively. They concluded firstly that applying an entry support plate was beneficial from the viewpoint of delamination suppression; however, its application may damage the composite surface. Secondly, the material of the support plate may significantly influence the speed of the tool wear.

5. Approaches to achieving high-quality drilling

The problems related to the drilling-induced minor and major cracks lead to inaccuracies in hole diameter and circularity. Further, the increase in temperature during the drilling of CFRP materials creates a deviation in the surface roughness of the hole wall. Also, the abrasive nature of these materials results in rapid tool wear, leading to increased entry and exit delamination damages; therefore, clean and green production methods are preferred by recent researchers to reduce such mechanical and thermal effects during drilling. The primary factor, which affects the surface quality of drilled CFRP hole walls, is the indentation of the quasi-stationary chisel edge of the drill. This indentation effect can be minimized by selecting modified drill geometries. This problem can also be further reduced by selecting optimal surface coatings to minimize the amount of wear. Since a more significant number of input factors are associated with drilling, finding the optimum drilling input parameters that produce the lowest thrust force, torque, and surface roughness is essential at present. Therefore, to address all the above-mentioned challenges, this section aims to discuss four different topics, namely optimization of drilling parameters, appropriate selection of tool geometries, appropriate selection of coatings, and advanced drilling techniques.

5.1. *Optimization of drilling parameters*

Achieving the dual demands of yielding the minimal surface damage and the longest tool life during the drilling of CFRP composites is a challenging task for manufacturers due to the heterogeneous and anisotropic characteristics of CFRPs. Bhushi et al. [184] optimized the drilling parameters for CFRPs using response surface methodology with a genetic algorithm and reported that the feed rate and helix angle are the two most influential factors affecting the surface integrity of CFRPs. According to their work [184], a spindle speed of 800 rpm and a feed rate of 0.12 mm/rev are two optimal parameters that yield better results. However, these speed and feed ranges are considered to be really low in the actual production industry. Abhishek et al. [185] performed a multi-response optimization for the drilling of CFRPs by focusing on the issues of thrust force, torque, and delamination damage. The authors used the principal component analysis with the Fuzzy and Taguchi technique and found that a spindle speed of 2800 rpm and a feed speed of 50 mm/min for a 6 mm diameter drill provide better performances in terms of hole quality.

Barik et al. [186] studied the optimization of drilling parameters for CFRPs using Grey Relational Analysis (GRA) method. The spindle speed of 3000 rpm, the feed of 0.025 mm/rev, and the point angle of 108° were found to be the optimal machining parameters for drilling CFRPs with minimal surface damage. Feito et al. [187] performed multi-objective optimization in drilling woven CFRP laminates by considering three different point angles, speeds, and feeds. The lower point angle within the range of 90–108° and the lower range of feed rates were found to provide better performances. Enemuoh and Okafor [188] conducted experiments to select cutting parameters for damage-free drilling of CFRP materials. They used Taguchi's experimental analysis technique and a multi-objective optimization criterion. A process map based on the results is presented as a tool for drilling process design and optimization for the investigated tool/material combination. Kim and Ramulu [189] optimized in terms of machined hole quality and machining cost for drilling of graphite/bismaleimide-titanium alloy (Gr/Bi–Ti) and reported that the optimum process conditions to achieve desired hole quality and process costs are a combination of low feed and low speed while using carbide drills and are high feed and low speed while drilling with HSS-Co tools.

The drilling optimization of CFRPs performed by Devitte et al. [190] using the Box-Behnken method revealed that the combined effects of the cutting speed and feed rate influence the delamination factor to a greater extent than their individual effect. The optimal values found from the study are the cutting speed of 20 m/min and the feed rate of 0.05 mm/rev with pre-corp drill types. Wang and Jia [135,191] used the Non-dominated Sorting Genetic Algorithm (NSGA-II) with the ANN technique to optimize CFRP drilling parameters and reported a point angle of 118° and a speed of 2400 rpm to be the optimal parameters. Various researchers [192–194] have conducted parametric optimizations for the drilling of CFRPs using multi-objective optimization and analysis of variance approach to improve the surface integrity of drilled CFRP holes.

The previous study conducted by Raj Kumar et al. [192] revealed that the performance of micro drills was better at the lower level of drilling parameters, whereas the performance of macro drills was better at the medium level of cutting speed and lower level of feed rate. Based on the desirability approach-based optimization in CFRP drilling, the optimal parameters were found to be a maximum cutting speed of 30 m/min and a minimum feed speed of 30 mm/min. Soepangkat et al. [195] studied the multi-objective optimization using BPNN-PSO approach on multi-stacked CFRP laminates. The optimum spindle speed was found at a maximum level of 2993 rpm, and the optimal feed speed was found at its lower range of 79 mm/min. The prediction was found to be very accurate with a minimum error percentage. Xu et al. [4] performed a detailed review of drilling-related issues for CFRP laminates. Based on their literature survey, optimization of machining parameters with respect to minimizing delamination damage continues to be a difficult task to evaluate the region of failure in cut CFRP holes. Also, the review shows that the influence of the feed rate on the drilling responses of CFRPs was more significant than the cutting speed.

The multi-objective optimization using response surface methodology with different drill geometries was studied by Feito et al. [196]. The medium levels of cutting speed within the range of 55–60 m/min and lower feed rates were chosen while using the brad and spur drill types. Abhishek et al. [197] performed the multi-objective optimization using the harmony search evolutionary technique in drilling CFRP composites. This technique was compared with the Genetic algorithm and Taguchi design approach. The optimal machining parameters found from their work were a spindle speed of 1000 rpm and a feed speed of 350 mm/min for a tool diameter of 5 mm. The multi-objective optimization using the desirability approach technique was performed by Samsudeensadham and Krishnaraj [198]. The input parameters were the cutting speed of 15–30 m/min and the feed rate of 0.025–0.1 mm/rev for the drilling operation. Based on their study, a cutting speed of 30 m/min and a feed of 0.025 mm/rev are determined to be the optimal machining parameters for achieving desired surface quality of CFRP holes. Table 3 summarizes the various optimization techniques used for optimizing the drilling processes of CFRPs.

Based on the literature survey, it can be inferred that higher speeds with lower feed rates result in finer chips, better surface finish, and longer tool life. However, at lower speeds and higher feeds, there seems to be more of a plowing action, which results in poor surface finish and more delamination. An increase in the feed rate increases the chip thickness, which results in increased thrust force and torque. Further, the elevated force increases the damage on CFRP hole surfaces while stacked against some other metallic phases. Based on the optimization of machining parameters, the cutting speeds of 30–40 m/min, along with fine feed rates, are recommended. There is an increasing need to increase the cutting speed range to the next level since the holes drilled for aircraft applications are large in number. High-speed drilling is the requirement of the day. Hence research on improving tool geometries and advanced drilling techniques to enhance the band of cutting speed has been intensified. Moreover, in recent years, the variable parameter drilling (VPD) technique has emerged and has attracted due attention among the composites manufacturing sectors due to its benefits in avoiding the formation of drilling-induced delamination damage. The idea of this novel method lies in the dynamic change of the drilling parameters during the chip removal to minimize the damage formation for CFRP composites. It entails the use of low feed rates for drills at the hole exit side to reduce the thrust force as an attempt to avoid the delamination formation, while it increases the speed and feed when the tool cuts the center of the hole walls to increase the machining efficiency. For example, Li et al. [199] proposed a new method of multi-element varying-parameter vibration drilling for the micro-hole machining of composite materials. The authors analyzed the cutting characteristics of thickness division, natural chip separation, and multi-separation chip-breaking characteristics in the interactive zone. The comparative results between the proposed method and the conventional drilling indicated that the proposed varying-parameter vibration drilling could significantly improve the micro-hole machining accuracies. Neugebauer et al. [200] studied a material identification method based on acoustic emission signals for drilling CFRP/Al stacks. It was found that this method can monitor different stages of the drilling process. The method can also implement controllable parameters in different drilling stages of CFRPs during hole processing. Zhang et al. [201] investigated the VPD process of Ti-CFRP-Ti laminated stacks based on the real-time sensing of axial drilling force. The authors successfully developed an intelligent tool holder system with the function of real-time

Table 3 – Summary of various optimization techniques applied for drilling of CFRPs.

Ref.	Optimization techniques	Optimal parameters	Effects on the surface quality
Bhushi et al. [184]	Response Surface Methodology (RSM) with Genetic-Algorithm (GA)	Cutting speed of 20.106 m/min and feed rate of 0.1 mm/rev	Reduction in delamination damage
Abhishek et al. [185]	Principal Component Analysis (PCA) with Fuzzy and Taguchi techniques	Cutting speed of 52.78 m/min, feed speed of 50 mm/min, and diameter of 6 mm	Reduction in entry and exit delamination
Feito et al. [187]	Response Surface Methodology (RSM) and Multi-objective Regression model	The lower range of feed and tool point angle, and the higher range of speed considered in this study	Improvement in tool life and reduction in delamination
Devitte et al. [190]	Box-Behnken method	Cutting speed of 20 m/min and feed rate of 0.05 mm/rev	Reduction in thrust force and burr formation
Wang and Jia [135,191]	Non-dominated Sorting Genetic Algorithm (NSGA-II) with ANN techniques	Cutting speed of 45.24 m/min, point angle of 118°, and diameter of 6 mm	Reduction in thrust force, surface roughness, and delamination damage
Soepangkat et al. [195]	Multi-objective optimization using BPNN-PSO novel approach	Spindle speed of 2993 rpm and optimal feed speed of 79 mm/min	Improvement in the hole quality of CFRPs
Abhishek et al. [197]	Multi-objective optimization using the Harmony Search Evolutionary (HSE) technique.	Cutting speed of 15.708 m/min and feed speed of 350 mm/min with a tool diameter of 5 mm	
Samsudeensadham and Krishnaraj [198]	Desirability Approach (DA)	Cutting speed of 30 m/min and feed rate of 0.025 mm/rev	Reduction in thrust force, surface roughness, delamination damage, circularity, and hole diameter error

cutting force measurements, and the cutting force signal processing method based on the compressive sensing theory was proposed. The results showed that the VPD could effectively reduce the hole wall surface roughness and improve the drilling efficiency while ensuring a small axial force. However, since the VPD entails the strict requirement of a high intelligence degree for the tool holder system, more endeavors need to be made to address this issue in the future.

5.2. *Appropriate selection of tool geometries*

Drill geometry has a significant influence on the tool wear and surface integrity of CFRP hole walls. Further, it can minimize the formation of exit burrs and provide an easy way for the evacuation of chips. The cutting mechanism and generation of cutting forces are mainly influenced by the indentation effects of the drill chisel edge on CFRP materials. Several modifications were implemented on the conventional drills in the form of multifaceted drills, modified point angles, and the inclusion of different groove geometries and stepped structures to minimize undesirable defects and simultaneously increase the drill life.

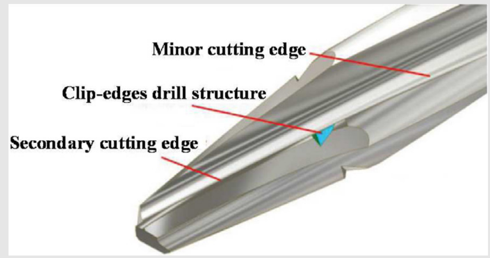
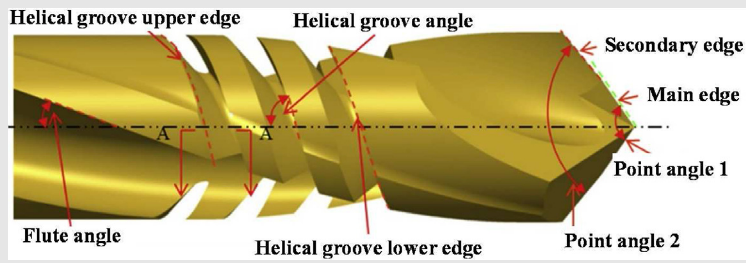
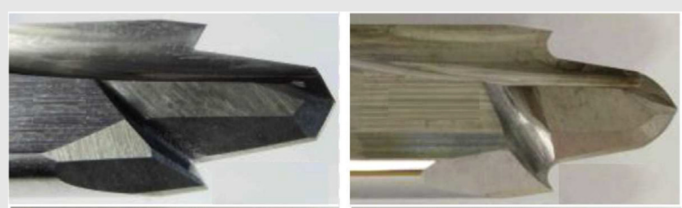
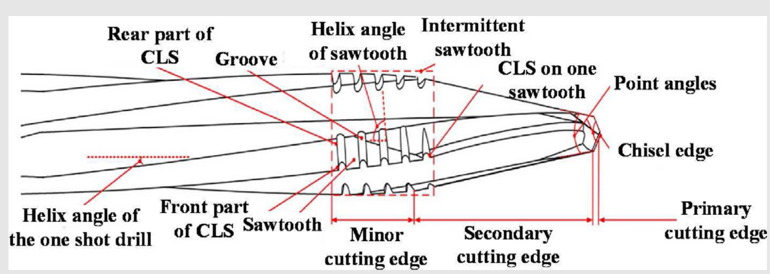
Several authors (Babu et al. [202] and Gaitonde et al. [203]) have evaluated the modified drill geometries during the drilling of CFRP materials. Persson et al. [204] compared the performance of three different hole machining methods for carbon/epoxy laminates, including the Kungl Tekniska Högskolan (KTH) method, a traditional drilling method using PCD drills, and a traditional drilling method using dagger drills. It was found that the holes drilled by the KTH method yielded the highest strength and the longest fatigue life with the best hole quality compared with those machined by the traditional drilling methods using the PCD and dagger tools. Tsao and Hocheng [205] studied the delamination factors by using twist drills, candlestick drills, and saw drills under various cutting conditions. They established a relationship between the feed rate, spindle speed, and drill diameter with delamination. The effect of various drill geometries on the thrust force was predicted analytically and compared with that of the twist drill. Moreover, the authors reported the need to control eccentricity in the twist drill and candlestick drill, which could negatively impact the quality of the composite material. Mathematical models were developed by them for both drills by considering eccentricity. These authors also compared computerized tomography (CT) and ultrasonic C-scan methods to inspect the delamination in CFRPs for various drills and demonstrated that the CT could be used as a feasible and effective tool for the evaluation of drilling-induced delamination.

Tsao and Hocheng [181] further concluded that by distributing the drilling thrust toward the hole periphery, the saw drills and core drills produced less delamination than the twist drills. Brinksmeier and Janssen [206] drilled holes on multilayer materials and concluded that the adapted step drills improve diameter tolerances and surface quality. Durão et al. [41] performed a comparative evaluation of delamination damage on modified drill point geometries while drilling CFRP composites. The results revealed that the influence of brad drills and dagger drills on the delamination of CFRPs is comparatively more significant than that of the twist and stepped drills, especially at higher feed rates. To achieve the minimal delamination factor, 120° twist drills can be chosen as a better alternative. Feito et al. [196] made a comparative analysis of different tool geometries while drilling CFRP laminates. Four uncoated carbide drills, including helicoidal tools, brad center tools, step tools, and reamer tools, were examined. The helicoidal drill was found much better in minimizing delamination damage at a higher range of cutting speeds than the step drill. The study concluded that the performance of the reamer tool was much better compared with the other tools. Samsudeensadham and Krishnaraj [198] performed a comparative analysis on drilling CFRP/Ti stacks with a standard drill and a modified (rake face grooved) drill (Ref. Table 4). The standard drill was modified by incorporating the chip-breaker groove along the rake face to minimize the damage induced by increased thrust force to the CFRP surface. The performance of the modified tool was found much better with respect to the surface quality of CFRPs at the higher range of cutting speeds.

Hao et al. [212] attempted to minimize CFRP damages induced by higher thrust forces through a clip-edge type of drill geometry (Ref. Table 4), which includes a reverse cutting edge. Reduced delamination and tearing damages of CFRP laminates were observed in the case of the clip edge-based drill. Yu et al. [213] implemented a novel helical groove edge on a standard drill to cut CFRP composites. A reduction in burr formation, delamination damage, and composite layer tearing was achieved with this modified novel helical groove. Su et al. [207] studied the mechanism of CFRP surface damage formation when using novel tool geometries. The authors studied the variation of thrust forces at 360° circumferences for four different types of modified drills (Ref. Table 4). The candlestick-type cutting tools with linear edges were found to produce minimal surface damage on CFRP laminates than the modified tools with arc-type cutting edges. Jia et al. [208] introduced a novel drill structure to one-shot drill bit (Ref. Table 4) for clean drilling of CFRP laminates. The intermittent saw-tooth design was implemented and its performance was compared with normal one-shot drills. The saw-tooth design-based tool was observed to perform better in terms of the number of burr-free holes, approximately six times more than the holes produced by a standard twist drill.

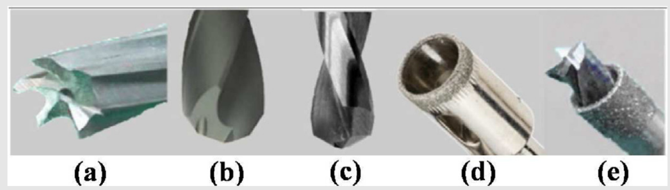
A review of the studies investigated shows how different kinds of drill geometries such as one-shot drills, multifaceted drills, dagger drills, modified dagger drills, modified saw-toothed structure drills, double point angle drills, core drills, special core drills, and hybrid designs such as core-twist, core-saw, core candle-stick drills, and brad and spur drills are used for enhanced drilling quality of CFRP materials. The current requirement of the industry is to make neat holes with better surface quality and non-delamination, along with higher tool life. Although numerous drill geometries are studied by researchers, the standard twist drill seems to be the preferred choice for the industries. This is because sophisticated geometries are expensive and difficult to regrind. Modifications in point angle, helix angle, and improved coating techniques are the desired objectives of the industry. Further, the drills should be reused without much effort.

Table 4 – Modified tool geometries and their morphologies for CFRP drilling.

Ref.	Tool morphologies
Hao et al. [212]	 Implementation of clip-edge on the one-shot drill bit
Yu et al. [213]	 Implementation of helical groove on the double point end drill bit
Su et al. [207]	 Modified dagger drills
Jia et al. [208]	 Modified one-shot drill with the intermittent-saw-tooth structure

(*continued on next page*)

Table 4 – (continued)

Ref.	Tool morphologies
Samsudeensadham and Krishnaraj [198]	 Implementation of macro groove on the rake face standard twist drill
Gao et al. [209]	 (a) Saw drill; (b) double point angle drill; (c) 8 facet drill; (d) core drill; (e) special core drill
Tsao and Chiu [42]	
Soepangkat et al. [195]	

5.3. *Appropriate selection of tool coatings*

The abrasive nature of CFRP materials often leads to rapid tool wear in drilling operations. Tool materials affect the wear development of drills as they influence the mechanical properties of the tool-composite interaction governing the CFRP drilling [210]. Tool coating is one method which minimizes chemical reactivity and the dispersion that arises in the contact regions of the tool; further, it increases the tool life. Wang et al. [171] and Yaşar and Günay [145] analyzed the life of the uncoated, diamond, AlTiN, and TiAlN-coated drills during the drilling of CFRP composites. The edge rounding-based wear induced by material stagnation was analyzed for uncoated and coated drills. Based on the study, the performance of the diamond-coated tool was better in minimizing the edge rounding wear compared with the AlTiN-coated drill. Increased cutting force was noted for the coated drills compared with the uncoated ones, whereas, considering the temperature, the uncoated drill produced higher temperatures than the coated drills, which led to poor hole quality. D'Orazio et al. [211] investigated the hole quality and tool life using diamond-like carbon (DLC) and nanocomposite TiAlN-coated tools during the drilling of CFRP/Al stacks. The major wear patterns, namely, chipping, abrasion, and edge rounding, were observed with DLC-coated drills, whereas abrasion is the only wear mechanism observed for the nanocomposite-based TiAlN-coated drills. The overall performance of the DLC-coated drill was much better compared with the nanocomposite TiAlN-coated tool.

Ashrafi et al. [214] evaluated the effects of uncoated and AlTiN-coated drills on the surface quality of CFRP materials. The uncoated drills were found to perform better in minimizing thrust forces and surface damage compared with the coated ones. Gao et al. [209] and Rampal et al. [215] reviewed various failure mechanisms and suppression strategies during the drilling of CFRPs. The authors studied the performance of coated drills through a comprehensive literature survey and concluded that the PCD drills yielded better performances than the WC drills. Also, the dual-layer coated microcrystalline diamond drill performed better in yielding longer tool life and lower cutting forces. The authors stated that the occurrence of wear of uncoated carbide drills could be attributed to the edge rounding failure, whereas oxidation (titanium oxide and aluminum tri-oxide) was the reason for the failure of the AlTiN-coated drills.

One of the requirements of CFRP machining is to have a sharper cutting edge along with a higher abrasion-resistant coating. Tool material also plays a vital role. Although the PCD tools are the preferred choice in drilling CFRPs, the carbide tools are more widely used in industries due to their lower cost. To improve the tool life, numerous researchers have conducted the performance evaluation of various tools with different coating materials. Based on the above literature survey, the performance of the diamond-coated drill is much better in reducing CFRP surface damages and increasing tool life compared with the uncoated drill. There is a critical need for highly abrasive coating with lower coating thickness, which keeps the cutting edge sharper. The development in coating techniques, especially nanocomposite coatings, can provide a solution to the demand of the composite drilling industry.

5.4. *Advanced drilling techniques*

Advanced drilling processes are introduced to minimize the thrust force and suppress drilling-induced damage for CFRPs. Dhakal et al. [216] and Montesano et al. [217] investigated the hole making of fibrous composites following an abrasive water jet drilling (AWJD) process to explore the surface damage variations. The authors conducted a comparative analysis on three different composite samples produced by the vacuum bagging process. The traverse speed of the water jet was noted as a major factor affecting the delamination and surface finish of cut composite laminates. The authors observed more crater damage on CFRP compared with the remaining materials, which could be attributed to the increase in the traverse speed of the water jet. Also, the authors reported that the use of AWJD could lead to zero tool wear compared with the conventional drilling processes.

Irina Wong et al. [218] studied the minimization of the kerf-taper and surface failures during the AWJD of FRPs. The traverse rate is found to be the most significant factor, which affects the entry and exit delamination of FRPs. The minimum kerf and surface damages were achieved by the minimal cutting speed with increased kinetic energy. Hole quality analysis of CFRPs using ultrasonic vibration assisted drilling (UVAD) process was performed by Ma et al. [219] to find the significance of the feed rate. Novel longitudinal and torsional coupled UVAD produces a minimal thrust force of around 40% compared with the traditional drilling process and this phenomenon leads to improved surface integrity in drilling CFRPs. Cao et al. [220] developed a mathematical model to suppress the delamination damage of CFRPs during the UVAD process. The axial force was considered a function of a mathematical model. The experimental results agreed well with the delamination prediction model.

Sadek et al. [221] performed the vibration-assisted drilling (VAD) process on CFRPs to minimize temperature-related defects. The VAD method improves the process by producing more than 40% damage-free holes compared with the traditional drilling operations. Further, it reduces the drilling temperature by up to 50%. Also, a few researchers (Huang et al. [222] and Makhdum et al. [223]) studied the UVAD process to achieve extended tool life and better surface quality of CFRPs through numerical and experimental methods. Ahmad Sobri et al. [224] performed the drilling of CFRPs using a laser-assisted drilling (LAD) process. The authors compared the LAD with the mechanical drilling process in terms of surface damages. The study reveals that the LAD is only suitable for lower thickness CFRPs, whereas, at higher thickness, it produces a larger heat-affected zone (HAZ) induced by the stagnated vaporized materials. Li et al. [225] drilled the CFRPs using the ultraviolet (UV) laser technology to improve the surface integrity via the reduction of HAZ induced by the laser. Also, the authors suggested that the accumulation of heat can be avoided only through the proper heat distribution provided in the hole region.

Sadek et al. [226] and Kong et al. [227,228] drilled the CFRP materials using the orbital drilling (OD) process to minimize the damages related to temperature and delamination issues. The holes are produced with lower temperatures and negligible delamination induced by reduced thrust forces during the OD. Also, the OD process maintains better repeatability on quality parameters even at higher speed ranges. Sheikh-Ahmad and Shinde [229] and Islam et al. [230] performed a feasibility study on the drilling and deburring of CFRPs through electric discharge machining (EDM). The gap-current, pulse-on-time, and two different electrodes were chosen as the primary input parameters to control the process. The performance of graphite electrodes was found to be better in terms of complete hole making on CFRPs, whereas the performance of copper electrodes was found to be better in terms of the deburring process of existing holes. A summary of the effects of different advanced drilling techniques on CFRP drilling is shown in Table 5 for easy understanding.

Finally, with respect to the abrasive water jet machining (AWJM), it is justified for the repair of CFRP laminates, whereas for making precise holes, it cannot be used. Kerf width and surface damage will be significant issues when the AWJM is employed. The ultrasonic-assisted drilling technique performs much better by enhancing hole quality. If an ultrasonic head is used, it can perform the drilling process equivalent to a conventional drilling technique. Although the LAD and EDM techniques are demonstrated for the drilling of CFRPs, they cannot be employed for the mass production of precise holes in composites because of the thermal degradation of polymers. From the advanced drilling techniques reported, both the VAD

Table 5 – A summary of the effects of advanced drilling techniques on CFRP drilling.

Ref.	Advanced drilling techniques	Effects on CFRP drilling
Dhakal et al. [216] and Montesano et al. [217]	The AWJD technique	Reduce the kerf-taper and surface failures
Sadek et al. [221]	The VAD technique	Minimize the temperature defects
Huang et al. [222] and Makhdum et al. [223]	The UVAD technique	Extend tool life and yield good surface quality
Ahmad Sobri et al. [224]	The LAD technique	Be suitable for lower thickness CFRPs
Li et al. [225]	The UV laser technology	Improve the surface integrity via the reduction of HAZ induced by the laser
Sadek et al. [226] and Kong et al. [227,228]	The OD technique	Minimize the geometrical defects such as delamination and uncut fibers
Sheikh-Ahmad and Shinde [229] and Islam et al. [230]	The EDM technique	Act as the deburring process of existing holes

and OD are promising approaches for making holes in CFRPs with improved surface quality and production rate.

6. Concluding remarks and future perspectives

This paper addresses the drilling mechanisms and machinability issues of CFRP composites through a comprehensive literature survey. A critical review reporting the state-of-the-art advances in the mechanical drilling of CFRP composites is presented to point out the existing challenges and potential approaches toward damage-free machining of CFRPs. The novelty of the review article lies in reviewing the fundamental drilling mechanisms, introducing the force/temperature features, summarizing the process optimization techniques, and overviewing the advanced machining techniques for high-quality drilling of CFRPs. Based on the current review work, the following key conclusions and future perspectives can be drawn.

- The inherent heterogeneity and anisotropy are the key cause of the complicated cutting mechanisms and poor surface finish of CFRP composites. The fiber orientation plays a vital role in chip separation and damage formation of CFRPs apart from the conventional drilling parameters. To date, most of the existing studies addressing the drilling damage formation of CFRPs rely on traditional experiments and simulation methods, and no systematic explanation for the damage formation mechanisms has been formed. Developing accurate and reliable thermo-mechanical coupling constitutive models for fibrous composites could be an alternative way to reveal the complicated drilling mechanisms of CFRPs at the micro-scale level, which will be a leading research direction for cutting mechanism investigations of CFRPs in the future.
- Drilling-induced damages are critical factors influencing the surface quality of cut CFRPs. Among them, delamination, burrs, tearing, and surface cavities are crucial issues that must be carefully suppressed to achieve damage-free cutting of CFRPs. Drilling parameters, tool geometries/materials, and cutting environments are confirmed to be important factors influencing the drilling quality of CFRPs. The use of high cutting speeds and low feed rates is found to favor the machinability and quality improvements of CFRPs. In the future, more research efforts need to be made on optimizing process parameters, developing suitable tool geometries/coatings, and applying proper cutting environments such as cryogenic cooling to significantly suppress the drilling damages and improve the quality of cut CFRP holes.
- Additionally, optimization of machining parameters with improved tool geometries/coatings can also play a major role in improving the production rate of CFRP drilling with longer tool life. Literature at present provides key issues associated with cutting mechanisms, optimized machining parameters and hole quality for selected conditions. However, not much work is reported on the high-speed drilling of CFRPs. To prolong tool life, future work can be focused on developing innovative coatings, especially oxide and diamond coatings, to overcome the abrasive nature of CFRP materials. Moreover, revealing the mapping mechanisms between tool geometries/materials, cutting environments, process parameters and CFRP hole-making quality and proposing a comprehensively optimized hole-making strategy are the key to improving the drilling quality and efficiency of CFRPs, which will be the future development direction of composites manufacturing community.
- Finally, more research work must be done on the optimization and improvement of hole dimensional accuracy for CFRPs, except for the suppression of drilling-induced defects. Additionally, the suppressing mechanisms of drilling-induced defects for hybrid composite materials such as CFRP/alloy need to be further addressed. In the future, the theoretical analyses and experimental optimization of advanced drilling methods such as VAD, OD, and VPD of CFRPs are anticipated to get more attention. These techniques are expected to greatly suppress the drilling-induced damage and improve the quality of cut composite holes.

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.

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Jinyang Xu is an Associate Professor and a Doctoral Supervisor of Mechanical Engineering at Shanghai Jiao Tong University, China. His research interests focus on composites machining, numerical modeling, micro/nano cutting, and surface texturing.

Norbert Geier is currently an Assistant Professor at the Department of Manufacturing Science and Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Hungary. His main research interests focus on manufacturing science and composites machining.

Jiaxin Shen is currently a master student at the School of Mechanical Engineering, Shanghai Jiao Tong University, China. Her research work focuses on mechanical drilling of CFRP composites.

Vijayan Krishnaraj is a full Professor at the Department of Production Engineering, PSG College of Technology, India. His research interests concern the machining of fibrous composites and difficult-to-cut materials.

S. Samsudeensadham is an Assistant Professor at the Department of Mechanical Engineering, PSG College of Technology, India. His research activities focus on mechanical manufacturing, mechanics of machines, and industrial automation.