Drilling of carbon fiber reinforced polymers for aerospace applications: A review

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Abstract

Drilling is considered as one of the more challenging problems in the aerospace structures stringent tolerance required for fasteners such as rivets and bolts to join the mating parts for the final assembly. Fiber-reinforced polymers are widely used in aeronautical applications due to their superior properties. One of the major challenges lays in the machining such polymers is the poor drilled-hole quality which reduces the strength of the composite and leads to part rejection at the assembly stage. In addition, rapid tool wear due to the abrasive nature of composites requires frequent tool change which result in high tooling and machining costs. This review intended to give in-depth details on the progress of drilling of fiber-reinforced polymers with special attention given to carbon fiber reinforced polymers. The objective is to give a comprehensive understanding of the role of drilling parameters and composite properties on the drilling induced damage in machined holes. Also, the review looks into the drilling process parameters and its optimization techniques, and the effects of dust/ aerosols on human health during the machining process. This review will provide the scientific and industrial communities with their advantages and disadvantages through better drilled-hole quality inspection.

Keywords: Drilling; Carbon-reinforced polymers; Drilled-hole quality; Process parameters, dust particles

1. Introduction

Fiber-reinforced polymers (FRPs) is the most commonly used composite material in aerospace structures. Their unique properties such as high performance, lightweight, higher stiffness and , and better corrosion resistance makes them attractive choice for aeronautical applications [1]. In FRPs, the reinforcement usually the fibers are the hard, stiff and strong dispersed phase of the composite embedded within the matrix [2]. The reinforcement is also the main load-bearing element because the load may be transferred to the other near fibers through the matrix, in case of any single fiber breakage [3]. While the matrix acts as a binder by surrounding the reinforcement. The matrix does not bear much of the load but protects the structure from surface damage and harsh environments like high temperature and humidity [3]. It also provides ductility and prevents cracks propagation from one fiber to another [4]. Therefore, fibers resist tension, matrix opposes against shear, and together both act to resist compression, reflecting the overall properties of the composites [3].

FRPs includes carbon fiber reinforced polymers (CFRP), glass fiber reinforced polymers (GFRP) and aramid fibers [5]. CFRP is primarily choice used in high technology applications. GFRP with the common types of E-glass (electrical) and S-glass (high strength) also exhibits superior properties where S-glass is used in aerospace applications [6]. Aramid fibers (trade name Kevlar) are commercially available as

Kevlar 49 and Kevlar 29. Kevlar 49 is principally used in aerospace, marine, and automotive applications where Kevlar 29 works for ballistic protection [3].

In the aerospace industry, CFRP is often used in the aircraft wing box, horizontal and vertical stabilizers, and wing panels [8]. GFRP is used in the fairings, storage room doors, landing gear doors, and passenger compartments [8]. FMLs are used in upper fuselage skin panel structures [9]. Most common examples are Boeing and Airbus airliners [8]. Dream-liner, Boeing 767, 787, and Airbus A350, A380, etc. increasingly used composite laminates over 50% of the whole vehicle weight. The airframe of Airbus A380 constitutes 25% of composites, including 22% of CRFP or GRFP and 3% of FML [10]. Figure 1 shows the material breakdown of the airbus structures [10].
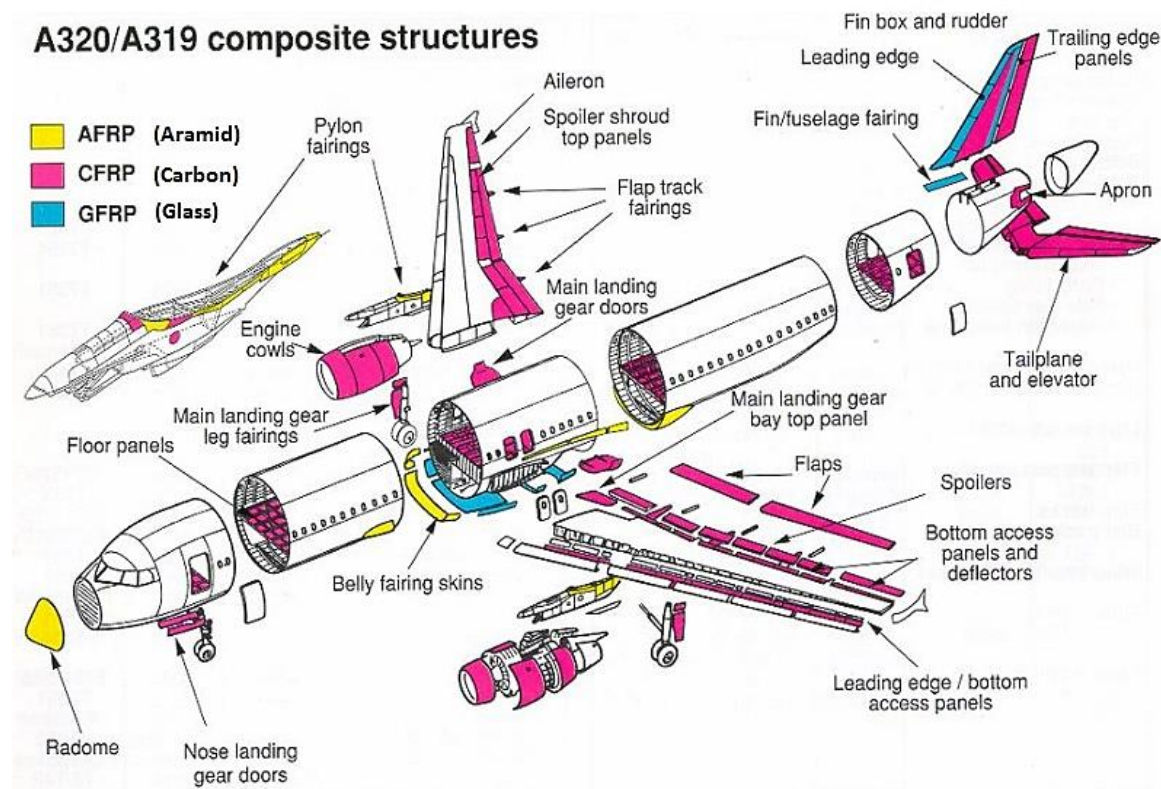

Figure 1: components made of FRPs used in Airbus [10]

In the aircraft structural parts, a large number of holes are required for producing riveted and bolted joints the assembly stage of drilling processes [11]. The range of the number of holes drilled a commercial aircraft is up to 1.5-3 million while a jet fighter is required with as many holes as 300,000 [12-14]. The challenges in drilling process of FRPs arises from their heterogeneous, anisotropic highly abrasive and hard nature of fibers, which causes drilling induced damage issues such as delamination [15]. The dimensional accuracy of machined holes and its surface finish are effected by delamination which ultimately leads to 60% of all part rejection at the assembly stage [16]. In addition, the abrasive

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nature of the fibers requires frequent tool change which results in high machining costs. Therefore, selections of suitable machining parameters and proper tool geometry are essential for producing acceptable hole quality in FRPs [11]. Other commonly drilling-induced hole damages in FRPs include matrix cratering, fuzzing, , fiber/matrix de-bonding, spalling, fiber pullout, fiber breaking, resin loss, surface cavities, uncut fibers, etc. [16]. Figure 2 illustrates some of the drilling induced damage in FRPs [17] where the SEM image of typical hole quality defects is given in Figure 3 [12].

Figure 2: Drilling induced hole damage in FRPs [17]

Figure 3: SEM images of hole quality defect [12]

All such failures come from the machining of the composite which ultimately degrades the strength and fatigue life of the components, hence reducing the performance of FRPs in long-term [18]. Therefore, drilling precise and damage-free holes is important to confirm the joint strength and avoid any rejected parts [19]. This is the reason that the research and development of composites drilling is an essential process and needs further in-depth investigations.

Researchers, in general, have sought to extend the literature survey on different aspects of drilling of FRPs for the improvement of better drilled-hole quality. For instance, Liu et al. [15] discussed different drilling operations of FRPs for the improvement of drilling-induced delamination. Khashaba [20] gave special attention to machinability parameters, the analytical damaged model and different factors affecting the drilling-induced delamination in drilling of FRPs. Kavad et al. [21] reviewed the impact of process parameters on the delamination of GFRP during conventional drilling, vibration-assisted drilling, high-speed drilling, and ultrasonic-assisted drilling. M'Saoubi et al. [22] presented recent advances in cutting of FRPs as well as aerospace alloys. In another study, by Xu et al. [23] the drilling solution to hybrid composites i.e., FRP/Ti was discussed and the multiple aspects of cutting responses were presented in a very comprehensive manner. Panchagnula and Palaniyandi [24] reported on the drilling of FRPs as well as Nano-polymer composite laminates and discussed different machining parameters to reduce delamination. Patel and Buch [25] attempted to review the various aspects of drilling of FRPs where the main focus was given on GFRP. Vigneshwaran et al. [26] discussed drilling operations of FRPs

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including GFRP, CFRP and natural fibers reinforced composites. The review gave in-depth detail about the drilling damages in response to the influence of various parameters. In another review by Karataş and Gökkaya [27] the conventional and non-traditional machining of both CFRP and GFRP were discussed.

Although there are several surveys available in the literature, however, the considerable limitations in FRPs drilling process and their ever-growing demand stimulate both academic and industries for further research and development. Therefore, there is still a need to explicitly understand the drilling behavior of FRPs for high quality holes and to minimize any defects [27]. Furthermore, the dust produced during machining of FRPs, especially, CFRP has a significant impact on health has not been discussed in detail and fewer studies in the literature have paid attention to the dust analysis. Therefore, this review focuses on drilling of CFRP in relation to the effect of fiber orientation, drilling-induced delamination and assessment, drilling process parameters and its optimization techniques, and the effects of dust/ aerosols on human health during the machining process.

2. Role of the orientation of the fibers in carbon fiber reinforced polymers

In CFRPs, the fibers have more strength than the matrix. It is estimated that about 70 - 90 % of the primary load carrying capacity are the fibers because the matrix is only considered as a binding medium. The important factor responsible for the damage tolerance is the direction of the fibers because composites are strong enough in the fiber direction [28]. In Unidirectional (UD), the CFRP is said to be anisotropic. The UD CFRP has maximum strength and stiffness along the direction of the fibers as compared to the direction perpendicular to the fibers because the fibers run only in one direction [15]. The bi-directional fiber-oriented woven-ply such as a plain weave fabric runs in two directions normally 90° apart with not necessarily the same strength in both directions [15]. Continuous fiber reinforcement is usually used in the UD or bidirectional (woven) forms to form a thin plate normally of 0.15 mm, called the pre-pregs ply [15]. Proper selection of ply orientation is important in CFRPs to get the optimum mechanical properties and provide an efficient structural design because the strength designs requirement depends on the direction of the applied load, the orientation of the plies and correct sequence. Therefore, plies of the UD require alignment at different orientations normally, cross-ply to form a quasi-isotropic composite laminate [29]. Figure 4 shows the schematic illustration of the FRP [15].
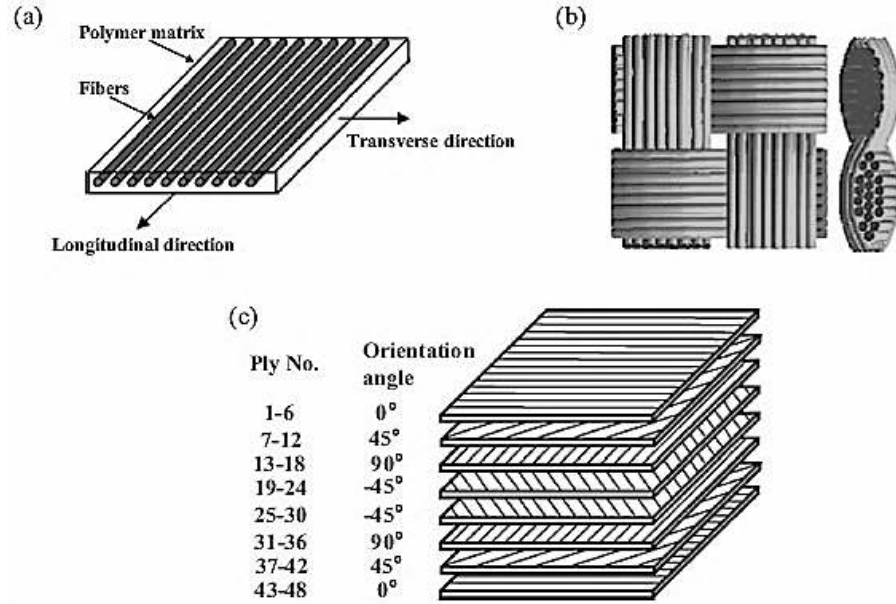
Figure 4: FRP: (a) UD-ply laminate, (b) woven-ply laminate, and (c) multi-orientated laminate with quasi-isotropic [15]

In a quasi-isotropic laminate structure, the laminate has an equal number of plies and should be stacked at 0°, - 45°, 45°, and 90° sequence. The plies in a direction of 0° is to react to axial loads, ±45° to resist the shear loads, and 90° to react to side loads. This is the most-used stacking sequences in actual production that simplify the analysis and design of the most fastened joints. In addition, this choice of quasi-isotropic pattern is close to having optimum properties because the orientations of plies in this direction are considered as isotropic materials. Furthermore, the quasi-isotropic arrangement is used in the aerospace structure to endure better loads and in this way, it is also expected that material, and hence the weight can be saved, which is essential in the aviation and aerospace industry [30]. Table 1 shows the quasi-isotropic laminate structure most recently investigated by various researchers.

The fiber orientation in FRPs is also highly dependent on chip formation [31]. At fiber orientation of 0°, delamination type and fiber buckling type chips are formed with the only difference of the cutting tool position. The chips produced in both the types are discontinuous where the buckling type chips are smaller as compared to the delamination type because the generation of cutting force in the delamination type is larger and fluctuating more than the buckling type [32,33]. The fiber cutting type continuous chips and discontinuous chips are produced when the fibers orientation is greater than 0° and less than 90°. The chips become discontinuous with a decrease in size when the fiber orientation reached up to 90° due to the inter-laminar shear stress at the fiber/matrix interface. Furthermore, Shearing with discontinuous chip are formed at 90° < θ < 180° [32,33].

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Furthermore, the fiber orientation also depends on the quality of the drilled hole [34]. Wang et al. [35] investigated that fiber orientation of 0 to 90° of machined epoxy reinforced UD carbon fiber gave lower surface roughness and increased as the orientation of fiber reached up to 150°. The same conclusion was reported by Ghafarizadeh et al. [36]. Gao et al. [37] concluded that surface roughness became worse as the fiber orientation increased from 45° to 135° because of the surface irregularities. Palanikumar [38] also reported that increase in the fiber orientation from 15° to 120° made the surface roughness poorer. Furthermore, H. Gao et al. [39] concluded that the exit drilled holes od UD epoxy composites were found more prone to damage with fiber orientation. The hole quality level improved if the fiber orientation decreased in the range of 0° to 90° while the defects at the drilled hole were more severe when the orientation of the fibers increased in the range of 90° to 180°.

3. Drilling process on carbon fiber reinforced polymer

The machinability of FRPs is considered more challenging because it needs different machining parameters than those required for conventional metal cutting [40]. The difficulty in the machining of FRPs arise due to the two phases of the composite with considerably different properties and thus making the behavior of composite machining different [41]. Furthermore, the cutting tools have to face a harsh environment due to high thermal resistance and abrasiveness and related wear [42]. This requires more reliable cutting tools to resist the varying mechanical and thermal loads [23]. There are several non-traditional machining operations but drilling especially, the conventional drilling with twist drill bits got extensive attention in composites [43]. Therefore, drilling precise and damage-free holes is important to confirm the joint strength and avoid any rejected parts due to poor hole quality [19]. Figure 5 shows the factors affecting the performance of drilling of composites and the summary of recent studies on drilling of CFRP is given in Table 1.
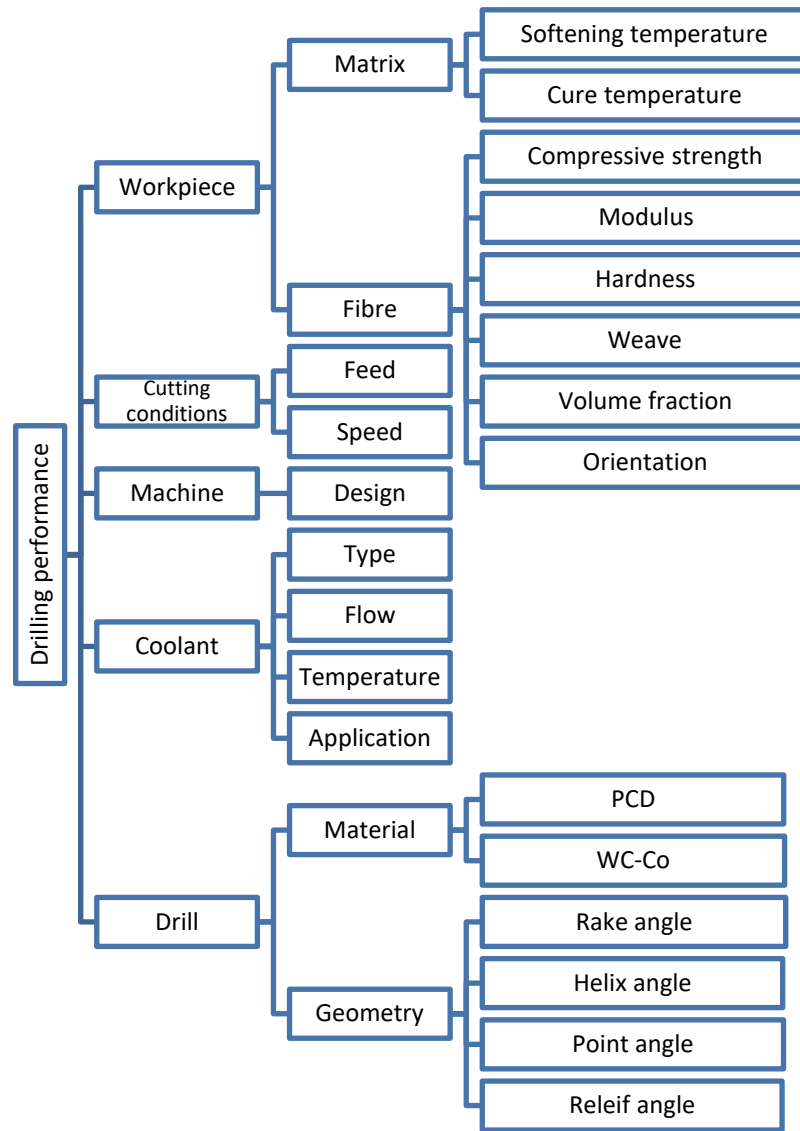
Figure 1: The main factors which determine the drilling performance of composites [44]

Table 1: Summary of the recent studies on drilling of CFRP

Composite	Cutting tool	Cutting parameters	Concluding remarks	Reference
CRFP: • Multidirectional quasi-isotropic • Total laminate thickness: 7.54 mm • average ply thickness: 0.1141 mm	Twist drill: • Uncoated Tungsten Carbide WC-9%Co • AlTiN coated has the 3μm thickness, • Diamond coated with a thickness of 12.5 μm	Spindle speed: 6000 rpm Feed rate: 0.0762 mm/rev Coolant: water-soluble cutting fluid at a constant flow rate of 16mL/min	• Edge rounding was significantly reduced using diamond coated drill as compared to other drill tools	[45]
CRFP: • Stacking sequence: [(0/+45/90/-45)₃]s • Thickness of the unstitched laminate: 7mm	Carbide Twist drill: • Drill diameter: 6mm	Spindle speed: 1800,3000,4200,6000 rpm Feed rate: 0.04, 0.1,0.2,0.3,0.36 mm/rev Dry cutting	• High feed rate has more impact on thrust force, torque and delamination factor than spindle speed • The low thrust force is most effective in reducing the damage risk • At Low feed rate, matrix cracking for the stitched composite is almost absent, measured using acoustic emission	[46]
CRFP: • Unidirectional • Plate thickness: 30 mm • Fiber content: 60% • Ply thickness: 250 μm	Solid carbide drill: • Tooltip angle: 140° • Drill diameter: 12 mm	Cutting speed: 100 m/min Feed: 0.05 mm/rev Dry cutting	• Abrasive wear was the main wear mechanism which contributed to increasing the temperature in the cutting edges and affects the final drilled hole quality	[47]
CRFP: • Fiber volume content: 65% • Stacking sequence [+45/-45/0/0/-45/90/45/0/-45/0/45/90/45/0]s	Twist drill: • Diameter: 4.8 mm • Helix angle: 35°	Spindle speed: 6000 rpm Feed speeds: 20, 30, 40, 50 mm/min.	• Analysis of mathematical model revealed that critical thrust force is related to material properties, the uncut thickness, tool geometry, and load distribution • Finite element analysis results revealed that high feed rate has	[48]

			direct effect on the delamination	
• Ply thickness: 0.1875 mm • Total thickness: 6mm			• The coated drill is more active in achieving best drilled-hole quality due to its smaller thrust force	
CRFP: • Density: 1.1 g/cm^3 • Manufacturing method: Hand layup • Stacking sequence 0°/90°	Drill Type: High-performance drill • Material: Solid Carbide • Coating: TiAlN	Drill speed: 800, 1200, 1600, 2000, 2400, 2800 rpm Feed rate: 50, 100, 150 mm/min Drill diameter: 6, 8, 10 mm	• Minimum torque, thrust force and delamination factor were noted at the highest cutting, lowest feed rate, and minimum diameter	[49]
CRFP: • Quasi-isotropic unidirectional based on pre-peg • Stacking sequence [0/45/90/-45] • Total thickness is 6 mm	UDX drills: • Uncoated WC-6wt% cobalt matrix • A 6µm thickness diamond coating • Drill diameter: 6mm • Point angle: 90°	Spindle speed: 5000 rpm Feed rate: 0.07 mm/rev Cutting speed: 94 m/min Feed speed: 350 mm/min	• Edge rounding abrasive tool wear was found more in uncoated tools as compared to the diamond-coated tool • Linear evolution of delamination damage over tool life was observed with uncoated drill bits	[50]
CRFP: • with upper part copper foil and lower part E-glass with pre-impregnated epoxy • Total Thickness: 9.5 mm	Countersink Carbide drill: • Diamond coated • Point angle: 90° • Nominal diameter: 4.825 mm	Feed rate: 0.10, 0.12 mm/rev Feed speed: 330, 396, 475 mm/min Cutting speed: 50, 60 m/min Drilled distance: 2500, 4400 mm	• High cutting speed and feed simultaneously showed reduced tool wear and delaying the delamination appearance	[51]
CRFP: • Unidirectional • Total Thickness: 4.9 mm	Uncoated twist drill and the stepped drill made of ultra-fine grain carbide • Diameter: 6mm • Point angle: 110° • Helix angle: 28° • Stepped drill pilot diameter	spindle speed: 1500, 3500, and 5500 rev/min, Feed rate: 0.01, 0.02, 0.03, 0.04, 0.05 mm/rev Dry cutting	• Stepped drill with the pilot diameter of 3 mm gave minimum thrust force and hole damage area	[52]

	of 4.5, 3, and 2 mm			
CRFP: • quasi-isotropic multidirectional carbon/epoxy pre-pregs • stacking sequence of [(45°/90°/-45°/0°)6]s • fiber volume content: 65%	• Diamond coated brad spur drill with a point angle of 118° and helix angle of 38° • Uncoated tungsten carbide twist drill with point angle 140° and helix angle of 35° • Uncoated solid carbide dagger drill with tow stage point angle of 118° × 25° and helix angle of 10°, ° and a 64.89 mm length of chip flute. • All drills have 6.35 mm diameter	Spindle speed: 1000, 1500, 2000, 2500 rpm Feed rate: 0.010, 0.015, 0.020, 0.025 mm/rev Dry cutting	• The most appropriate technique for detecting the delamination damage was the Ultrasonic C-scan • Dagger drill is worst among all to achieve damage-free delamination	[53]

Many researchers have investigated the drilling performance of CFRPs. For instance, Wang et al. [45] used uncoated tungsten carbide and diamond and AlTiN coated drills to on drilling of CFRP. The cutting speed chosen was 6000 rpm with a feed rate of 0.0762 mm/rev and these conditions were fixed for all drill tools. A water-soluble cutting fluid was used with a flow rate of 16 mL/min of the mist coolant. It was concluded that the diamond coating performs well as compared to other drill tools in reducing the edge rounding wear. Turki et al. [46] studied that high feed rate has more influence on thrust force, torque and delamination factor than spindle speed. At low feed rate, matrix cracking for the stitched composite was almost absent. Also, the low thrust force is found to be more effective in reducing the damage risk. In another study by Ramirez et al. [47], cemented carbide drills were used to find the relationship among the tool damage, cutting forces, temperature and hole surface quality of the CFRP. It was revealed that the main abrasive wear was the wear mechanism which then contributes to increasing the temperature gradually and subsequently, affects the final surface topography of the drilled hole. Wei et al. [48] developed a mathematical model based on classical plate bending theory and linear elastic fracture mechanics to conduct the analysis of the drill bits on the delamination of CFRP. It was concluded that large feed speed contributed more in the occurrence of delamination. In addition, the coated drill tools achieved better drilled-hole quality due to its small thrust force. Abhishek et al. [49] drilled CRFP using the high-performance solid carbide drill with TiAlN coating. The selected drill speeds were 800, 1200, 1600, 2000, 2400, and 2800 rpm, feed rates were 50, 100, and 150 mm/min and, drill diameters were 6, 8, and 10 mm. It was concluded that minimum torque, thrust force and delamination factor were obtained at the highest cutting, lowest feed rate, and minimum diameter. Gaugel et al. [50] worked on drilling quasi-isotropic unidirectional CFRP based on pre-peg with a stacking sequence of 0/45/90/-45. An uncoated WC-6wt% cobalt matrix and 6μm thickness diamond coating drill bits were used to analyze tool wear and delamination in CFRP. Edge rounding abrasive tool wear was found more in uncoated tools as compared to the diamond-coated tool. Fernández-Pérez et al. [51] used the countersink carbide drill with the diamond coating to drill CFRP. It was noted that high cutting speed and feed simultaneously showed low tool wear and less delamination. Qiu et al. [52] used uncoated twist drill and the stepped drill made of ultra-fine grain carbide to drill CFRP. The stepped drills with the pilot diameter of 3 mm perform better drilling performance. It was investigated that the drilled-hole damaged area was increased as the spindle speed increased. However, the lower thrust force showed lower defects in the holes. Xu et al. [53] concluded that drilling-induced delamination in CFRP depends on drill geometries and cutting parameters. Dagger drill is not recommended for damage-free

delamination. For detecting and characterizing delamination damage, ultrasonic C-scan was found to be a feasible technique.

3. 1. Hole Quality and Drilling induced Damage in fiber-reinforced polymers

In the aerospace industry, the strict requirement is impost to produce high quality machined parts including drilling holes with minimum defects. Therefore, the quality of drilled hole depends on the types of material, drilling conditions and the desired tolerances in an industry. Some of the drill hole damages are shown in Figure 7 [54]. The details of different defects during drilling and the relevant factors affecting these damages are discussed in the following sections.
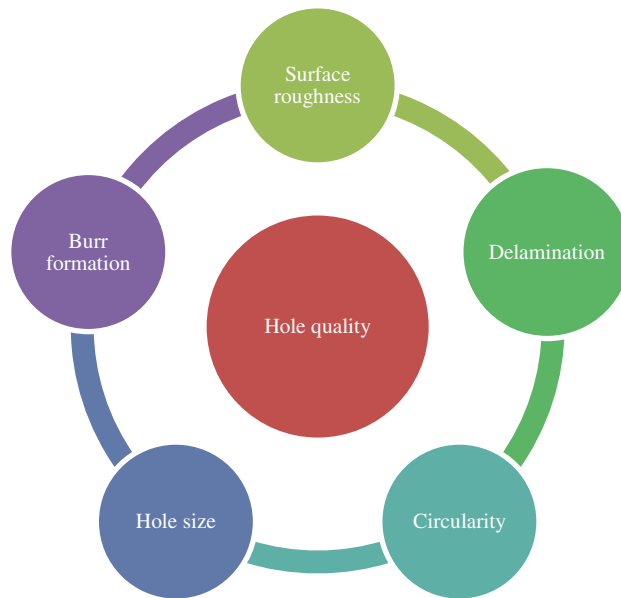
Figure 2: Hole quality inspection criteria [54]

3.1. 1   Drilling-induced delamination and assessment

In FRPs, the damage induced due to drilling commonly occurs through a series of several defects [55]. Among all, the damage caused due to delamination of the drilled- holes is a very serious problem because it leads to a substantial number of part dismissals, especially in the aircraft industry [56]. Delamination can affect assembly tolerance and reduce overall performance because of its great impact on composites structure integrity [26].

Experimental investigations have shown that drilling-induced delamination normally occurs around the drilled hole corresponding to the hole entry and exit [57]. Peel-up delamination zone is the region where the composite layers become spiral up soon the drill approaches the surface of the composites and starts cutting. Push-out delamination occurs at the exit point of the drilled material. As drill advances towards the end of the workpiece. The workpiece thickness decreases and the uncut plies below the

drill lose its resistance against deformation caused by the drill feed force. Finally, the exit delamination region develops when the dill tool enters the exit point [58]. This is the reason that push-up delamination is most frequently observed in composites than peel-up delamination because the strength of the inter-ply bonding reduces when there is higher thrust force exerted by the drill [21]. Figure 5 shows the classification of delamination during FRP drilling [59].
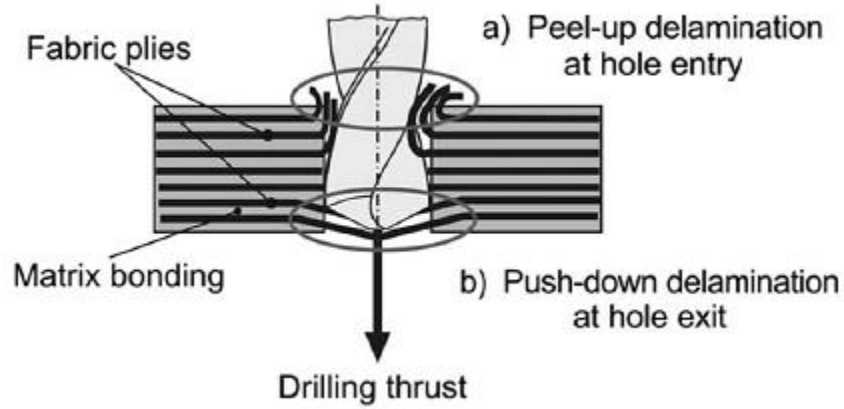
Figure 5: Classification of delamination during FRP drilling [59]

There are several methods for the assessment of delamination level around the drilled holes. The most common characteristic of delamination parameter in composite's drilling is the delamination factor [60]. Table 2 shows a summary of the different evaluation criteria for drilling-induced delamination in composites.

Table 2: Summary of evaluation criteria for drilling-induced delamination

Delamination factor	Equation No.	Associated expression	Remarks	Reference
1D conventional delamination factor	Eq. (1)	$F_d = \dfrac{D_{max}}{D_{nom}}$	D_{max} - maximum diameter of the delamination area D_{nom} - nominal diameter of the drilled hole	[62]
Minimum delamination factor	Eq. (2)	$F_{dmin} = \dfrac{D_{min}}{D_{nom}}$	D_{min} - minimum diameter of the drilled hole	[63]
Delamination size	Eq. (3)	$Delamination\ size = R_{max} - R$	R_{max} - radius of the maximum damage R - is the drilled hole radius	[64]
2D delamination factor	Eq. (4)	$F_a = \left(\dfrac{A_{del}}{A_{nom}}\right)\%$	A_{del} - delamination area A_{nom} - nominal area of the drilled hole	[65]

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Damage ratio	Eq. (5)	$D_{RAT} = \dfrac{D_{MAR}}{A_{AVG}}$	D_{MAR} - hole peripheral damage area A_{AVG} – nominal drilled hole area	[66]
Delamination factor	Eq. (6)	$F_d = \dfrac{A_d}{A}$	A_d – Area of the envelope of the damaged area, including the hole area	[67]
Adjusted delamination factor	Eq. (7)	$F_{ad} = \alpha \left(\dfrac{D_{max}}{D_{nom}}\right) + \beta \left(\dfrac{A_{del}}{A_{nom}}\right)$	where α, β are parameters used as weights $\alpha = 1 - \beta, \beta = \dfrac{A_{del}}{A_{max} - A_{nom}}$	[68]
Equivalent delamination factor	Eq. (8)	$F_e = \dfrac{D_e}{D}$	$D_e = \sqrt{\dfrac{4(A_{del} + A_{nom})}{\pi}}$	[69]
Three-dimensional delamination factor	Eq. (9)	$F_v = \dfrac{1}{p} \sum_{k=1}^{p} F_a^k$	Where $F_a^k = \dfrac{A_d^k}{A_{nom}}$ signifies the 2D delamination factor of the kth CFRP layer. A_d^k - delaminated area of the kth CFRP layer A_{nom} - the nominal drilled hole area P - the total number of the delaminated layers	[53]

Chen, [62] defined the delamination factor as the ratio of the maximum diameter of the circle encompassing the delamination zone of the circle to the hole nominal diameter as indicated in Eq. (1). This is the one dimensional (1D) delamination factor and does not take into account the actual damage, but gives only the delamination up to the maximum extent in the radial direction. Therefore, this parameter may not be considered as a full representation of the drilled-hole quality. For instance, two holes characterized by the same delamination factor parameter may be qualitatively different and depicts different delamination patterns. For example, in GFRP which shows a regular pattern of delamination this conventional delamination gives acceptable results. However, in case of CFRP, the delamination patterns are irregular due to fine cracks [68] and the conventional delamination might be inappropriate because of the lack of indication of delamination area during calculation [70]. Later, Da Silva [63] presented a similar parameter which is minimum delamination factor for the calculation of the drilled hole delamination given in Eq. (2). However, this method also does not contribute to the damaged area for the assessment of delamination [70]. U. A. Khasaba [64] assessed delamination factor using the method given in Eq. (3) to evaluate the damaged around the hole by measuring the size of

delamination. The delamination damage is characterised with different maximum damaged radius and the one with higher damaged radius value shows the greater delamination. However, this method has the same problem as the delamination factor because it was calculated from the same measurement. Other alternative delamination characteristic parameters proposed in the literature include the two dimensional (2D) delamination factor which evaluates the delamination based on area. This indicator extracts the cumulative peripheral damaged area and the nominal drilled-hole area in percentage given in Eq. (4), proposed by Faraz et al. [65]. However, long cracked damage is not accurately measured by this method. Mehta et al. [66] suggested another method similar to the 2D delamination factor i.e. the damage ratio which is the ratio of the drilled-hole peripheral damaged area to the nominal drilled-hole area given in Eq. 5. This method is presented as a factor instead of a percentage which is the only difference from the 2D delamination factor. However, this method lacks to differentiate the defects of the drilled holes with same area in which the deformation in one hole is uniform at its neighborhood while the other has deeper and longer cracks. Therefore, this method is suitable when the delamination of the drilled hole has different damage areas. In addition, Mohan et al. [67] also proposed similar delamination factor which is named as delamination factor and is given in Eq. 6. It is the ratio of delaminated area to the nominal area. This method also consider only the damaged area and is not appropriate for the contribution of the maximum crack length which is the same drawback as in the case of 2D delamination factor and damage ratio. Davim et al. [68] introduced the adjusted delamination factor which signifies the comprehensive consideration of both 1D and 2D delamination factor. The first part of the Eq. (7) contributes in the crack size while second part accounts for the contribution of the damaged area. Tsao et al. [69] proposed the equivalent delamination factor, which is the ratio of equivalent delamination diameter to the hole diameter, calculated according to in Eq. (8). Furthermore, Xu et al. [53] proposed a three dimensional delamination factor given in Eq. (9) which can identify the inter-laminar failure inside the composite based on a 2D delamination factor.
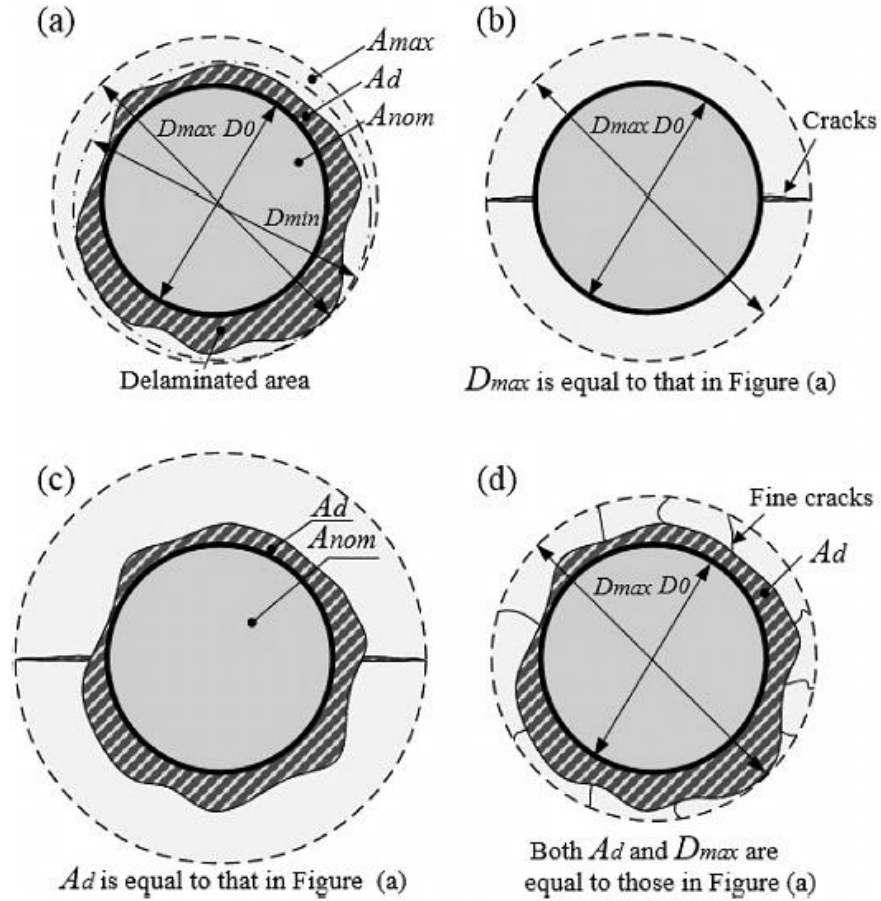
Figure 6: Drilling induced hole damage of CFRP: (a) uniform damage, (b) cracks, (c) uniform damage with cracks and (d) uniform damage with fine cracks [70]

In addition to the above criteria for the evaluation of delamination, other inspection includes there visual or non-destructive techniques. Visual inspection is the simplest way of detecting the composite defects to see the delamination, cutting tool marks and some other surface defects. But, it is likely that in some cases the defects are inside and cannot be seen properly visually. In this case, non-destructive techniques are important to inspect the damage around the drilled hole. Scott et al. [71] summarized the most common non-destructive techniques which include: ultrasonic testing, holography, and thermography. Other non-destructive methods include: optical microscopy, computerized tomography and CT-Scan [72], laser imaging [73], microwave near field non-destructive testing, thermal imaging [74], digital photography [68,75], radiography [76-78] and sonic IR imaging [79]. The comparison of the most common method to inspect the damage in the FRPs is given in Table 3.

Table 3: Comparison of major inspection methods [80]

Damage	Delamination	Fiber breakage	Matric cracks	Surface defects	Damage size	Distance from surface
Deply	✓✓	✓	✓	✓✓	✓✓	✓✓
Fractography	✓✓✓	✓✓	✓	✓✓	✓✓	✓✓✓
Visual inspection	✓✓	✓	✓	✓✓✓	✓	✓
Ultrasonic	✓✓	X X X	X X X	X X	✓✓	✓✓
Radiography imaging	✓	✓✓	✓✓	O	✓✓	✓✓
Thermal Imaging	✓	X X	X X	X X	✓	X X
Acoustic emission	X X	X X	X X	X X X	X X X	X X X
Laser based optical imaging	✓	X X	X X	X X		X X X
Microwave	X X X	X X	X X	O	✓	X X X
Eddy current testing	X X X	✓✓	X X	X X	✓	X X

✓✓✓ = Very good, ✓✓ = Good, ✓ = Fair, X X X = Very poor, X X = Poor, O =None

3.1. 2   Surface roughness, Hole size and circularity, and Burr formations

One of the major characteristics in the drilling process is the surface roughness which is used to measure the surface texture or finishes by examining the irregular surface of the workpiece. Drilled holes with high surface roughness in any workpiece result in excessive wear, fatigue and lower the material ability to resist corrosion [81]. Therefore, good surface roughness can give quality drilled hole for the performance of any machined parts [14]. Surface roughness can be assessed by profiling methods and area methods. The profiling methods are accurate but produce point by point surface height information, where the area methods are faster but produce average area properties. The most widely used method of measuring surface roughness is through the use of a mechanical stylus tracing for linear roughness measurements. Figure 7 shows further classification of the two methods for the measurement of SR techniques. For more details readers are referred to Vorburger et al. [82]. Furthermore, Surface roughness is greatly influenced by machining parameters, tool parameters and the vibration produced by the cutting tool [16].
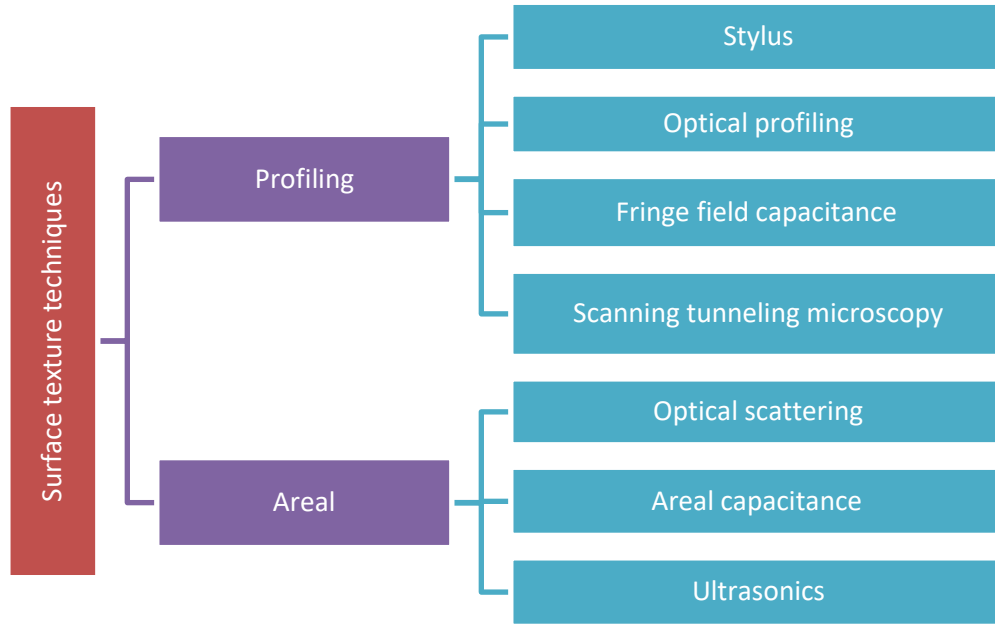
Figure 7: Surface texture measurement techniques [82]

In addition to Surface roughness, the deviation of the drilled-hole size from the nominal diameter such as circularity also contributes to the performance of the machined parts [83]. It is considered as the most important fundamental forms for engineering components for the quality assessment of drilled holes [54]. The circularity error range for CFRP is 80-250 μm [84], for GFRP the range by [85] is 4- 41 μm and 42.5-312 [6] where for CFRP/Al2024 the range is 6-25 [86]. Least Squares Circle, Minimum Zone Circle, Minimum Circumscribed Circle, Maximum Inscribed Circle are some of the methods used to find the circularity error [87]. Kurt et al. [81] concluded the drill-hole diameter deviates from its original size and may increase in size due to high cutting speed. This is because there are more drilling vibration and chatter at high spindle or cutting speed which affects the accuracy of the drilled hole. Furthermore, the drill tool dynamic behavior also contributes in larger diameter at the hole exit due to the fact that when drill touches the workpiece, the vibration may have its maximum value.

Furthermore, in drilling operations, some of the materials get plastically deformed and not removed completely creating sharp edges called burrs normally formed at the entrance and exit of the drilled holes. Burrs at the entrance of the hole are usually smaller than the exit hole and can be easily removed by chamfering the hole where exit burr is not easy to remove [88,89]. Burrs are responsible to cause stress concentration which results in fatigue failures, corrosion and reduces the life of the aircraft [90]. Generally, de-burring is required to remove burrs which takes up to 30% of the total manufacturing cost [91] because it results in increasing the total machining time and reduces the production efficiency [92] because the de-burring process is usually done manually due to difficulties in automation [89]. Figure 8

shows the most common types of burrs formed from drilling operations. All burr types are unacceptable except Figure 8 (a) and should remain until the hole dimensions or surface to surface contact in mating parts are not affected [93].
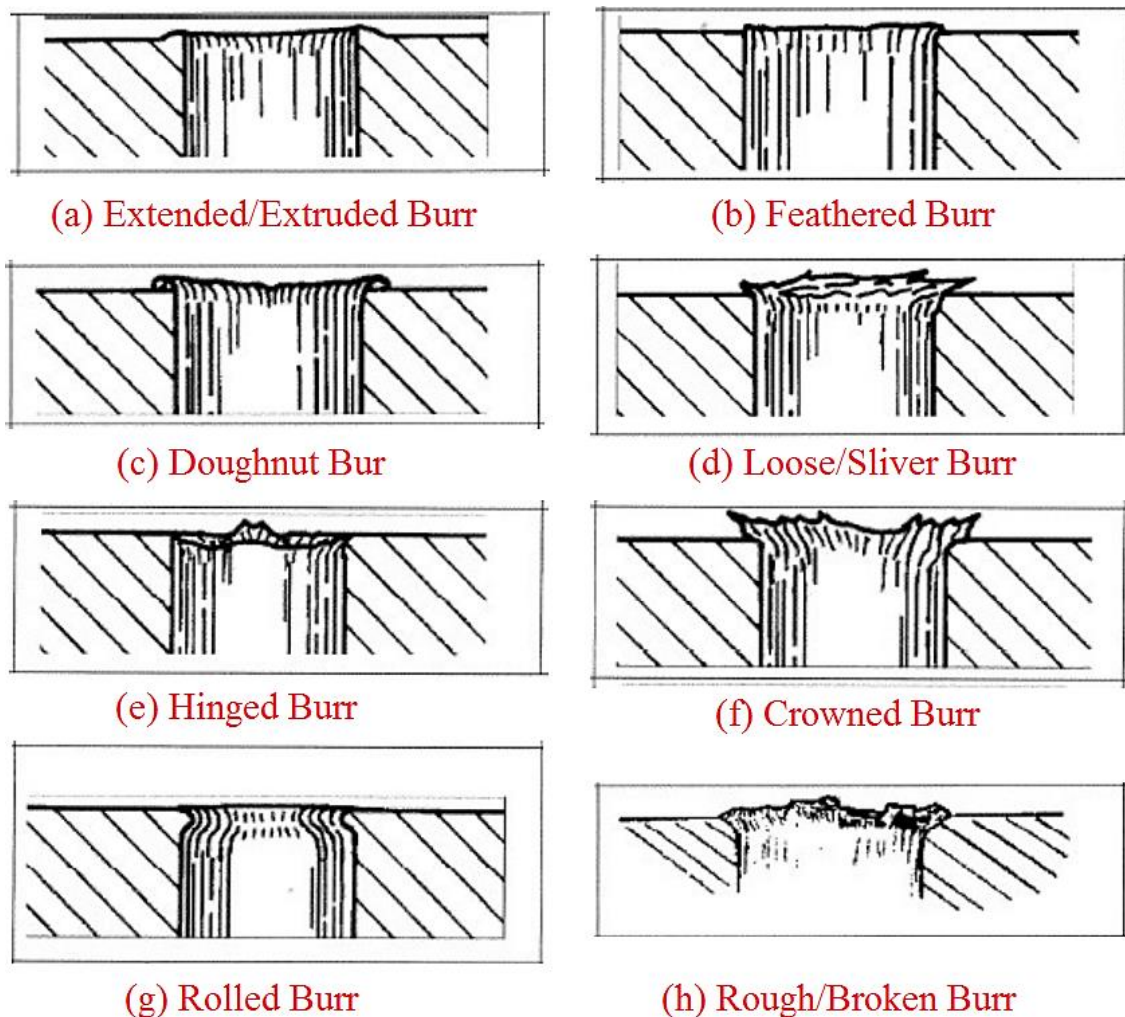
Figure 3: Illustrations depict the most common types of burrs [94]

Burrs can be measured through its height and root thickness. burr size can be measured using the Optical microscopes [95], surface profile-meters [96], image processing software and by means of a surface roughness profile-meters. Further details about the methods used for detection and measuring burr according to various criteria can be found in reference [97].

4. **Drilling process parameters**

High-quality drilling of composites depends on the proper selection of process parameters given in Figure 9. Process parameters include machining and tool parameters which has a direct impact on the output parameters. The machining parameters include the feed and the spindle speed while the tool

parameters include the tool types, tool geometry, tool materials and coatings [98]. The machining parameters are interrelated to the tool parameters. These input parameters have a direct impact on the output parameters that include the online and offline parameters. Online parameters include the thrust force and torque while, offline parameters are the delamination, surface roughness, hole size, and circularity error and tool wear. Therefore, selection of proper process parameters is necessary for drilling operation because optimum process parameters help in the best performance of drilling operation and reducing the occurrence of delamination which represent will give less damage to the machined components and acceptable surface finish [24].
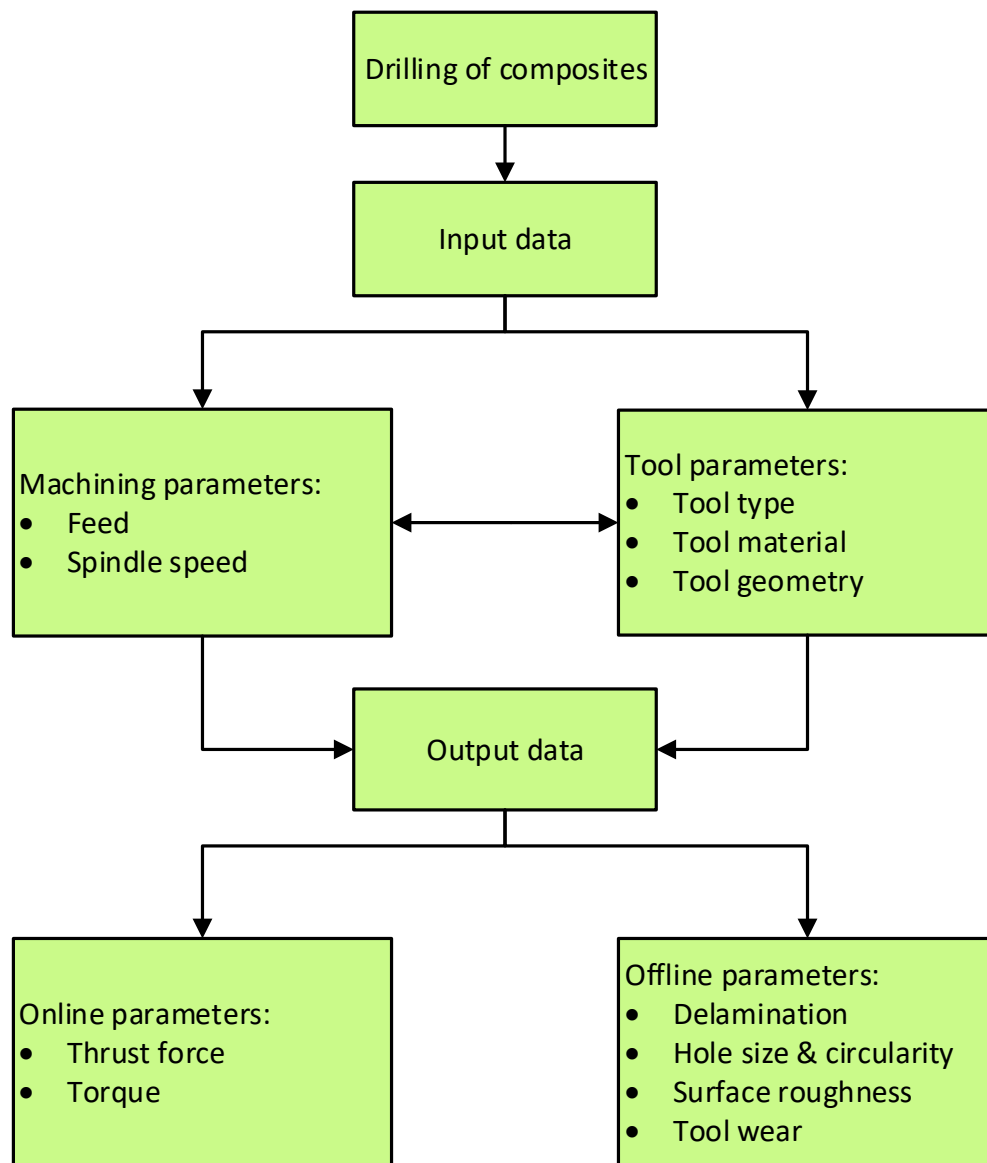

Figure 9: The schematic representation of the drilling of composites

4. 1.   Role of machining parameters on delamination and cutting forces

Machining parameters highly depend on the cutting forces and the drilled hole quality [24]. The relation among machining parameters and the drilling-induced delamination is given in Table 3 which shows that feed rate has a great impact on delamination. However, the influence of cutting speed on drilling CFRP are somehow debatable [58].

Table 3: Impact of process parameters on delamination

Variation in machining parameter	Impact on delamination	References	
		Entry delamination	Exit delamination
Cutting Speed (High)	Increase	[99,100]	[99-102]
	No/slight effect	[103,104]	[103,105]
	Decrease	[106,107]	[106,108,109]
Feed rate (High)	Increase	[18,102-105]	[110,104,106,111]

In terms of cutting speed, literature is somehow controversial. It is investigated that peel-up delamination increases, decrease or in some comments show an unclear trend if the cutting speed increases and same is the case with the exit hole delamination. Davim and Reis [99,101] concluded that higher cutting speed results in less damage at both sides of the drilled holes. Findings of Krishnaraj et al. [102] showed that variations in spindle speed have no effect on the hole entrance delamination while hole exit defects were more sensitive at higher spindle speed. Abrao et al. [100] discussed that high cutting speeds resulted in softening of the material due to rise in temperatures at the cutting zone which ultimately increased the drilled induced damaged area. In another study by Rubio et al. [112], it was concluded that there is less damage in the drilled hole when there is an increase in the spindle speed. While the feed rate directly impacts the thrust force which ultimately resulted in large delamination. The same investigation was found by [113]. This is because lower feed rates contribute in decreasing the cutting depth per revolution and the drill bit does not require to cut more material volumes per revolution and to break more fibers [52]. Therefore, the feed rate also shows impact on the drilled hole quality of CFRP [114]. Gaitonde et al. [18] proposed a model which proved that there are more chances for drilled-hole delamination as the feed rate increased due to higher thrust force. Paul et al. [107] also recommended that there was less drilling-induced delamination and surface roughness at lower feed rate and higher cutting speed. Furthermore, Davim et al. [115] reported that delamination factor was highly influenced by the feed rate. In addition, surface roughness of the drilled holes also increased at high feed rate while decreased with the cutting velocity. In addition to delamination, an

acceptable thrust force and torque are also produced at lower feed rate and high cutting speed [23,26]. However, most of the investigators noted that cutting speed had less influence on the thrust force in the drilling of FRPs and a slight decrease in the thrust force is observed at higher cutting speed. While feed rate has a direct impact on the thrust force followed by delamination [65]. Therefore, to reduce drilling-induced delamination, a lower thrust force is required which is possible at a lower feed rate [112]. Hocheng and Tsao [116] also performed drilling of CFRP using different drill bits each having 10 mm diameter and in all experimental drill bits at lower thrust force the drilling-induced delamination was minimum. Recently, Qiu et al. [52] also reported that higher feed rate generated high thrust force is responsible for increase in delamination. For more detail about the acknowledgement of feed rate and cutting speed, readers are recommended to references [15,22,24,26,27,58]. However, it is concluded that high cutting speed and low feed rate gives acceptable performance and yields minimum torque, minimum thrust force, and minimum delamination during drilling of FRP.

4. 2.   Role of drill tool geometry, tool materials, and coatings

Besides, cutting speed and feed rate, the drill tool geometry, tool materials, and coatings have also shown a greater impact on the status of the drilled-hole quality [24]. Drill tool geometry has a significant role in reducing surface damage, delamination and tool performance in drilling CFRP. However, drill bits which option better for FRPs drilling contributes to making good quality and accurate holes because ordinary drill bits cause the composites to damage [24]. Depend on the drill bit size and the hardness of the materials, the recommended lip relief angle varies between 8° and 24°. Generally, for hard materials, small relief angle is required while high relief angles are suggested for soft materials [43]. Drill tool point angle has also impact on the thrust force, torque and chip formation. The range of drill point angle depending on the machined materials varies between 80° and 140°. However, a point angle of 118° is considered the most common. Helix angle also contributes to reducing the cutting forces. The most common helix angle ranges between 12° to 38° depending on the application [117]. Moreover, the contact area of the drilled hole increases as the drill's diameter increases which subsequently, increases the thrust force and more delamination [52]. Generally, drill holes in aerospace machined structures range between 4.8 and 6.4 mm [16].

The literature study has shown that different researchers have tried focusing on a variety of tool geometries. Some of the drill tool geometries used are given in Figure 10.

Twist drills [45,46,53,52,48,118]

Brad & spur drills [119]

Step drills [52,120]

Straight-flute drill bit[121,122]

Slot drill bit [65]

Saw drills [116]

Dagger drill [123]

Candlestick drill [116]

Core drills [109]

Core-twist drill [124]

Core-saw drill [124]

Step-core-candlestick drill [124]

Core-candlestick drill [124]

Step-core-twist drill [124]

Step-core-saw drill [124]

Countersink drill [51]

Tapered drill reamer [125]
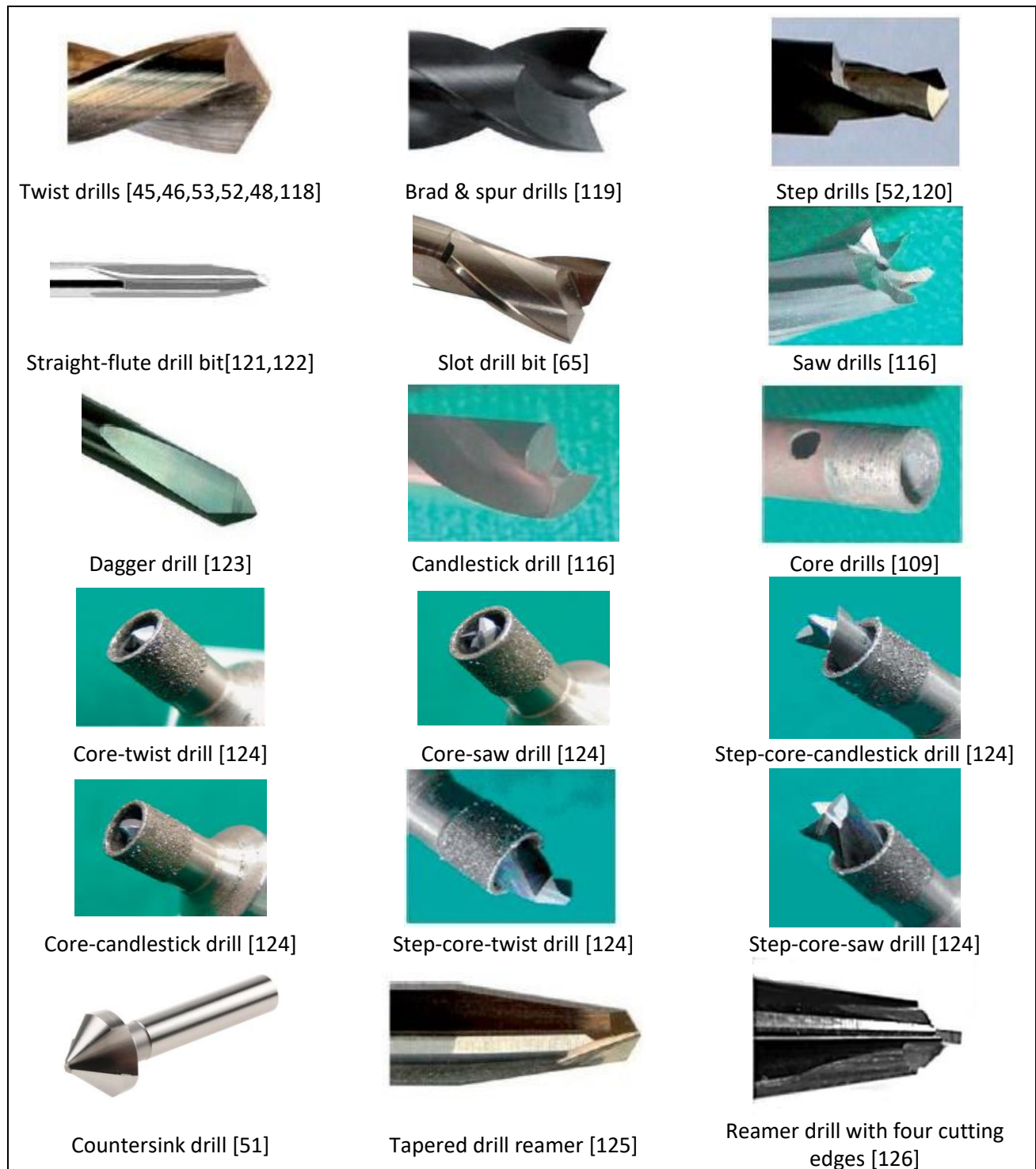
Reamer drill with four cutting edges [126]

Figure 10: Drill tool geometries used in CFRP

For instance, Brad & spur drills were recommended by [119], step drills were used by [52,120], dagger drills by [123], saw drills by [116] , core drills by [109], Slot drill bit by [65], candlestick drill by [116], core-twist drill, core-saw drill, step-core-candlestick drill, core-candlestick drill, step-core-saw drill, and step-core-twist drill were used by [124], countersink drill by [51], and tapered drill reamer was used by [125]. Figure 7 shows some of them schematically [127]. It is seen that many authors have used different tool geometries for CFRP drilling however, majority researchers including [45,46,53,52,48,118] have recommended twist drills because they represent an industrial standard and give the lower thrust force values with better drilled-hole quality [24]. Figure 11 shows some of the most commonly used drill bits for machining composite and metallic materials[127]. The standard geometry of the twist drill is shown in Figure 12 [128].
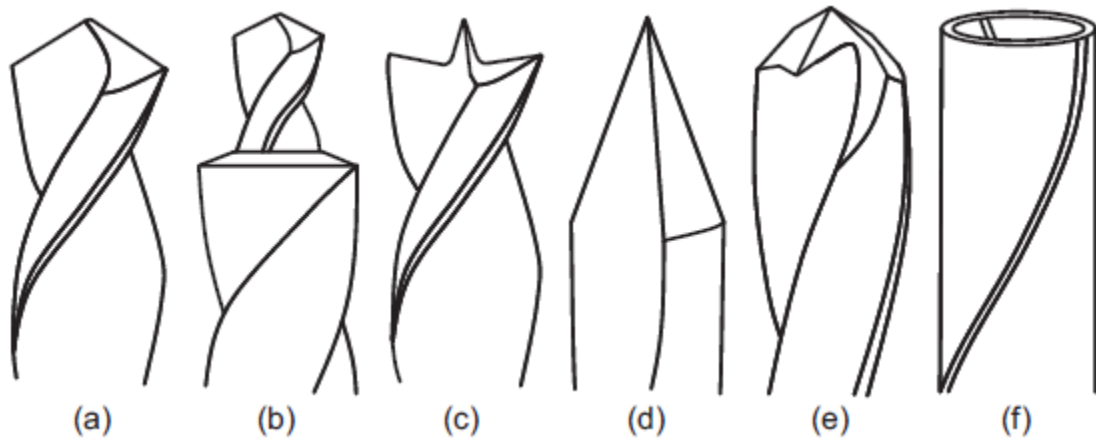
Figure 11: Schematic representation of drill bit geometries: (a) standard twist drill; (b) step drill; (c) candlestick drill; (d) dagger drill; (f) multi-faceted drill; (e) core drill [127].
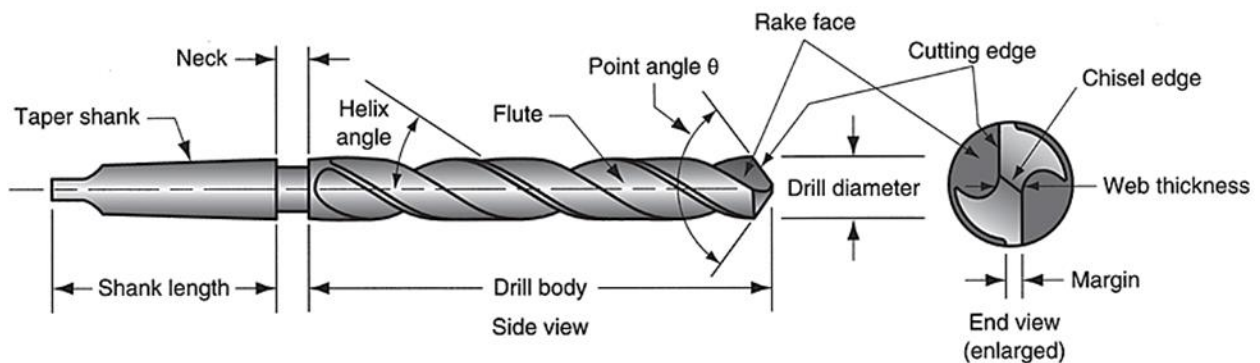

Figure 12: Detailed geometry of the twist drill [128]

In addition to drill tool geometry, drill tool materials and coatings also have a significant role in overcoming the drilling-induced delamination [12]. Cutting tool materials are available in a wide range

of application that includes the high-speed steels (HSS), cemented carbides, coated carbides, ceramics/super hard materials and polycrystalline diamond (PCD) [15]. HSS drill bits are the primary choice for performance based on wide availability, low cost, highest toughness at the high cutting speed [15]. However, they are not recommended due to their inability to hold up hardness at harsh temperatures. Therefore, HSS is unsuitable to drill abrasive materials like CFRP due to its moderate strength [32]. Ceramic tools have the ability to perform at high-speed machining where the cutting temperatures are extremely high. However, ceramic tools do not withstand interrupted loads or heavy cuts because their toughness is not too good and are easily suffer from failure. Furthermore, their production cost very high [32]. Another member of tool materials is the cemented carbide which is mostly the tungsten carbides. The tool blanks are produced from a suitable mixture of carbide grains and metal binder, such as cobalt. The carbide phase gives the cemented carbides the hardness and the binder metal provides the desirable toughness. The combination of high hardness and toughness makes the carbide tools suitable for FRPs' machining [32]. Many researchers including Harris et al. [5], Wang and Kirwa [29], Gaugel et al. [50], El Bouami et al. [129], Wang et al. [45], Rimpault et al. [130], Zitoune et al. [131], Xu and El Mansori [132], Ramirez et al. [47], Turki et al. [46] Fernández-Pérez et al. [51], Xu et al. [133], Xu and Zhang [53], Qiu et al. [52] have recommended the carbide drill tools in their investigation for drilling of CFRP given in Table 1. PCD tools were found to give outstanding performance due to their excellent wear resistance and high thermal conductivity [134]. However, they cover small market share as compared to the HSS and tungsten carbide due to its difficulty in fabrication and its high cost [11].

Therefore, the recommended drill tool material for drilling composites is cemented tungsten carbides. This type has the ability to provide high hardness, strength and can sustain their properties at high temperatures. They are also easily available in mass production and at low cost and can fit in many applications [32]. In addition, Tungsten carbide performs better in terms of wear resistance, delamination and surface roughness during drilling of FRPs [32].

Also, to further enhance the performance of the carbide drills, it is important to use some coating. The advantage of using the coating is to increases wear, corrosion and oxidation resistance that consequently improve the tool life to produce better quality of holes [32]. The coating process of the cutting tools is performed using physical or chemical vapor deposition methods PVD or CVD [135]. PVD coating method is more common for cemented carbide cutting tools and is performed by exposing the cutting tool to a vapor of the coating material at high temperatures up to 1000 °C allowing it to adhere to the cutting tool. In the CVD coating method, the coating is applied by creating chemical reactions

between the cutting tool and the coating material in its gaseous form. For coated tools, literature has shown that TiAlN coating outperforms as compare to other coatings like TiN and TiC because it gives better result in reducing the cutting forces, improving the surface roughness and providing better resistance against tool wear. Another coating material is diamond which is an excellent choice but it has a very high cost [16]. Therefore, the economic impact of the coatings in the drilling process should also be taken into consideration. Generally, the best cutting tool for drilling of CFRP should be the match of appropriate drill tool material and coatings and optimal drill tool geometry. Regarding drill tool materials and coatings, those with high wear resistance, high hardness, toughness, and high thermal conductivity should be the first choice. However, more investigation is required for the improvement and selection of optimal dill tool geometry with better tool materials and coatings in the future.

4. 3.   Optimization of process parameters

Optimization techniques play a significant role in the selection of the best process parameters [136]. Therefore, the optimization of process parameters is important in the drilling of CFRP to performance in an effective manner [137]. This can help in giving the best drilled-hole quality and better drill tool life in a more useful manner [138]. Researchers have tried different optimization technique to find the relation between input and output parameters. The summary of the different techniques used for the optimization of process parameters is given in Table 4. It is clear that the majority of the optimization problems have been studied using the Taguchi method because it is a simple approach used without an expert background in statistics to form a set of standard designs [139].

Table 4: Summary of drilling process parameters optimization review

Optimization technique	Reference
Taguchi method and Sequential Quadratic Programming algorithm	[140]
Genetic Algorithm	[141]
Taguchi method and Neural network	[142]
Taguchi method and regression model	[18]
Taguchi method and ANOVA	[104,143]
Taguchi method and Genetic algorithm	[102]
Grey fuzzy logic	[144]
Harmony search algorithm, Nonlinear regression, Fuzzy Inference System	[145,146]
Response surface methodology	[147,148]
Artificial neural network	[149]

Taguchi method and fuzzy logic	[150]
Taguchi method and response surface methodology	[147]
Taguchi method, response surface methodology, ANOVA	[151]
Taguchi method	[152]
Group method data handling algorithm	[153]
Ant colony algorithm	[154]
Particle swarm optimization and gradient-based training of artificial neural network	[155]
Particle swarm optimization–Gravitational search algorithm	[156]
Artificial Bee Colony algorithm	[157]

5. Effects of dust/ aerosols on human health during machining of fibre-reinforced polymers

During machining of FRPs, especially CFRP, the carbon fibers are easily broken into fine dust particles and get into the surrounding atmosphere which can affect human health. The typical health problems include the irritation of the eyes and upper respiratory tract, dizziness, drowsiness, nausea, and vomiting [158]. It was reported by Kwan [159] that nearly all the dust particles trapped in the nasal cavity with an aerodynamic diameter of more than 10 µm. Majority of the particles with a diameter in the range between 5 and 10 µm deposited in the nasopharynx region and about 40% of the particles with diameter range in between 2 and 5 µm deposited between the trachea and the terminal bronchi. In addition, particles smaller than 2 µm have a high probability of reaching the terminal bronchi and the alveoli region of the lungs which is near the lung walls and where the particle has the greatest potential to damage the lung.

In the literature, only few studies deal with this problem. Iyer [158] recommended protection from CFRP by studying the percentage extraction of dust using Grimm Aerosol Spectrometer 1.109 during machining of the composite using a CNC machine. The criteria were based on particulate matter aerosol standards defined by (Occupational Safety and Health Administration) OSHA in regards to safety and well-being. It was reported that particles in the range of 5-10 µm can cause irritation in the nose and throat, 3-5 µm enter the windpipe and there are chances that 1 to 2 µm particle size can enter the lungs through arteries and veins. Furthermore, particle sizes less than 1 µm enter the alveoli and can enter the bloodstream via the ciliary interchange. Therefore, it was highly recommended to use of heavy style gloves, full goggles, a dust mask which must be fit tested to the individual and use of elastic cuffs on the protective clothing. Furthermore, the use of specific vacuum cleaners which is specially designed to extract conductive substances with high-efficiency particulate air filter was recommended to avoid the

short circuits of the machine tools from the conductive nature of the carbon fibers. Haddad et al. [160] also reported the dust generation and particle counts during machining of CFRP using GRIMM 1.209 dust monitor. The study claimed that the chips broken into dust particles during machining of CFRP were in the range of 0.25 to I μm size and it was more likely to cause multiple irritations in the body. It was predicted that about 90% of the particles exceeded the occupational exposure limit and can reach the pulmonary alveoli. It was also noted that the dust volume was approximately 2-8 times more during high-speed trimming. In another study by Haddad et al. [161] experimental trials confirmed that machining parameters also contribute to the formation of very fine dust particles. The dust monitoring showed the presence of very fine particles which is indeed hazardous to human health. This gave the possibility of 87% to 95% of the dust particles (Figure 13) reaching the pulmonary alveoli to cause multiple irritations.
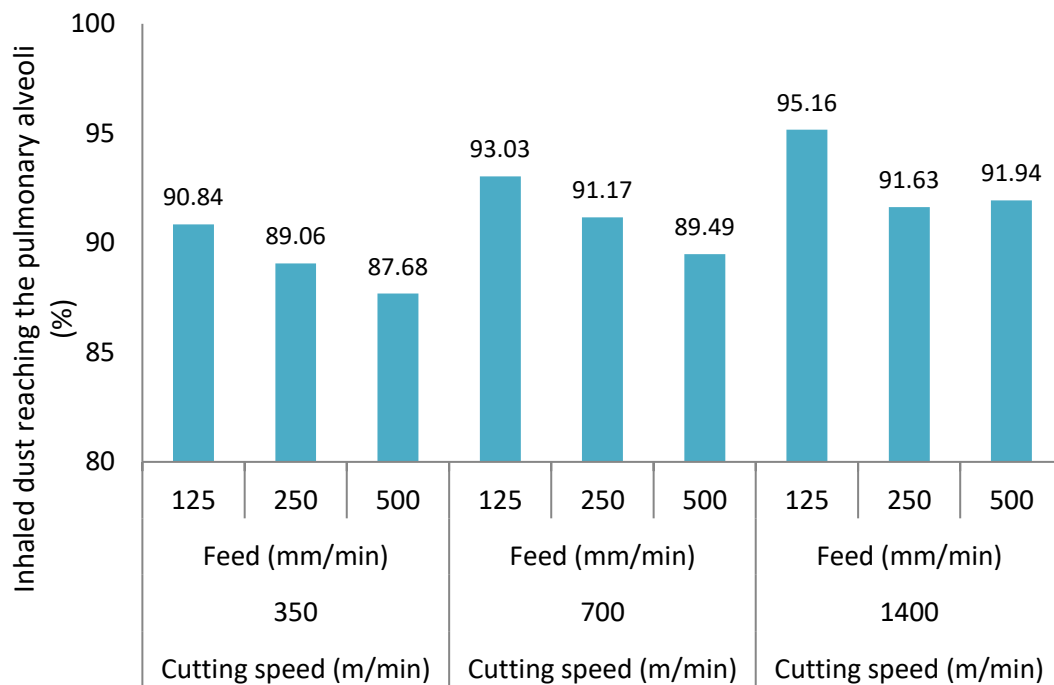
Figure 13: Percentages of dust reaching the pulmonary alveoli [161]

Recently, Ngoc Nguyen-Dinh [162] studied the trimming process of CFRP using a 5-axis CNC machine. A GRIMM dust monitor (model 1.109) was utilized which counted the number of particles with size ranging from 0.25 μm to 32 μm present per one liter of the air. The interval for each measurement was set up for 6 seconds. Experimental results showed that the dust particles possess the ability to damage the respiratory system and can cause toxic irritations. It was also found that high cutting parameters

contributed to the mass concentration of dust particles. This can be seen from Figure 14 (a) in which the particles generated using feed speed 500 mm/min have fewer chunks than those generated using feed speed of 1000 mm/min (Figure 14b).
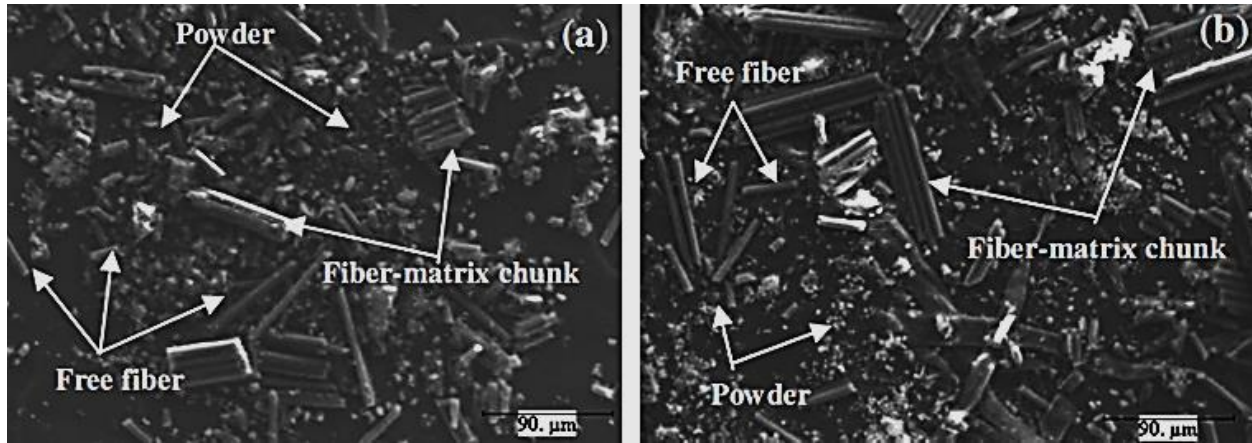

Figure 14: Typical SEM images of dust particles at feed speed of: (a) 500 mm/min, (b) 1000 mm/min [162]

Ramulu and Kramlich [163] stated that during machining of the FRPs, chips in the form of dust particles and powders containing fiber and/or cured matrix material were produced which are health hazardous [163]. Klocke et al. [164] also concluded that cutting speed and tool material influenced the concentration of dust particles. It was noted that tools that yield a better cutting edge produce a higher fraction of small (respirable) dust particles. Furthermore, high cutting speed increased the dust particles concentration. When the cutting velocity increased from 200 to 1000 m/min, the airborne concentration of dust increased from 5 mg/m^3 to as much as 13 mg/m^3. Furthermore, Kwan [159] used a particle fractionating Andersen air sampler with a series of collection plates to separate particles by their aerodynamic diameters. The samples were collected at close proximity to the machining surface where the particles were generated. Gravimetric analysis was done with samples from the Andersen sampler to determine particle size distribution by weight. Kwan also collected particles using a sampling pump and a 25 mm diameter, 0.2 μm pore size filter to collect particles. Based on samples collected for gravimetric analysis from the Andersen air sampler, Kwan found that the non-respirable (aerodynamic diameter > 5 μm) fraction of airborne particles ranged from 51% for a milling operation to 88% for a drilling operation.

Though, the small dust particles during machining of FRPs have shown a significant impact on the health. Still, the impact of these hazardous dust particles on human health has not been seriously felt. However, the above study concluded that the small size dust particles reach the lowest part of the respiratory

system which causes serious problems. Therefore, proper care with extreme precaution both for human health and machine tools should be used. Furthermore, low cutting speed and high feed rate contribute to lowering the dust particles however; it can affect the drilled hole quality. Therefore, a compromise between the cutting parameters for quality drilled-holes and dangerous dust particles should be made.

6. Conclusions

The paper represents the literature review on recent progress in the drilling of fiber-reinforced polymers mainly including the role of fiber orientation, hole quality and its assessment, drilling process parameters and its optimization techniques, and the effects of dust/ aerosols on human health. On the basis of comprehensive observations several conclusions should be made as follows:

I. FRPs especially the CFRP encouraged its use in several applications and are playing a significant role in the current and future aerospace industry due to their desirable properties such as low weight, adequate fatigue resistance, high strength, and stiffness.

II. The direction of the fibres has an important role in defining the damage tolerance of the composites, the chips formation, thrust force, and surface roughness. The most used stacking sequences recommended by different researchers is the quasi-isotropic laminate structure with an equal number of plies and a stacking sequence of 0°, - 45°, 45°, and 90°. This choice of pattern is acknowledged to show near optimum properties and can endure better loads, save materials and hence gives minimum weight which is very important in the aviation and aerospace industry.

III. Overall, for better drilled-hole quality and minimum material damage during drilling of FRPs, low feed rates, and high cutting speed favours acceptable performance and yields minimum torque, minimum thrust, and minimum delamination.

IV. Twist drills represent an industrial standard and are recommended for better drilled-hole quality. Regarding drill tool materials and coatings, cemented tungsten carbides are considered the best drill tool material for drilling of FRPs because of their good properties. Apart from diamond coating which has a very high cost, TiAlN coating is suggested to give better result in reducing the cutting forces, improving the surface roughness and providing better resistance against tool wear. However, in future, more research is required for the improvement and selection of optimal dill tool geometry with better tool materials and coatings.

V. For the optimization of process parameters, multi-attribute decision-making technique is used by different researchers, however, the majority have studied the Taguchi method due to the

reason that gives a simple approach without an expert background in statistics to form a set of standard designs.

VI. During drilling of FRPs, small dust particles with sharp edges are produced which are harmful to human health. There are high chances that these dust particles tend to stay at the lowest part of the respiratory system causing serious damage. Therefore, it is highly recommended to follow extreme precautions by using heavy style gloves, full goggles, dust mask, and protective clothing. Furthermore, specific vacuum cleaners combined with a suitable high-efficiency particulate air filter should be used to avoid machine tool from conductive carbon fibres.

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