Recent advances in twist drill design for composites machining: A critical review

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Abstract

In the field of composites technology, inefficient and poor designs of twist drills contribute immensely to the challenges facing drilling of composite materials. An attempt to report some of the drill design methods and their inherent challenges confronting composites machining necessitates the writing of this paper. A critical review has been conducted to offer a clear understanding of current advances in the field of mechanical drilling of composite materials, focusing on geometry, material and parametric tool designs. The inter-dependable effects of thrust force, cutting speed, feed rate, cutting force and torque on drill design are similarly reviewed. This paper also reveals other associated issues facing composites drilling include delamination, surface roughness, rapid tool wear and drill breakage. Well-designed drill geometry and good knowledge of drilling parameters afford the producers of polycrystalline diamond (PCD), Carbide and high speed steel (HSS) tooling materials better opportunity of developing a drill that will minimise delamination of the reinforced composites, tool wear and produce a high quality surface. Twist drill manufacturers and users will benefit from this paper as they seek to have well designed and improved drills.

Keywords: Twist drill, design, composite materials, drilling, delamination, tool wear

Introduction

The kinematics of drilling is a process of using a rotating drill bit to create or enlarge existing round holes in a workpiece.[1] Drilling is one of the most frequently processes used in manufacturing industry among machining operations.[2] Tonshoff et al.[3] noted that drilling takes about 25% of the total machining

time and 33% of all the total machining operations of a manufacturing process. It is a preliminary step for many other machining operations, such as reaming, tapping and boring.[4, 109]

Drill, as a rotary end cutting tool, has one or more cutting lips and flutes for the release of chips and the access of a cutting fluid. Presently, drill bits are the most frequently and extensively used material cutting tools.[5] Geometrically, a twist drill is a complex material cutting tool, as depicted in Figure 1. Both the geometrical shape and dimensions of a twist drill determine the cutting performance; influence the cutting forces, tool wear, cutting dynamics and, the quality and integrity of drilled holes.[6–9] These make the design of twist drill of a critical importance. A poorly designed cutting edge results in an undesired distribution of the cutting angles along the drill cutting edge[10–13], causing inefficient performance, loss of cutting ability and increase in total manufacturing cost.

This paper reviews recent advances in twist drill design for machining of composite materials. The main objective is to critically review the literature, focusing on the effect of twist drill design parameters on composites drilling. An attempt is made to outline the fundamental limitations of the currently developed and applied designs. The first part of this paper focuses on the variation in geometric design of twist drills, followed by tooling materials with respect to composites drilling; hence, common limitations associated with composites drilling and drilling parameters are lastly considered.

Twist drill geometric design concept

The complexity of the geometry of a twist drill requires careful design consideration. The cutting dynamics, drilling forces and tool wear[14–19] strongly depend on the drill dimensions and geometry. The machine tool requires much more energy and power when its cutting tool is poorly designed, in addition to tendency of damage on the machine.

Fetecau et al.[20] reported that the efficient approach to reduce drill wear in order to increase the drill performances is to have well defined geometry of the main cutting edge only, such that it could lead to a constant unitary energetic load along the main cutting edges. In an attempt to redesign a drill for an optimum performance, the flute profile has often been designed by incorporating ‘forward’ and ‘backward’ simulation analyses, to decide on an optimum geometry of the flute grinding process.[22] A straight lip and parabolic heel flute profiles, computer-aided design/manufacture software were used to establish a design flute profile from the drill specification. The application of the software and model to

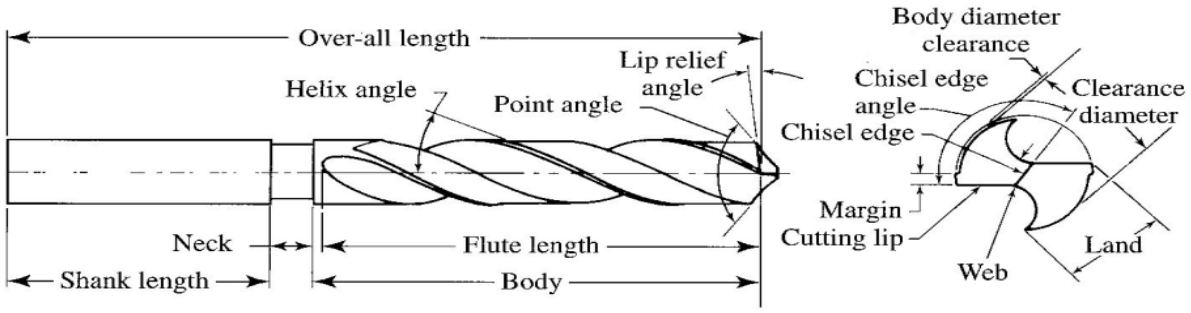


Figure 1. Characteristics of a typical double fluted drill.[21,40]

flute showed that the required wheel profile parameter with respect to the diameter could be represented by simple regression equations.

Piquet et al.[23] studied the drilling of thin carbon/epoxy laminates with two types of drills: a helical drill and a drill without chamfer on the cutting edge, made up of HSS and "micrograin" tungsten carbide (K20 rating) respectively. It was concluded that both drills caused damage at the entrance of the wall and the exit of the hole, but K20 tungsten carbide geometry drill produced reduction in the final damage.

Cutting edges and angles

The design of cutting edges has focused on point design with consideration of cutting forces for arbitrary cutting geometries[24], stress analysis[25], and design and optimisation using simplified drill geometry models.[26-30] Majority of the drill geometrical improvements has often been limited to the chisel edge region. This proved to be effective in reducing the total thrust force, but marginally reduced the torque and the power which are major determinants of the tool performance.[2] Furthermore, significant design features such as reverse web taper and internal cooling channels, cutting lips and chisel edge geometries including verification of grindability which is important for the drill cross sectional design has been reported to be considered in an acceptable drill geometry model.[31]

Thinned purpose and faceted point together with the patented 'circular centre edge' designs have been developed, using predictive force models.[32] The predictive mechanics of cutting models for thrust and torque were numerically and experimentally tested, and found that the drill designs substantially reduced the thrust force when compared to un-thinned drills and differences in the forces for the three designs were minimal after comparison.

A practical method to determine the cutting edges and rake angles has been carried out by Li et al.[33] Cutting edge points and the rake angles were examined using 2D tool microscope and image-based instrument and numerical computation respectively. This method proved effective compared with common unaffordable labourious analysis required in rake angle determination, because it does not require high level of co-ordinates transformation and mathematical competence.

Lip Geometry

Sambhav et al.[34, 36] established a methodology to model the geometry and cutting forces of drills with generic point. With the aid of non-uniform rational basis spline, CAD geometric models were used for a fluted drill in terms of bi-parametric surface patches. Generic and mechanistic models were presented for the cutting lip and chisel edge, and prediction of the forces respectively. The mechanistic model was applied to calculate the forces for each element and determined the drill total thrust and torque. Similarly, a new paradigm to model various twist drill geometries in terms of three-dimensional parameters was established by Tandon et al.[37] Their work outlined the construction of a detailed CAD model for a fluted tool. A new well detailed and broad 3D definition of the drill geometry was established.

Point Angle

Durão et al.[38] experimental techniques showed that the most effective tool was 120^{o} point angle drill for minimal delamination and at higher feed rates. They reported that a good alternative could be a step drill designed for a particular composite though presently, not yet available commercially. Vijayaraghavan[39] reported a tool which could generate automated 3D CAD drill geometric models and manufacturing parameters as a required component of numerical/finite element analysis models of FRP drilling. The outputs of the tool gave variety of solid geometry formats of drills and through meshing, it was used in different FEA analysis packages.

Drilling of thick fabric woven CFRP composite laminates was experimentally performed, using uncoated carbide (UC) and diamond coated carbide (DCC) twist drills. The effects of the geometries of double pointed angle drills were investigated.115 The UD, DCC-I and DCC-II have 6.35, 6.91 and 6.38mm diameters; 140-60o, 130-60o and 140-60o drill tip angles respectively, with rake, clearance and helix angles of 7o, 11o and 30o respectively. The geometries of both UD and DCC-II drills were the same, while the tip angles, primary and secondary cutting edge lengths of DCC-I and II drills were

different. The diamond particles size as well as the coating condition and thickness determined the performance of the drills. It was concluded that the geometry of DCC-II was appropriate than the DCC-I drill during high feed drilling of the composite material, producing critical hole diameter tolerance than delamination drilling-induced damage.

Table 1. Effects of different drill point angles and helical angles on interface normal stresses.[40]

Normal stress (GPa)	Point angle (degree)			Helical angle (degree)		
	90	118	135	20	30	40
σ_{rmax}	1.217	1.227	1.234	1.24	1.23	1.21
$\sigma_{\Theta max}$	2.78	2.89	2.94	3.05	2.89	2.73

Chao et al.[58] stated that edge radius has the greatest effect on the interface stresses by deposition. Tensile radial normal stresses affected the reliability of the coating bond and changed helix angle, point angle and web-thickness. These stresses influenced a difference in drill tip from 10^0 to 20^0 point angles. Meanwhile, point angle increased with the normal stresses unlike helical angle, as shown in Table 1, where σ_{max} is the maximum stress, though depends on the tooling material, but decreased with delamination.[38, 41] Stresses on the tool reduce its life. Kilickap[73] observed that increase of HSS drill point angle leads to decrease in delamination effect during unidirectional-ply GFRP composite laminate conventional drilling. During drilling (high speed and conventional) of woven-ply CFRP, Gaitonde et al.[91] reported that cemented carbide K20 point angle increases with increase in delamination damage.

Lip flute profile

Armarego and Kange[22] reported that the generated lip and heel flute profiles closely formed the ideal profile for the creation of straight lip and a parabolic curve respectively, with the curve being tangential to the web diameter and passing through the corresponding heel corner. A multi-objective geometry optimisation was realised by Sardinas et al.[42] by implementing meta-heuristic algorithms. The subsequent geometry was validated and verified by constraint functions including chip flute grindability verification.

Tooling material selection

Tooling material influences drilling-induced damage, such as delamination effect[14, 15, 43], and variation in cutting forces[44] which have significant effects on both drill life and the structural integrity of composite materials.

Drill tool materials

The life of a drill depends mainly on hardness, toughness, wear and thermal resistance. A good drill must possess ability to resist wear, fracture, quick rupture and retain hardness at the state of hot hardness. The major properties of different tool materials are shown in Figures 2 and 3. From these Figures, hardest tooling material; PCD possesses least toughness property as its sharp deformation occurs around a temperature of 600°C unlike HSS with the best toughness, but deforms around 700°C when compared with other tooling materials.

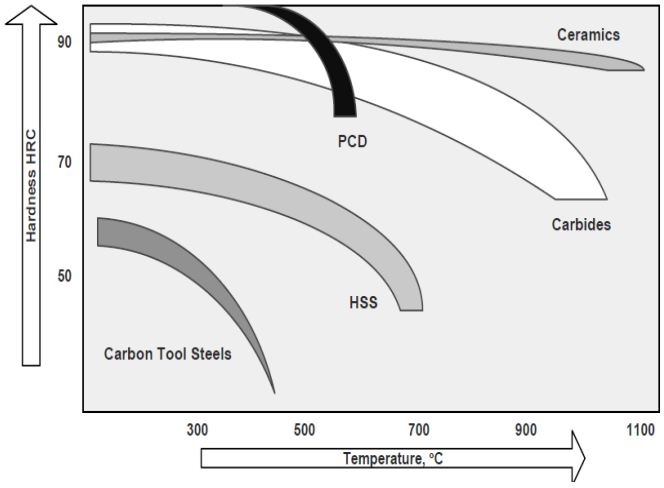


Figure 2. Relationship between hardness of drill materials and temperature. [45]

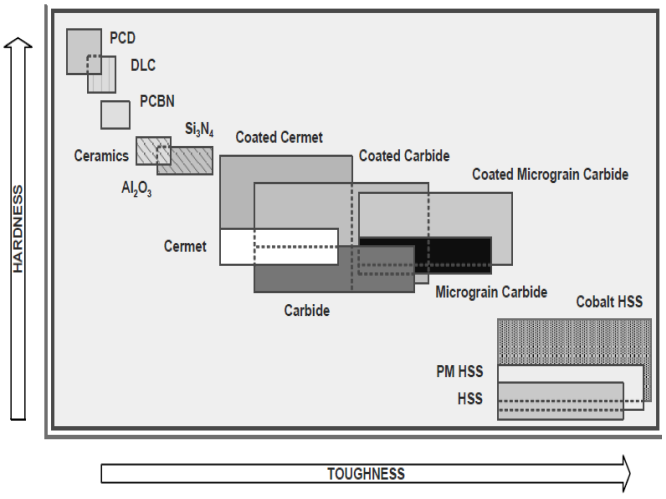


Figure 3. Relationship between hardness and toughness of drill materials. [45]

High speed steel

Liu et al.[46] reported in their review study of drilling composite laminates that HSS or Carbide drill bits have primary attraction based on better performance at high cutting speed compared with

other drill bits. Some studies[48-50] used HSS drills frequently; making it the most widely used tooling material due to its availability, low cost and highest toughness, as shown in Table 2. It has a highest percentage (47%) of applications; 24 applications out of 51 research works considered.

Table 2. Various twist drill materials for drilling composite laminates.

	Tooling materials			
	PCD	CCC	UCC	HSS
Reference	[51], [55], [56], [57], [58]	[16], [40], [58] [59], [60], [61] [62], [63], [64]	[19], [42], [43], [51], [52], [53], [54], [65], [66], [67], [68], [69], [70]	[9], [14], [15], [17], [18], [43], [46], [47], [48], [49], [50], [51], [53], [54], [68], [71], [72], [73], [74], [75], [76], [77], [78], [79].
Total	**5**	**9**	**13**	**24**

Cemented Carbide

Carbide drills performed better in terms of wear resistance, delamination effect and surface finish when compared with HSS under comparative low speed and feed at high temperatures when drilling the same composite materials18, 43, 49, 51-54, as indicated in Figures 2 and 3. When the radius apart from the corner was measured, almost null wear land was shown in the flank surface of carbide drills, while HSS drill had considerable wear.[49]

Polycrystalline Diamond

Garrick[55] reported producing a veined drill that was capable of drilling carbon composites and its stack with titanium. However, he observed that, after 200 holes had been successfully drilled, a wear land was formed on the cutting edge of the 86 series PCD veined drill which necessitated re-sharpening of the drill. In addition, it was reported that in order to strengthen its cutting edge and make PCD drills viable, it might require modification with k-lands. Also, further suggestion was made, that an assessment of the drill process and delamination would be useful in the design and optimisation of new PCD drill geometry that might give a better output. Investigation of the effect

of the cutting parameters on drilling carbon/epoxy and carbon/peek was done by Chambers and Bishop.[56] They concluded that the drilling of carbon composites is dependent upon the characteristics of the matrix. The helical PCD drill geometry gave the best overall performance when compared with other cemented carbide drills, but more reactive to feed rate changes, when delamination was considered[51].

Heath[57] reported that PCD being a stronger tool material could be used for machining of composites because of its ability to withstand the severe abrasion of the carbon fibre reinforced composites. However, PCD is found to be too fragile to withstand the high cutting forces required for metal such as titanium[57] especially when stacked with composites. Furthermore, the configuration of the core drill had been proved better the traditional twist drill. Therefore, the outstanding advantages of core drilling, using a solid PCD drill has been reported by Butler-Smith et al. 111 A novel designed core drill produced 26% reduction in thrust force, reduced drill surface clogging, cutting force and drilling temperature, producing reduced delamination damage possibility during composites drilling. The novel micro PCD core drill possessed laser generated cutting micro-teeth formed onto a tungsten carbide backing. The performance of this novel drill was experimentally compared with electroplated diamond tool during micro-core drilling. The electroplated diamond micro (EDM) core drill produced cutting forces that were 36% and 190% greater than PCD core drill at new state of the tool and after 216 drilled holes, resulting to terrible composite delamination. Similarly, up to 11% and 25% greater drilling temperatures were generated by the EDM core drill than the PCD core drill at new state of the tool and after 216 drilled holes. Also, at 216th hole 1.8 times higher thermal spread was produced by EDM core drill than the PCD core drill.

Problems associated with drills

Rapid tool wear

Tool wear is an unwanted phenomenon in machining process, whereby tool lost an amount of matter. It affects the quality of the drilled surfaces (holes) and geometry of the material workpiece. The chip produced during the drilling of carbon composites is abrasive dry powder. The ineffective extraction of these chips is one of the major reasons for high tool wear rates. The most common type of wear; crater wear occurred to a major extent as a result of discontinuous

chip formation, caused flagging of the tool which propped up cutting edge chipping.51 The cutting force increased with the workpiece-drill tool interface temperature, followed by the increased drill wear, resulted to workpiece deflection and drill bit breakage.[108] The flank wear decreased near the corner of the drill chisel edge, while the maximum flank was common at the drill outer corner. Increase in thrust force, torque on the drill bit and the number of drilled holes caused a proportional increase in the drill tool wear. [108]

There have been some research on the tool wear processes during drilling of carbon composites, as well as the effect of tool wear on the drilling forces and quality of the holes produced. Some investigated the drilling process and correlated it with delamination, while others correlated the drill geometry and feed rate to delamination.[41, 52, 78, 80-83]

Karpuschewski et al.[71] reported that consistent rounding of the drill cutting edges improves the quality of the corner edges and tool surfaces that form the cutting edge, citing that rounded corners allow the avoidance of run-in periods. Consequently, the high wear of the drill is reduced which leads to 80% increased tool life. Ramkumar et al.[76, 77] and Zhang et al.[74] stated that vibration assisted twist drill could be used to improve drilling operations and reduce wear. Lin and Chen[84] concluded in their study on drilling CFRC materials at high speed that an increase in the cutting velocity led to an increase in the drill wear which directly caused a rise in the thrust force. Furthermore, an analysis and monitoring of occurrence of a flank wear on a 10mm diameter twist drill tool had been carried out effectively by Sivarao 108, using Mamdani fuzzy inference system (FIS). He reported the reliability of the Fuzzy application as a tool condition monitoring technique. Statistical and mathematical methods have been used comparatively, to determine the wear on two 10mm diameter twist drills during drilling operation.110 The drill tools X and Y experienced the same process parameters, but slightly different in specification. Drill tool X had 57HRc, 86mm and 136mm, while tool Y possessed 55HRc, 87mm and 133mm of hardness, flute and overall lengths respectively. Drilling operations were carried out with and without lubricant conditions. Tool wear analysis was performed by applying regression analysis and inverse coefficient matrix (ICM) method, considering these drilling variables: thrust force, feed rate, cutting speed and drilling time. In both drilling conditions and within drilling parameters selected, the results obtained from the statistical analysis were much better in terms of

accuracy and reliability, when compared with the expected values got from the mathematical analysis. Also, Tool X proved superior to tool Y in terms of design, quality and functionality.

Wear mechanisms of PCD and tungsten drills when drilling CFRP stacked on top of titanium (Ti) has been studied by Park et al.[58]. The wear rate and progression of the tool surface were periodically monitored by using a scanning electron microscope and a con-focal laser scanning microscope. Micro-chipping was observed at the cutting edges near the PCD drill margin which reduced the tool performance. Major chipping was observed at the cutting edges when drilling titanium as a part of the constituents of the stacked composite due to the brittle nature of the PCD. However, the PCD drill was comparatively better than a tungsten drill tool in terms of wear resistance.

Edge chipping and breakage

Edge chipping is a process whereby small pieces of the drill is removed or cut off as a result of high cutting and thrust forces, as depicted in Figures 4 and 5.[85, 86] Ineffective removal, control of the various

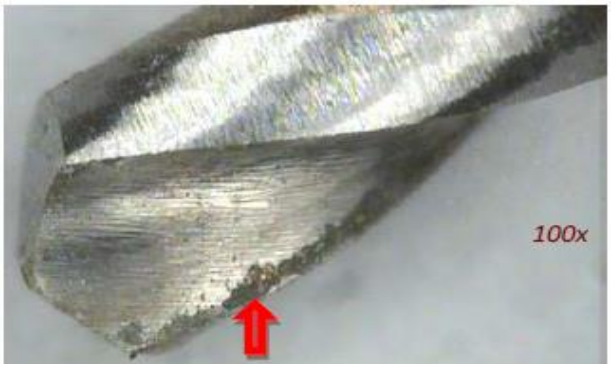


Figure 4. Twist drill edge chipping type of wear at lip.[85]

chip formation, poor cooling of the drill and improper selection of the drill point angle, helical angles, chisel edge and inadequate knowledge of the composite materials could lead to reduction in tool life and eventually, tool breakage. These occur when there is no effective space between the tool and workpiece due to poor design of drill geometry and thermal resistance, causing catastrophic rise in drill temperature.

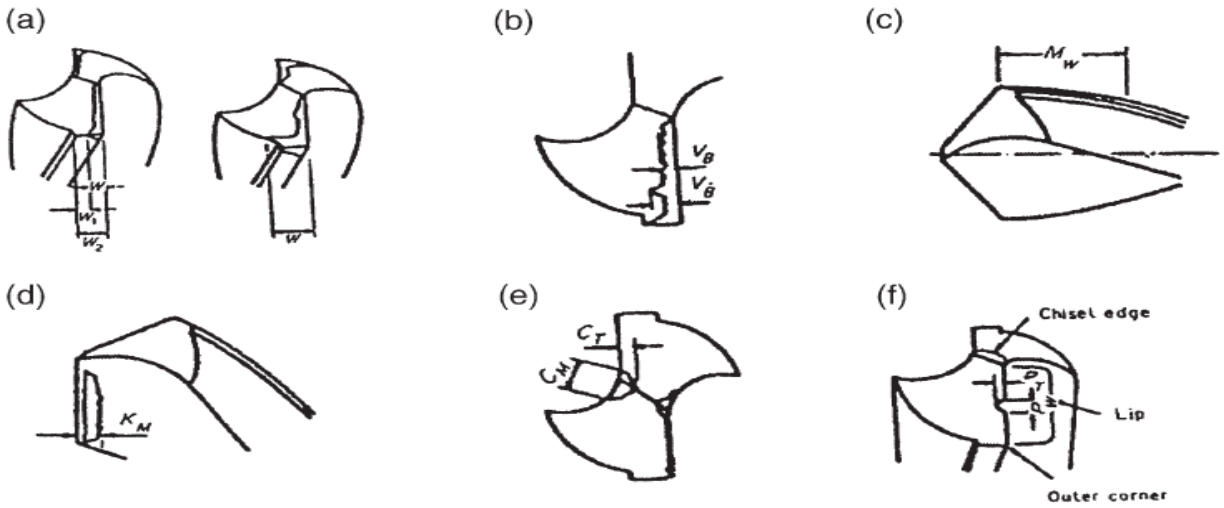


Figure 5. Types of drill wear: (a) Outer corners; (b) Flank; (c) Margin; (d) Crater; (e) Chisel edge and (f) Chipping.[86]

Tool coatings

Improvement and better performance of twist drill life could be achieved, especially at high cutting parameters such as cutting speed and feed rate, and during dry machining, by coatings.[45] Coating increases wear resistance, surface quality of drilled composites, corrosion resistance and oxidation resistance. Factors include coefficients of friction, interface temperature and thermal energy that aids wear could also be reduced using appropriate coatings on correct drill bits. Coatings are rampant on both cemented carbide and HSS drills.

Coated cemented carbide

Drill geometry effects on the deposition residual or interface stresses in diamond coated carbide drills has been investigated by Chao et al.[40], through the performance of a solid modelling of diamond-coated two-fluted twist drills. They concluded that diamond-coated drills have a potential for high performance drilling and for drilling of difficult-to-machine materials. Researchers have concluded that coated drills performed better than the uncoated, as a result of their increased wear resistance and consequently, improved tool life.[61-63, 87]

Coated high speed steel

Investigation on effectiveness of WC-8C_O electro-spark coating on HSS drills has been reported by Raju et al.[72] They stated that ESC performance enhances the drill bit life, as high as 5 fold compared to the uncoated HSS drills, based on the machining conditions of variable spindle speed at fixed feed. In comparison to bare drill bit, ESC coated drills performed better in terms of tool life even when drilling at higher speeds.

Performance and effects of tool coatings

The better or improved performance of drill bits are achieved through coating. In machining technology, several processes have been used in coating cutting tools. In the past nearly 40 years, the thermal diffusion and thin-film processes have been well and rampantly used. Also, it could be chemical and physical vapour deposition (CVD and PVD, respectively) coatings. Contemporarily, 40% and 50% of high speed steel and super hard tools, while 85% of carbides utilised in company are subjected to coating, either on the substrates or entire tools.[45] The later application attracts more cost. The coating method could be combination of multiple layers. Among the tooling materials, carbides have been found to be an excellent substrates, irrespective of the types of coatings, including solid lubricant, soft, hard or super-hard, single and multi-layer coatings, as well as PVD: Chromium nitride [CrN], Titanium nitride [TiN], Titanium aluminium nitride [(Ti,Al)N)] and Titanium carbonitride [TiN(C,N)], to mention but a few.[45] Audy [113] performed a comparative experimental and quantitative investigations on TiN, Ti (C,N) and Ti (Al,N) coatings and found that Ti (Al,N) coating produced the lowest force components and 'edge' forces, using cathodic arc evaporateds PVD coatings. Sivarao et al.[107] have reported in their experimental work that the TiAlN coated 8mm diameter twist drill tool performed better when compared with the TiN coated type, under the same dry drilling conditions and parameters in terms of reduction in burrs formation (height). However, using 5mm diameter drill tool, TiN coating proved better when considered the caps formation. The characteristic performances of these coatings are based on their ability to function at high speed, high temperature and dry or semi-dry condition of machining.

In addition, Iliescu et al.[114] had modelled and experimented the uncoated and Balzers (BS) and Cemecon (CN) diamond coated twist drills wear in CFRP drilling. The drills were manufactured

by Diager and Sofimag manufacturer. The results obtained revealed that higher life expectancy of the CN diamond coated drills than the BS coated type, while the Diager and CN coatings were better than the Balzers coating. Furthermore, in a single shot conventional drilling operation on 30mm thick Ti-6Al-4V/CFRP/Al-7050 stacks, a comparative experimental evaluation of the effects of diamond-like carbon (DLC) and chemical vapour-deposited (CVD) diamond tool coatings on drill wear modes and quality of drilled holes were carried out by Kuo et al.[118] The DLC and CVD diamond coated drills experienced abrasion (and brittle fracture) wear mechanism initially and untimely flaking/delamination of the coating primarily, respectively. They concluded that the holes drilled with CVD diamond coated drills were clearly better than holes produced with DLC coated drills, in terms of burrs reduction and when circularity was considered.

Drilling of composite materials

Composites refer to physically and chemically joined materials of dissimilar phases which are separated by a distinct boundary (Figure 6). The dissimilar systems are joined together in a bid to achieve structural and desirable properties which are unattainable homogeneously by each constituent.[87] Composites have become attractive materials today with various applications such as defence or military (naval and marine), transportation (automobile, marine and aerospace), structural (houses and buildings), communication and manufacture engineering as highly demand for materials of low weight, high strength, required stiffness and resistance to high wear, shear stress, impact, fatigue and temperature is increasing.[88-90,116,119,120, 121] Carbon fibre reinforced polymer composites are rampant workpiece in experimental composite materials drilling.

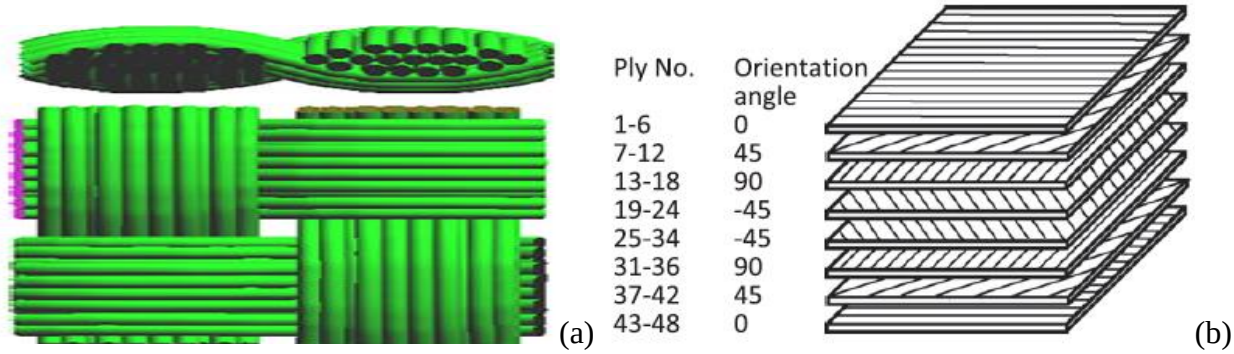


Figure 6. (a) An orientations ply of bi-directional fibre and (b) Schematic representation of unidirectional-plies CFRP composite laminate.[46]

Composition of carbon fibre composites

Composite is basically made up of fibres and a matrix. Carbon fibre contains textile, melt-spun, polyolefin and lignin. Table 3 depicts some constituents of a CFRP composite laminate.

Table 3. Constituents of a typical CFRP composite laminates.[91]

Material	Type
Matrix	Epoxy: araldite M
Reinforcing	240gm^{-2} Carbon fibre
Matrix maximum strength stress	82.55 MPa
Matrix modulus of elasticity	2.15 GPa
Hardener	HY 956

Carbon fibre and matrix formed the reinforcement material and binder of a typical carbon fibre reinforced composite, respectively. Carbon fibre has good mechanical properties in terms of strength and modulus of elasticity.

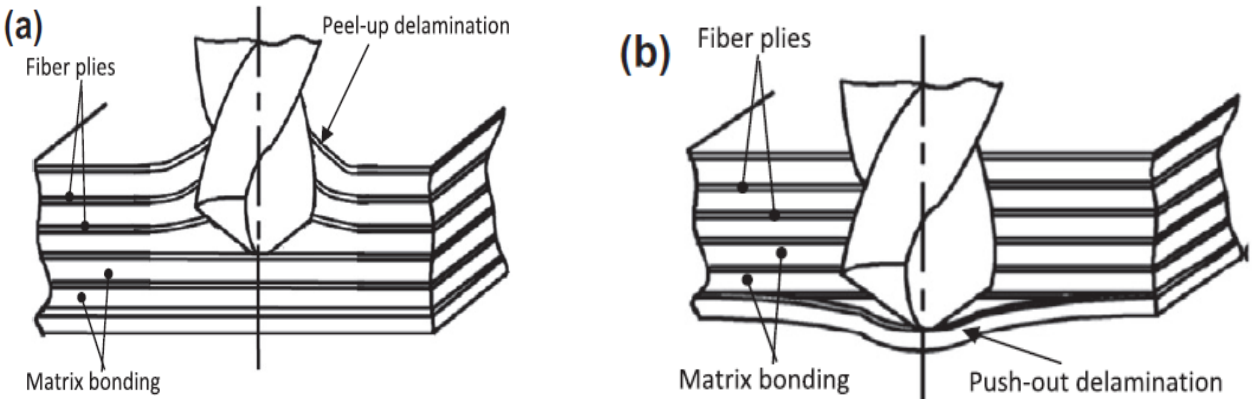
The mechanism of drilling composites is a process different from that of conventional materials (especially metals and their alloys) for a good quality hole to be obtained.[116] Velayudham et al.[92] stated that due to the coexistence of hard abrasive fibres and a soft matrix, there is need for an appropriate selection of cutting conditions. Carbon fibre composites have a challenge of poor machinability as a result of their highly abrasive nature, which limits its applications. This causes its fast replacement with natural fibre composites. There are damage caused on drilled composite materials as a result of their composition such as delamination, hole dimensional inaccuracy, surface roughness, fuzzing and composite fibre-pull out or uncut fibres.[93, 116,117] The damaged composite materials are susceptible to fatigue strength and load bearing capacity.[117]

Problems associated with drilling of CFRC laminate materials

Kim and Ramulu[43] reported that for years, carbon fibre composites have been drilled using the same methods applied in drilling metals. These have resulted in poor finish quality and excessive tool wear.[43] Abrasive, heat sensitivity and heterogeneous nature of composite materials make its

drilling a complex operation.[49] For applications where quality demand is high, drilling of the composite structures remains a major challenge, especially where carbon reinforced composite is stacked to metal parts.[19, 43] This scenario increases the severity of the problem and requires a more robust specially designed drill and better drilling processes.

In addition, drilling of carbon fibre laminates has several common problems. These setbacks include surface scorching, delamination, excessive tool wear, fibre cratering, matrix- melting and softening.[94] Among these, delamination is the most critical defect as it has the highest level of impact on accuracy and quality of a drilled hole.[51, 117]



Peel-up delamination. (b) push- out delamination.

Figure 7. Types of delamination phenomena.[46]

Delamination

Delamination in a composite material occurs whereby reinforced fibre plies separate, either by peel-up or push-out phenomenon. This defect occurs at the upper most layer of laminate from the rest of the body and/or on the drill bit's tip which pushes the bottom layers of the laminate respectively[75, 96] (Figure 7). In drilling, delamination occurs mainly at the critical entry and exit locations of the drill bit when the thrust force is greater than a threshold value.[60, 65, 70, 93] Delamination depends on many factors such as composite fibre nature, drilling parameters, drill design and laminate orientation. When the drill tip exerts compressive thrust force on the uncut composite laminate plies, and the point loading is greater than the inter-laminar bond strength of the composite, delamination occurs. It reduces composite dimensional accuracy, structural integrity, surface quality and durable applications.[49, 51, 93] Madhavan and Prabu[51] indicated that an increase in cutting

speed reduces the delamination for HSS drills, whereas an increase in feed rate increases the delamination effect in case of carbide drills. An analysis of the differences in delamination mechanisms has been carried out by Capello[47] when drilling laminate composites with and without a support device placed under the workpiece. His results showed that the proposed device drastically reduced delamination.

An analytical approach to identifying the process window of chisel edge length concerning drill diameter for delamination-free drilling has been studied by Tsao and Hocheng.[97] The approach was based on linear elastic fracture mechanics of fibre reinforced composites. An optimal range of diameter of pilot hole associated with chisel edge length was derived. They concluded that composite laminates drilling at higher feed rate without delamination damage could be conducted by controlling the ratio of chisel edge length and preferring medium to large hole. Isbilir and Ghassemieh[98] studied that the delamination free drilling process might be obtained by the proper selections of drill point geometry and the process parameters: high spindle speed and lower feed rate. They showed that effective tool choice could minimize delamination effect. Most importantly, the use of higher feed rates is achievable provided there is sufficient knowledge of the effects on thrust force and delamination for each selected drill.

Analytically, F_d has been generally used [14, 49, 51, 66] to describe the intensity of damage on the composite both at the drill entry and exit. It is expressed as $F_d = \frac{D_{max}}{D}$, where D_{max} and D are the maximum diameter of the delamination zone and the drill diameter [112,119] respectively (Figure 8). The higher the F_d, the greater the delamination effect.[14, 66, 112]

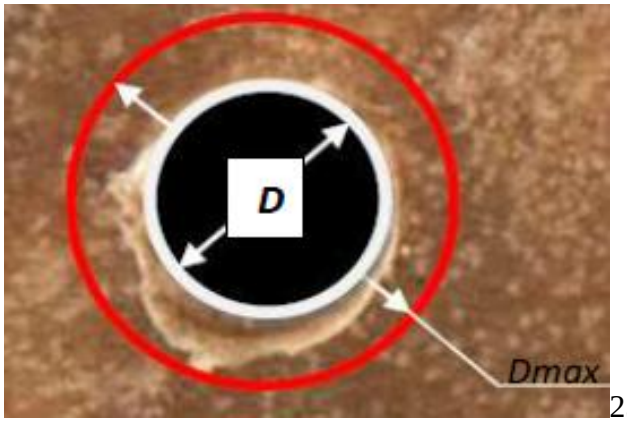


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Figure 8. Analysis of determination of delamination factor.

Surface roughness and dimensional inaccuracy

The importance of surface integrity, quality, dimensional and geometric tolerances of holes when drilling CFRP composites can never be compromised. Surface roughness is basically measured using two distinctive methods: direct and indirect methods. The former involves the use of stylus (contact) instruments and the later depends on optical (non-contact) instruments.[109] As a result of the nature of some composite materials, very little has been accomplished to improve on surface roughness and dimensional integrity.[18, 19, 52, 63, 68, 70] The roughness of the drilled surface has not been accounted for as a major issue based on its application.[99] In addition, formation of burrs and caps are another causes of dimensional inaccuracy, as reported by Sivarao et al.[107] They both reduced the fatigue life of the assembly components. Burr occurred as a resultant effect of a plastic deformation of a material under machining process (drilling). Practically, the burrs formed at the entrance of a drilled hole are usually smaller than the exit burrs.[107] The surface roughness in drilling with two different tools has been comparatively analysed and modelled, using regression analysis and ICM method.[109] It was concluded that the statistical (regression) analysis produced better results than the mathematical analysis (ICM). The evaluation was based on the proximity of their results to the actual values.

Poor surface finish as well as delamination occurs due to the heat generation (friction) between drill edges and the composite. The heat aids the softening of the matrix. Also, poor surface finish could be aided by improper selection of drilling parameters and tooling materials. Ogawa et al.[102] reported that surface roughness varies at different speeds, but speed is only of minor influence. They also stated that feed rate seems to affect the surface roughness most. Thereby, it is a great task to obtain the required surface quality for accurate assembly of some structural parts.[19, 51] Ogawa observed that smoothest surfaces of almost 0.1μm were produced with PCD drills, followed by Carbide drill at the same speed of 100 mm/min which produced good appearance holes but with high roughness of 6.5μm while HSS has the highest surface roughness of 8.0μm. Cutting speed increases with decrease in surface roughness. Comparatively, PCD drills provided good surface finish at high cutting speed and feed rate.[51] It was concluded that the surface roughness of drilled

holes on composites increased with increase in feed rate irrespective of the drill diameters unlike the spindle speed which has a small effect on surface roughness. Meanwhile, the machine spindle speed, drill diameter and feed rate increased with decrease in the dimensional accuracy of drilled hole [85] (Figure 9), where TD represents the tool diameter.

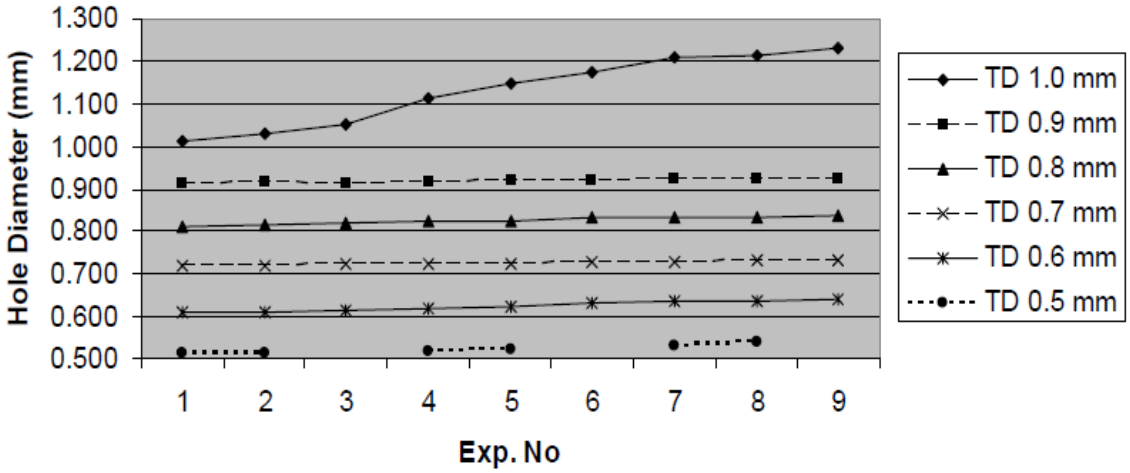

Figure 9. Drilled hole dimensional accuracy using different tool diameters.[85]

From Figure 9, the experimental numbers increased with the diameters of the drilled holes. Most importantly, increase in the TD caused a significant increase; deviation in form of errors in the desired hole diameter. This was more evident at 0.6 and 0.8mm TD immediately after experimental number 5, at most in 1.0mm TD progressively. Dimensional errors ranging between 5 to 10% were recorded.[85] Summarily, it has been reported that the surface roughness of a drilled hole depended on the hardness of the workpiece and drill, geometry of the drill, drilling parameters and machine rigidity.[109]

Other associated problems

Abrao et al.[99] suggested in their review paper that the cutting speed should be kept below 60 m/min; due to the fact that high cutting speed values led to higher cutting temperatures, which caused composite matrix softening, followed by matrix cratering and thermal damage of its constituents, particularly the binders.

Fibre pull-out and uncut fibre (Figure 10) are separate relevant problems. Zitoune et al.[101] reported the significance of correct choice of process parameters especially when drilling multi-

material stack. Their experimental results depicted that the quality of drilled holes could be improved by proper selection of cutting parameters as the drilled hole circularity increased with feed rate: around R_a of 6μm (at low feed rates) to 25μm in CFRP. From drill wear test results, they showed that thrust force significantly increased to 90% in CFRP compared with 6% in aluminium after the first 30 holes were drilled. When the number of holes increased to 60, composite fibre pulled out and parts of the fibres remained uncut (Figure 10).

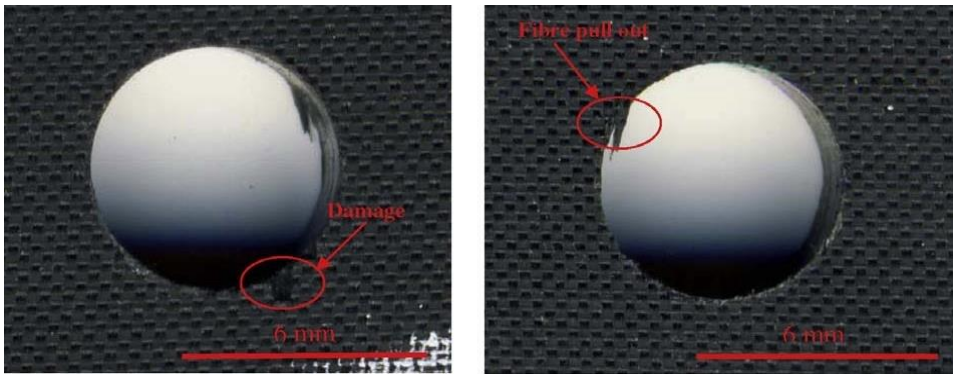

Figure 10. Fibre pull out and fibre uncut defects at hole entry and exit.[101]

Chip formation and separation

Composite fibre orientation determines chip formation during machining**.** The chip formed on the drill increased as cutting speed increased during composites drilling.[84] FEA drilling model that showed chip formation at the exit surface has been developed by Min et al.[44] The model was used to simulate the formation of both crown and homogeneous chips which were formed at higher and lower feeds respectively. They based the failure criterion governing the chip formation on the equivalent discrete element-plastic strain. Also, the same plastic failure criterion was used to model chip separation by Klocke et al.[100]

Parametric design (input variables)

Drilling parameters are the machining variables and conditions that affect the entire drilling process. They are machine capacity and function-dependents. Among them include cutting force, thrust force, torque, feed rate, material removal rate, coolant flow resistance and cutting speed. It has been reported that thrust force and torque increased with the size of the drill bits. Also, increase in feed rate caused an increase in both thrust force and torque, while both decreased

with the spindle speed. [108] The effects of drill wear and composite thickness on thrust force and torque has been investigated by using 'one shot' drill bit.[73, 103] They concluded that the thrust force increased with number of drilled holes for twist drill bit, unlike torque. Decrease in composite thickness caused increase in thrust force due to wear, while increase in feed affected thrust force causing increase in the rate of the tool wear. Hence, thrust force and torque significantly depends on drill feed rate, bit, wear, and composite thickness.

Experimental results of CFRP composite drilling using Carbide, HSS and PCD drills conducted by Modhavan and Prabu[51] and Mohan et al.[64] revealed the effect of feed rates, drill geometry and cutting speeds on chip formation, delamination, surface roughness and cutting forces. They stated that feed rate increased with delamination factor and surface roughness. Chip formation increased with increase in cutting force. Similarly, variations of cutting forces with or without onset of delamination during the drilling operations has been studied by Chen[50] and concluded that the delamination-free drilling processes might be obtained by the proper selections of tool geometry and drilling parameters such as cutting force.

During drilling, thrust force is the applied force on workpiece by the machine tool through speed and feed in downward direction. It is the plunging force of the drill bit unlike cutting force which is rotating force. Delamination effect, occurred principally at the drill exit in composite materials, has been reported to be mainly caused by the thrust force.[95,117] An optimisation of twist drill point geometries in order to minimise thrust and torque in drilling has been carried out by Paul et al.[13], using conical, racon and helical drill point geometries. Racon drill showed a marked reduction in thrust while the optimised helical drill reduced thrust by over 40% when compared with conical. Lazar and Xirouchakis[67] experimentally determined the axial and tangential cutting loads distribution by analysing the thrust on drilling CFRP composites with three different types of drills. It was shown that the maximum thrust forces occurred on the fibre plies in contact with the drill tip. Analysis of delamination in various drills: saw, candle stick, core and step drills has been analytically and compressively carried out by Hocheng and Tsao.[48] They predicted the critical thrust force that caused the initiation of delamination mathematically. They concluded by comparing the results obtained with that of a twist drill for all the available drills and predicted the decrease of critical thrust for the different drills and the points at which they were reduced to the twist drill. Theoretical predictions of critical thrust force at the

inception of delamination, of different special drill bits have been carried out by Hocheng and Tsao[104] using experimental investigations. Their results on critical thrust forces were confirmed and agreed with both the analytical findings of critical thrust forces and industrial experiences, that drill geometry has significant effect on the thrust force, as supported by works of Madhavan and Pradu [51], Wang et al. [53]

Moreover, formulation of a detailed analysis for the critical thrust force ratio related to the peripheral drilling moment has been conducted by Tsao and Hocheng. [95] Special drill bits such as saw, core and candle stick were used for the composites drilling. It was concluded that the special drill bits possessed a lower critical thrust force at peripheral drilling moment than without peripheral moment. This indicated that at the exit of drill bit in the composite materials, the peripheral moment caused bigger delamination drilling-induced damage. Prediction of thrust force during All 100/10% SiC metal matrix composites (MMCs) drilling has been performed.[122] Both experimental method and ABAQUS/Explicit FEA were used, with close agreement in their results. Drilling the typical MMCs with a low cutting speed and feed rate, for reduction in thrust force, were recommended.

Xiong et al.[6] used mapping method to develop 81 major mathematical equations in a new methodology for designing a curve-edged twist drill. They distributed the cutting angles along the tool cutting edge randomly. Their results were validated experimentally, and the drilling torque and the thrust force were compared. It showed that the new curve-edged drill reduced the drilling torque and thrust force by 28.5% and 24.6% on average respectively. Nagaraja et al.[105] reported that an increase in spindle speed and feed rate led to increase in torque, delamination and thrust force when drilling carbon fibre epoxy composite using HSS drill. They concluded that spindle speed has insignificant effect on torque and thrust force.

Liu et al.[46] stated that feed rate had the greatest influence on drill wear, thrust force and delamination.[35] Low feed rate coupled with high cutting speed reduced delamination and prolonged drill life.[46] Research on the development of suitable models with intelligent control scheme in the machining of composite laminates has been carried out by Dharan and Won.[60] Drilling experiments were conducted using carbide-tipped twist drills on composite material to obtain thrust force and torque responses for a wide range of feeds in high-rate drilling. Empirical expressions relating the thrust force and torque to the feed and drill diameter were obtained from

the results of the experiment. Isbilir and Ghassemieh[98] declared vividly that the detailed understanding of the effects of higher feed rate on delamination and thrust force is essential before embark on its application. They concluded that step drill reduced torque and thrust force (delamination) when compared to twist drill at similar feed rate and speed.

Material removal rate (MRR) is another drilling parameter that determines the efficiency of a drill. A good designed drill should be able to evacuate chips easily and rapidly. An attempt to determine the drilling process for carbon laminates, Sardinas et al.[42] proposed a multi-objective optimisation of the drilling process. Two mutually contradictory objectives were optimised: material removal rate and delamination factor, which represented the productivity and characterised the superficial quality respectively as jointly contradictory objectives were optimised. Increase in cutting speed and feed led to increase in MRR while delamination factor increased with decrease in MRR.

During wet machining, flow rate of coolant is imperative. Abele and Fujara[31] designed a drill geometry performance characteristic model and used it to obtain drill performance characteristics, numerical simulation of 3D FEA models and calculated coolant flow resistance. Their models also captured prediction of coolant flow, effects of coolant channel diameter and its surface roughness.

The cutting speed of a drill determines the rate of production of holes in composite materials. Cutting speed has less effect on delamination when compared with feed rate.[46] HSS drill supported a high cutting speed when compared with carbide (coated and uncoated types) and PCD.[51] Isbilir and Ghassemieh[106] stated that surface roughness and delamination damage reduced with increase in cutting speed when drilling CFRP composite with multi-layer TiAlN/TiN PVD tungsten carbide tools. They concluded that drilling parameters influenced drilling outputs significantly. Gaitonde et al.[91] investigated process parametric effects on delamination during high-speed thin woven-ply CFRP composite drilling. Cutting speed, one of the process parameters considered, was used to analyse the delamination-damage factor. Their investigations showed that the delamination tendency decreased with cutting speed and further suggested that combined low values of feed rate and point angle would reduce the damage.[116] Conversely, Sardinas et al.[42], Davim et al.[49] and Kilickap[73] studied delamination during conventional drilling of composite laminates and optimisation of cutting parameters using

genetic algorithms, design experiments and Taguchi methods respectively. They reported that delamination increased with cutting speed. Lastly, High spindle speed as well as lower feed rate favoured delamination-free composite drilling. Thus, thrust force and delaminations go together and depend on other drilling parameters such as cutting

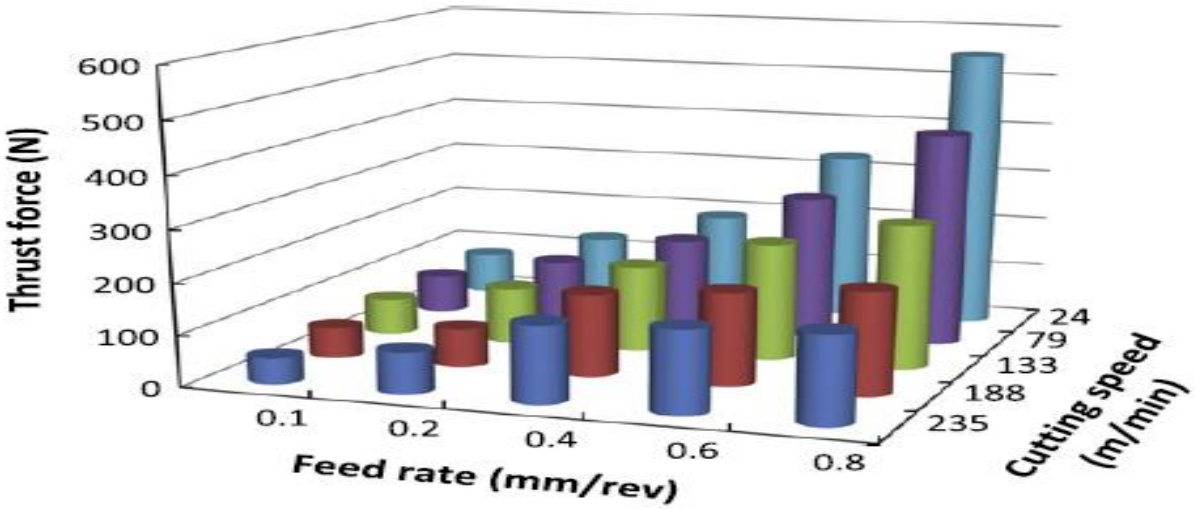

Figure 11. Parametric effect of cutting speed and feed rate on thrust force in CFRP composite drilling.[46]

speed[73], feed rate (as illustrated in Figure 11), drill geometry and wear.[17, 46, 54,116] From the 3D plot of Figure 11, the highest thrust force of more than 500N was recorded at highest feed rate of 0.8mm/rev and lowest cutting speed of 24m/min. These results evidently implied that the thrust force of the drills increased as the feed rate increased, but decreased as the cutting force increased during CFRP composite (conventional) drilling. Also, a lowest feed rate of 0.1mm/rev and thrust force of nearly 25N were recorded at maximum cutting speed of 235m/min.

Conclusions

A highly efficient twist drill is the outcome of innovation and ingenuity. Recent advances in twist drill design with respect to composites drilling have been critically reviewed and presented. The following summary can be made:

- HSS twist geometry is the most commonly used type of drilling tool due to its outstanding performance with regards to better chip removal, availability, mass production and cost effectiveness.

- The chisel edge, point and helical angles are the most important parts of twist drill design geometry.
- The quality of drilled hole depends greatly on the drill geometry, design, materials and selected drilling parameters.

- Delamination of composites and rapid tool wear are the main problems encountered when drilling CFRP accounting for drilling-induced damage as high as almost two-third of the total drilled products.
- PCD provides good surface finish at high cutting speed and feed rate. Improved surface quality and dimensional accuracy of composite materials could be achieved using carbide especially coated types and PCD drills.
- Good knowledge of drilling parameters, composite materials and well-designed drill geometry afford better opportunity of developing drills that will minimise delamination effect on the reinforced composites, tool wear and produce a high quality drilled hole surface.

The drill design engineers and manufacturers will obtain a comprehensive understanding of the recent advances in twist drill design for fibre reinforced composites drilling by going through this review paper, with intention of improving and optimising the efficiency of drills and solving challenges confronting composites drilling.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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Appendix 1

Notations

(Ti,Al)N	titanium aluminium nitride
D_{max}	maximum diameter of the delamination zone, *mm*
BS	balzers
CAD	computer aided design
CC	cemented carbide

CCC coated cemented carbide

CFRC carbon fibre reinforced composite

CFRP carbon fibre reinforced plastic

CN cemecon

CrN chromium nitride

CVD chemical vapour deposition

D drill diameter, mm

DCC diamond coated carbide

DLC diamond-like carbon

DLC diamond-like carbon

EDM electroplated diamond micro

ESC electro-spark coating

F_d delamination factor, $\frac{D_{max}}{D}$

FEA finite element analysis

FIS fuzzy inference system

FRP fibre reinforced polymer

GFRP glass fibre reinforced plastic

HSS high speed steel

ICM inverse coefficient matrix

MMCs metal matrix composites

MRR material removal rate

PCBN polycrystalline cubic boron nitride

PCD polycrystalline diamond

PM HSS powder metallurgical high-speed steel

PVD physical vapour deposition

R_a surface roughness, μm

TD tool diameter, *mm*

TiN	titanium nitride
TiN(C,N)	titanium carbonitride
UC	uncoated carbide
UCC	uncoated cemented carbide