Chapter 2

Influence of Drill Geometry Design on Drilling-Induced Damage Reduction in Fibre-Reinforced Polymeric Composites

Sikiru Oluwarotimi Ismail

Department of Engineering, Centre for Engineering Research, School of Engineering and Computer Science, University of Hertfordshire, Hatfield, Hertfordshire AL10 9AB, England, United Kingdom.

Corresponding Author: S. O. Ismail, s.ismail3@herts.ac.uk +44(0) 1707 28 5213

Abstract

Drilling is an extensively used manufacturing process for boring different and widely used fibre-reinforced polymeric (FRP) composite materials, among various machining operations. This process is inevitable for assembling/coupling of parts of systems. Despite of the good inherent properties of the FRP composite materials, they are not easy to drill, due to the dissimilar properties of their constituents (mainly fibre/reinforcement and matrix). More than a few drilling-induced damage (DID) on FRP composites: delamination, surface roughness, fibre-pull out/uncut, among others, severely affect the quality, structural integrity and applications of the drilled composite components. The most rampant among these damage is delamination; either peel-up or push-out type. Importantly, these damage are frequent and attributed mainly to the geometry design of the drill bits used. It is highly germane to consider and further study the influence of the drill geometry design (DGD) on reduction of DID on FRP composite components and improve the quality of the drilled holes. Therefore, this present chapter focuses on a current status/trend in the drilling of FRP composites and comprehensively reports optimum drill geometry designs (DGDs) for different FRP composites. It was evident that a combination of an efficient drill geometry (chisel and cutting edges, helix and point angles, diameter, length, material, among others) design and suitable selected drilling process parameters (cutting speed, feed rate, depth-of-cut, material removal rate, among others) produced minimum DID on FRP composite components. This knowledge is required to guide drill designers, manufacturers, machinists and researchers in the search for high performance drilling phenomenon.

Keywords: Drill geometry design (DGD), Drilling, Fibre-reinforced polymeric (FRP) composites, Drilling-induced damage (DID), Delamination.

2.0 Introduction

A minimum of two different materials make up a composite material. These materials are known as fibre and matrix; reinforcement and binder, respectively. They improve performance and reduce production costs of the composite materials. For many decades, fibre-reinforced polymeric (FRP) composite are the right materials for many industrial applications, such as automotive and aviation components, marine as well as oil and gas industries. The wide application of FRP composite materials depends on their outstanding mechanical properties (Callister 1999). However, drilling operation remains unavoidable for FRP composite components in the process of completing assembly. Mechanical couplings for joining FRP components with screws and pins are commonly used in various industrial applications. Whenever holes are needed for assembling of FRP components, drilling operation is unavoidably necessary.

Fibres are harder to break or drill than resin and the interfacial bond or strength within the fibre and the resin is less than the strength of the reinforcing fibres, according to Zitoune and Collombet (2007). Therefore, in FRP composite drilling, delamination damage is the most critical and rampant, followed by fibre pull-out among several drilling-induced damage (DID), as reported (Zemann 2015). Other DID include surface roughness, de-bonding, fibre uncut, cracking, matrix melting and cratering, among others. These damage decrease the bearing capacity of FRP composite parts and shorten the service life of the assembled parts. DID are difficult to repair. Also, they lead to poor quality of holes, which accounts for 60% of all rejected components, mainly caused by delamination. The rejects and refusal of these parts are very expensive (Tsao and Hocheng 2005). DID lead to severe reduction in properties of FRP composites, especially on mechanical behaviours and load-carrying capacity of the composite parts.

Moreover, the aforementioned DID on FRP composite materials have been attributed to many factors. These factors include, but are not limited to, chosen drilling process parameters, the nature of the FRP composite samples and importantly the drill geometry design (DGD). Drill is a complex cutting tool that rotates when creating hole on a material or producing chips by shear deformation. It contains both cutting lip(s) and flutes. Flutes support the removal of chips and passage of cutting fluid (Ismail et al. 2017a). It is a mostly used cutting tool (Ismail and Dhakal 2017). The geometries of drills are complex, as shown in Fig. 2.1.

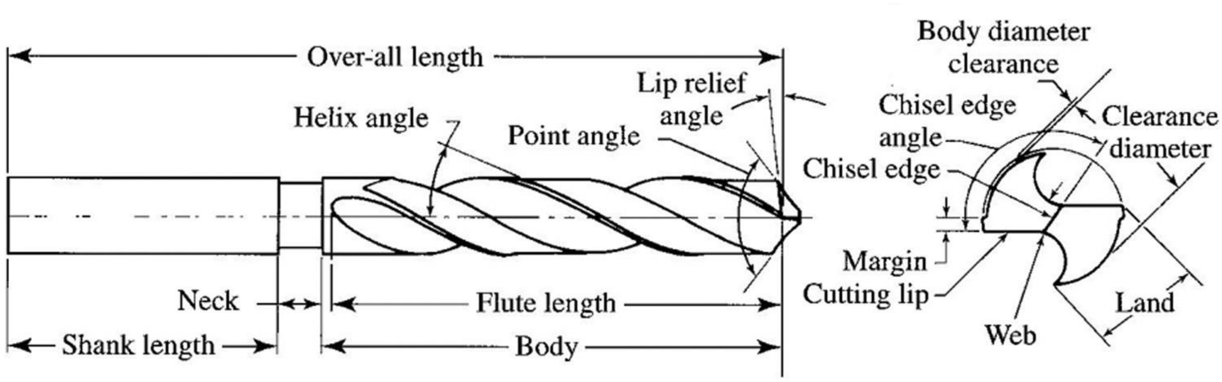


Fig. 2.1 Parts of a typical drill bit, showing complexity of its geometry design (Ismail et al. 2017a)

Today, there are different drills available in the drilling world. These include hole saw, core, digger, step, twist and special, to mention but a few. They are used to perform different drilling purposes. Twist drill is the most common type and used. A nearly 250 million twist drills are consumed by American manufacturing industries yearly (DeGarmo et al. 2003). The GDD greatly determines the quality of drilled holes. A well-designed drill produces a less damaged component. This is because both the concentrated and uniformly distributed loads depend on the DGD, as reported (Ismail et al. 2017b; Ojo et al. 2017). The concentrated and uniformly distributed loads occur at initially entrance of the drill and during maximum engagement of drill in the FRP composite materials during drilling operation, respectively. These two forces contribute to the type of damage on the FRP composite materials.

For instance, the values of point, helix and lip relief angles determine the amount of torque and thrust force developed from the cutting force and feed rate, respectively during drilling operation. A strong connection exists between the feed rate and thrust force. Precisely, thrust force depends on feed rate. Feed rate often increases with thrust forces during drilling process. It has been reported that the major factor that responsible for the occurrence of delamination was thrust force (Ojo et al. 2017; Ismail et al. 2017a; 2017b). Delamination damage occurs whenever the drilling force exceeds the threshold value. It is rampant in multi-layer or hybrid FRP composite laminates, as illustrated in Fig. 2.2.

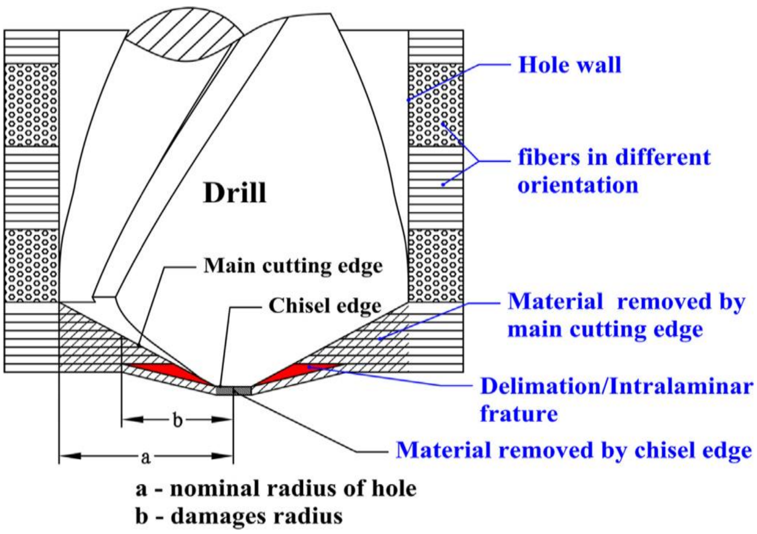


Fig. 2.2 Diagram of removed materials and delamination/inter-laminar fracture damage caused by different cutting edges (Jia et al. 2016)

A further elaboration coupled with an extensive discussion on drilling-induce delamination will be provided in the later sub-chapters.

2.1 Composite Materials

The making of material structures has evolved from metallic to composite materials. Presently, composite materials are widely used, because of their outstanding physical and mechanical properties (Sardin˜as et al. 2006). Composite can be simply defined as a combination of two or more classes of materials to form a single material with an improved property for a required application. Composites are either metal matrix, ceramic matrix or polymer matrix composite type. According to Goni et al. (2000) and Soldani et al. (2011), polymer matrix composites (PMCs) have been extensively used to manufacture numerous engineering components by many companies. These applications are rampant in automobile, marine, power/energy, telecommunication, security, military, sport/game, aerospace industries, to mention but a few. The widely use of composite materials can be attributed to their lightweight, high strength, exceptional corrosion and acoustic properties, among other outstanding properties, especially when compared with several metallic and alloy materials.

Furthermore, composite materials provide an extensive range of potential automotive applications. Composite automotive parts include, but are not limited to, intake manifolds, door linings, brakes, dash boards, interior finish, suspension, bumper systems, bonnets, steering, wheel covers and body panels. For instance, the structural application of carbon FRP composites proved better than many engineering materials (Das 2001), due to their supreme strength-to-weight ratio. Moving forward, the concept of light weighting is essential for high performance in automobile racing. The recent advances in design and development of various innovative composite materials has increased their applications in automotive industries. Nowadays, components of various cars and aircrafts are products of various types of composite materials. Therefore, both cars and aircrafts become lighter. Consequently, the rate of fuel consumption is reduced, making application of composite materials more economical when compared with other conventional and older engineering materials. It has been reported that composites offer 50 – 70% reduction in automotive mass, when compared with the use of steel (25 – 35%) and aluminum (40 – 55 %), with specific strength 2 – 6 times higher than that of metals (Basavarajappa, 2008).

Notwithstanding, there are many challenges that are associated with both manufacturing and drilling of heterogeneous FRP composite materials. Soldani et al. (2011) stated that research conducted in the field of drilling is not only expensive, also it requires enough time and money. Also, it has a tendency of causing fewer dangers against human health with natural (hemp, jute, sisal, cotton, flax, to mention but a few) FRP composites, when compared with the synthetic (glass and carbon, among others) FRP composites. With the presence of long fibres in the eliminated chip of some FRP composite materials, machining of long FRP composites must be wisely conducted. Industrial machining of FRP composites attracts some complications, due to the presence of long fibres in some FRP composite materials and hence resulting to the risk of damage on both tools (drills) and materials/workpiece (composites) during the drilling process (Mkaddem and El Mansori 2009). Therefore, the drilling parameters, process design and drill geometry must be properly selected for a particular FRP composite in a bid to obtain an optimised drilling operation.

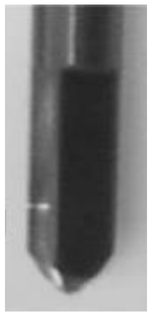
2.2 Drilling, Drill Geometry and Types

Drilling process is one of the hole-creating operations that are widely used in many machining industries. Among the manufacturing processes, drilling is a frequently used process (Sanjay 2006). Drills are solid, rigid, multi-point rotary cutting tools with a range of cutting angles, edges and various shanks, as earlier depicted in Fig. 2.1.

There are several drill geometries (Fig. 2.3). Each of these drills is used for various drilling operations. It depends on the nature of FRP composite materials, desired quality of drilled holes, chosen drilling parameters and conditions.

Drills of various geometries have been designed, manufactured and used to create holes of different diameters on numerous materials, including FRP composites. These drills include, but are not limited to, twist drill, one-shot, brad-centre, reamer, step, among others, as listed in Fig. 2.3 and subsequently discussed.

(a) Twist drill  (b) Brad drill  (c) Brad-spur drill 

(d) Dagger drill  (e) Step drill  (f) 4-flute drill 

(g) Saw drill  (h) Core drill  (i) Step core drill 

(j) Candle stick drill  (k) Compound core drill 

(l) Double point angle drill  (m) Tapered drill reamer 

Fig. 2.3 Various drill geometries already used for carbon FRP composite drilling (Feito et al. 2016)

Several twist drills have been used in many decades ago. They were designed to accommodate a few specific point geometries. Therefore, there are limitations to the extent they could be used to obtain damage-free drilling. They were originally designed for a specific application; drilling of metals and few alloys that were available. These conventional DGDs include, but are not limited to, planar, cylindrical, conical, ellipsoidal or hyperboloidal. Both inputs and outputs of a drilling process depend on the geometry of a drilling tools, commonly referred to as drills. Therefore, a geometric modelling of a drill plays an important role in its design.

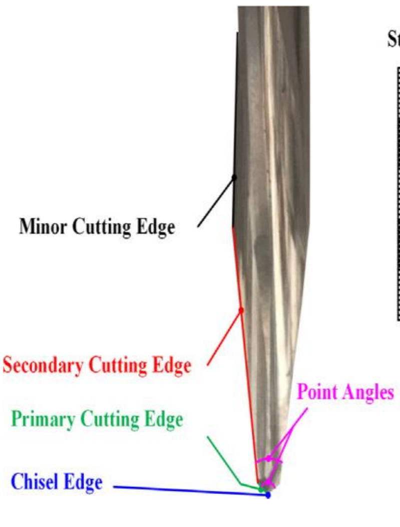
In addition, drilling performance is a function of the drill geometry shape as well as dimensions. They both determine the drilling performance: drill wear, drilling forces (thrust and torque), drilling dynamics and resultantly, the quality if the produced holes (Xiong et al. 2009). This makes the DGD attracts a great importance and uncompromised consideration. An inefficiently designed drill usually produces a poor distribution of forces along the cutting plane, resulting into bad performance and undesirable cutting ability. It therefore increases the machining and/or manufacturing costs. A loss of cutting ability increases drill wear rate, which adversely increases the energy consumption, as rubbing effect replaces an efficient cutting or drilling. Both drilling thrust (along the drilling axis) and torque are the two main drill performance characteristics. These characteristics are determined by the drill point geometry (Paul et al. 2005).

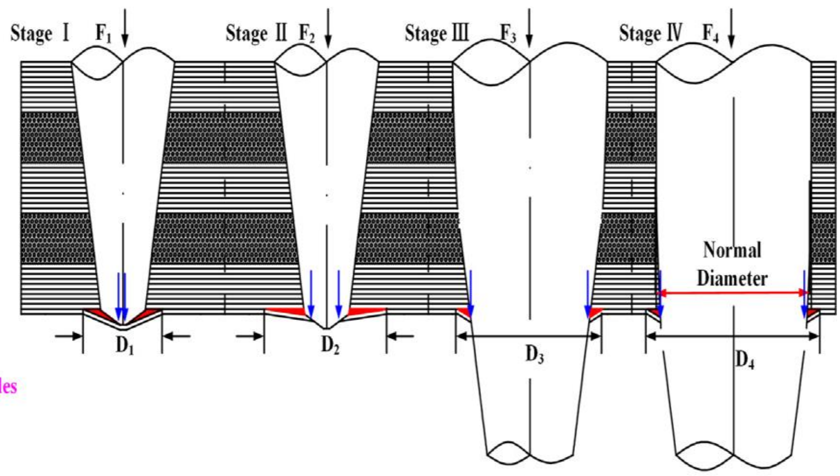
2.2.1 Twist Drill

Twist drill is the widest used drilling tool for many drilling processes. They possess several parts (angles, lips, edges, grooves, plains and lands) that work together to achieve drilling operation (Fig. 2.1). The complexity of drill bit geometries, such as twist drill needs careful consideration during design and choice for operation. They are different types of twist drills. They are used according to their appropriateness for a particular drilling activity. Twist drills can be classified based on the shapes of their shanks (straight, square, taper and bit), flutes (double/two, three, four and straight), angles (helix, clearance and point of different angles) and land (sub-land), to mention but a few. Twist drills are also categorised based on the material used: high speed steel (HSS), cobalt, carbide, diamond, tungsten carbide (WC), polycrystalline diamond (PCD), among others. Also, there are coated (titanium and tin) and uncoated twist drills. These names are combined to give drill a descriptive label, such as diamond-coated carbide twist drill, titanium coated HSS twist drill, among others. Drilling dynamics and twist drill wear depend on its size and shape. Machine tools require power, but much when cutting tools (including drills) are not well-designed (Ismail et al. 2017a). Therefore, one of the effective ways to prevent rapid wear of twist drill wear as well as increase drilling efficiency is by selecting clearly defined geometry of the primary cutting edge. In a bid to design a new drill for a best performance, its flute profiles have been generally designed to combine simulation analysis for forward and backward manoeuvres (Fetecau et al. 2009).

2.2.2 One-Shot Drill

One-shot drill possesses a primary or main, secondary cutting edges and two points, produced by both the main and secondary cutting edges. The structure of one-shot drill expands the drilling process in stages, as described in Fig. 2.4 by Jia et al. (2016). Stages 1-4 show how long the edge of the chisel pushes the last layer of the FRP before drilling takes place. After that, the removal of the remaining material at stage 2 is carried out by the primary cutting edge. Stage 3 then reveals a secondary cutting edge with a small angle associated with material removal, and finally, the secondary cutting edge gradually penetrates and the cutting edge begins milling close to the end of the drilling operation, at final step 4. To reduce the impact of DID at exit point of the drill, the direction of cutting in the last stage 4 is expected to be reversed towards the drilling point. A periodic saw-tooth structure the drill cutting edges to achieve the purpose of reversing the cutting direction was then proposed.





(a) **(b)**

Fig. 2.4 A typical one-shot drill, depicting its parts and (b) four stages of its drilling process (Jia et al. 2016)

2.2.3 Brad-Centre, Reamer and Step Drills

Feito et al. (2015) comparatively investigated the effect of three uncoated special 6 mm drill geometries (Fig. 2.5) on drilling of woven carbon FRP composite materials, using different cutting conditions.

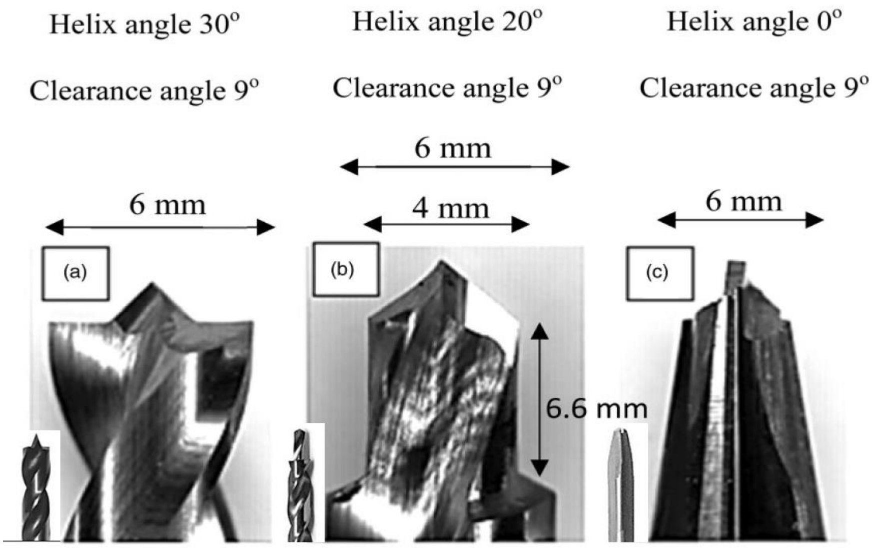


Fig. 2.5 (a) A brad-centre, (b) step and (c) reamer drill geometries/dimensions (Feito et al. 2015, Feito et al. 2016)

The results depicted that the two classes of delamination increased with feed rates for both step and brad drills, while it was nearly constant for the reamer drill, especially with exit delamination almost recorded delamination-free drilling (Fig. 2.6). The step drill recorded highest entry delamination, followed by brad drill and reamer drill exhibited lowest entry delamination damage. Conversely, brad drill recorded highest exit delamination, followed by step drill, while reamer drill still maintained least delamination damage response. Therefore, an optimal result was obtained with reamer drill geometry. This can be traced to the lowest values of both drilling forces (thrust and torque) during drilling evolution, as detailed in another similar and more comprehensive study (Feito et al. 2016). The results of both developed drilling forces are presented in Fig. 2.7. These forces determine the possibility of occurrence of both types of delamination, because delamination extent, area or factor often increased mainly with thrust force (Feito et al. 2016, Ojo et al. 2017, Ismail and Dhakal 2017, Ismail et al. 2017a, Ismail et al. 2017b). Summarily, it was stated that combination of a correct geometry of drill tip and selection of feed rate was an indispensable factor required to decrease drilling-induced delamination.

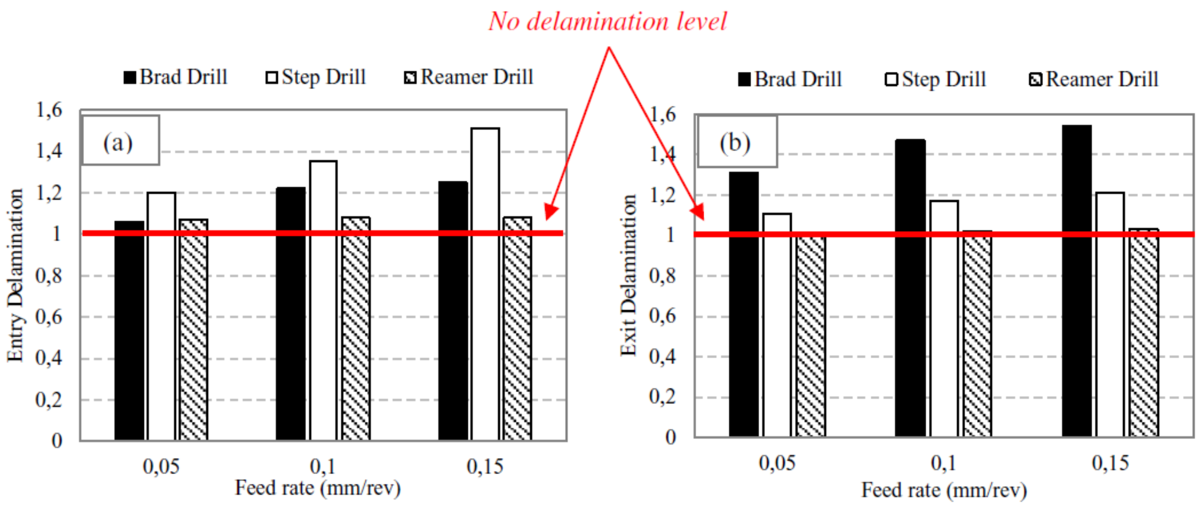
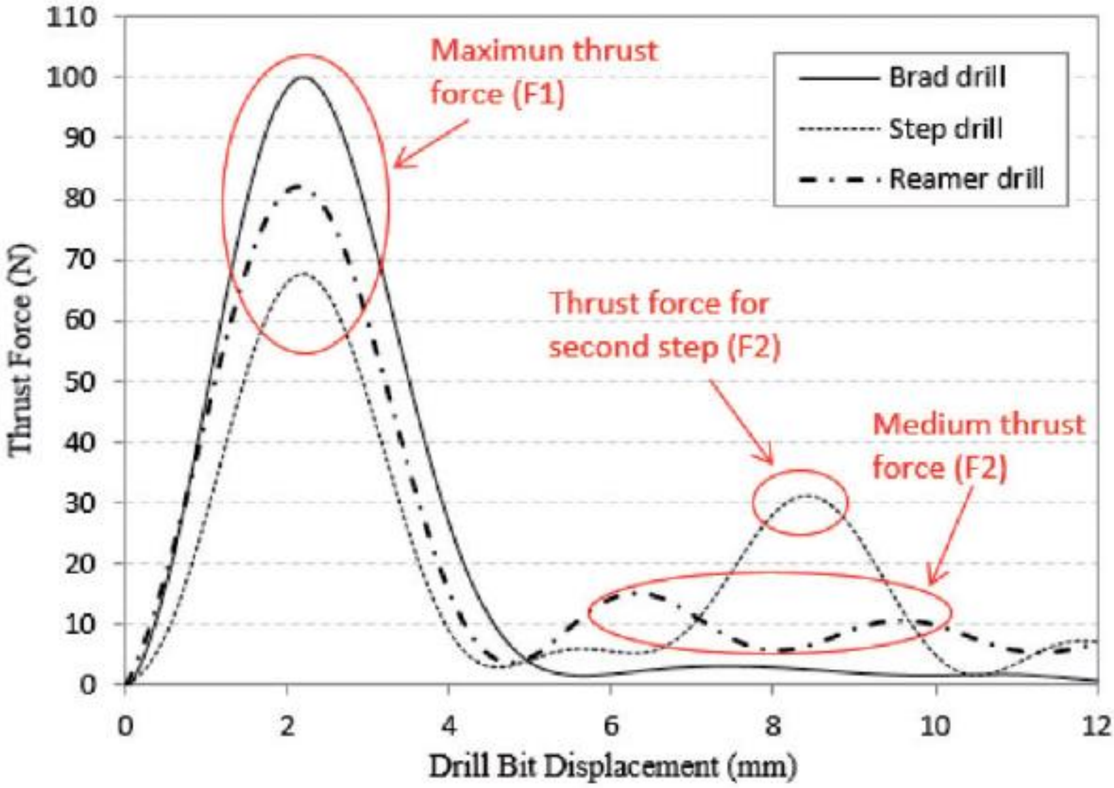


Fig. 2.6 Influence of drill geometries on both (a) entry/peel-up and (b) exit/push-out delamination (Feito et al. 2015)



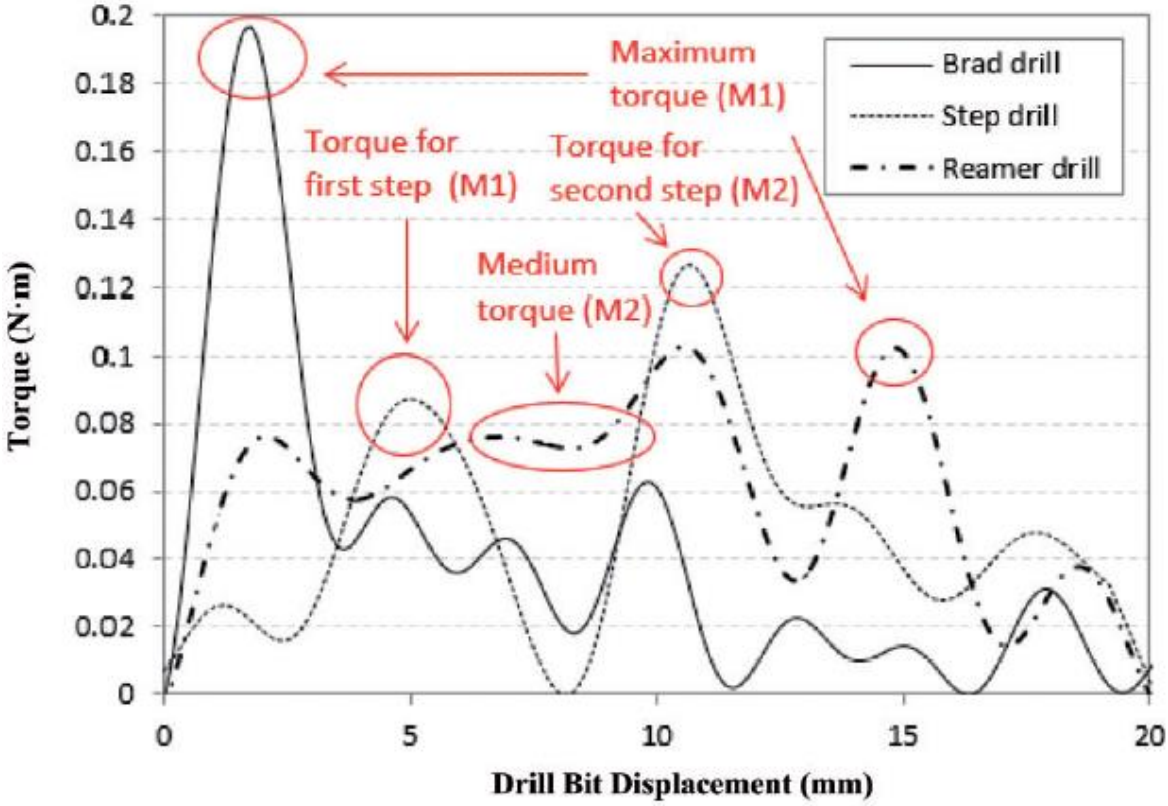


Fig. 2.7 Effect of drill geometries (brad, step and reamer) on thrust force and torque during drilling of carbon FRP composite materials (Feito et al. 2016)

2.3 Other Important Drill Geometry Designs

2.3.1 Diameters

Dharan and Won (2000) stated that an increase in drill diameter led to an increase in both thrust force and torque developed when drilling carbon FRP composite laminates of fibre volume fraction and thickness of 0.63 and 9.9 mm, respectively. These results were similar to that of Zitoune et al. (2010), when drill diameters of 4 and 6 mm recorded lower thrust forces and torques than drill diameter of 8 mm when drilling carbon FRP/aluminium composite. This observation was attributed to higher chisel edge length and steep rise in chip cross-sectional area of a bigger diameter of 8 mm. Conversely, Lee et al. (2008) reported a remarkable increase in thrust force when drill diameter of 8 mm was increased.

2.3.2 Angles

Chen (1997) recorded a decrease in torque developed when point angle of a twist drill was increased during drilling of carbon FRP composite laminates. This occurred, because an increase in point angle of a twist drill leads to an increase in the drill orthogonal rake angle. This occurred at each point on the main cutting edge. However, the point angle increased with thrust force. Hence, in an attempt to achieve a reduced thrust force and consequently, a decreased delamination damage on carbon FRP composite during drilling process, a choice of smaller point angle is recommended. In addition, a higher helix angle produced a lower drilling forces (thrust and torque). Similar to that of point angle, helix angle of a twist drill increases with its orthogonal rake angle. Therefore, both drilling forces are decreased. In addition, a larger drill chisel edge rake angle produced a lower drilling forces, as reported. A decrease in the drill chisel edge length produced an increase in chisel edge rake angle, consequently, it reduced the drilling forces. Both drilling forces increased when the drill web thickness was increased. Hence, the correct choice of a smaller chisel edge web thickness and web-thinning are required to decrease the thrust force and achieve an optimal drilling process.

In addition, Shyha et al. (2009) compared the effects of two step drill geometries (point angles of 118^o and 140^o) on thrust force developed during experimental drilling of carbon FRP laminate. It was observed that a lower thrust force was obtained with a higher point angle of 140^o. This was attributed to a smaller interaction occurred between the step drill chisel edge and the carbon FRP laminate. Additionally, influences of two helix angles (24^o and 30^o) of step drills were further investigated. From the results obtained, it was observed that difference in their helix angles attracted insignificant response in terms of DID recorded. Similarly, highest force and minimum delamination damage were recorded with a higher 120^o point angle twist drill, when compared with a smaller point angle 85^o twist, a special step, a dagger and a brad drills, under the same drilling parameters and conditions (Durão et al. 2010). Conversely, Karnik et al. (2008) stated that drill point angle has a significant influence on drilling-induced delamination. Hence, lower point angles of twist drills produced smaller delamination factor. This implies that thrust force reduced with the lower point angles. This was in agreement with similar results reported by Tsao (2008) and Palanikumar et al. (2008). Tsao (2008) stated that a decrease in twist drill point angle led to a significant increase in the drill relief angle and consequently, it reduced thrust force and its associated delamination damage. And, Palanikumar et al. (2008) studied the effects of three point of angles (85^o, 115^o and 130^o) of twist drills when drilling glass FRP composite laminates. From the experimental results, it was observed that twist drill with the smallest point angle of 85^o recorded an optimal results, when compared with others. Consequently, it exhibited a lowest value of drilling-induced delamination response.

2.4 *General Drilling of FRP Composite Materials*

FRP composites are quite different from metals. Fundamentally, metals are homogeneous materials and FRP composites are heterogeneous, with isotropic and anisotropic properties, respectively. With the heterogeneous nature of FRP composites due to the dissimilar properties of their constituents, drilling of composite structures has remained a major challenge. This is traced to the different responses of various fibres/fillers (reinforcements) and matrices (binders) under same cutting forces (torque and thrust) and interfacial drill-composite temperature. A combination of more dissimilar constituents in a single composite material increases the possibility and degree of the drilling problem. It requires a more robust drill tool and a better drilling process. For instance, when a carbon reinforced composite needs to be fastened to metal parts of the automobile, it is inevitably required that a hole needs to be produced in the material stack, which comprises the composite and metal. A report from the Abrasive Technology (2001) showed that polycrystalline diamond (PCD) – a stronger material can be used as a cutting tool (drill) material. The presence of diamond in PCD drill increases its resistance against a severe abrasive nature of many synthetic carbon FRP composite materials. Nevertheless, PCD cannot withstand required high cutting forces for metal-matrix composites (MMCs) drilling, particularly with titanium metal.

More also, Veniali et al. (1995) studied the drilling responses of an aramid FRP plastics, a smear occurrence on the drilling tool was reported. The possibility of controlling both entry and exit delamination-induced damage (Fig. 2.8) was later concluded, by having a good relationship between machining/drilling parameters. The entry and exit delamination phenomena are technically referred to as a peel-up and push-out type, respectively. Consequently, this relationship produced forces and torque, which determined the degree of the DID on the FRP composites.

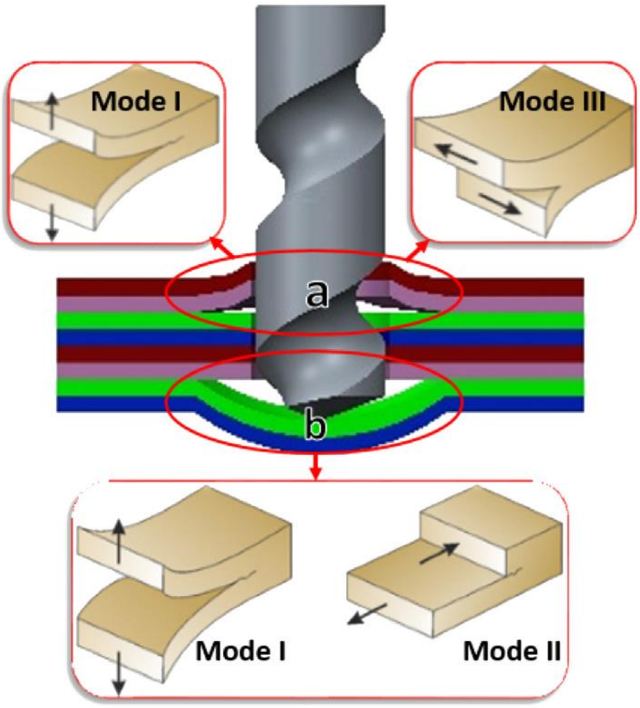


Fig. 2.8 Delamination-induced damage, showing (a) peel-up or entry and (b) push-out or exit types and their associated modes/mechanisms of deformation (Ojo et al. 2017)

2.5 Drilling-Induced Delamination Damage

Jain and Yang (1994) modelled the delamination zone of FRP composite laminates, caused by both critical feed rates and thrust forces. Concerning drill geometry designs (DGDs), chisel edge breadth has been reported to be most significant factor which determined the measure of thrust force and therefore delamination damage. To further establish this finding, a diamond-impregnated tubular drill was designed and experimentally tested. The results showed that diamond-impregnated tubular drill tool produced a minimal thrust with a higher hole quality when compared with commonly used twist drills. Further investigation on drill geometries (chisel edge, cutting lip and point angles) and their influences on critical thrust force, above which delamination occurs has been carried out by Ismail et al. (2017b), as illustrated in Fig. 2.9 and later explained in sub-chapter 2.7 (Fig. 2.17).

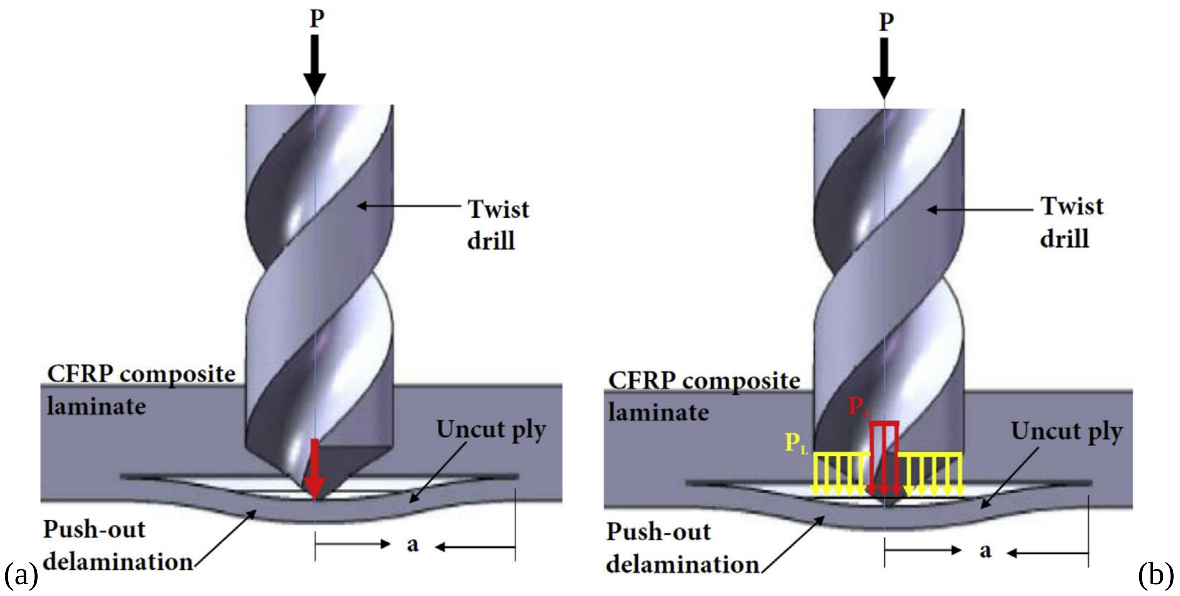


Fig. 2.9 Delamination phenomenon, caused due to the (a) concentrated load and (b) distributed loads on chisel edge and cutting lips (Ismail et al. 2017b)

Furthermore, Lazar and Paul (2011) experimental analysed drilling of FRP composites to determine the cutting loads distribution along thickness of the workpiece and drill radius. The loads were axially and tangentially distributed. Three different drills were used to analyse the thrust and torque curves. An occurrence of maximum loads on the plies in contact with the drill tip was observed. The initiation of an exit delamination was attributed to the period when the drill tip exited the workpiece. However, cases where the initial interlaminar crack extended outside the limits of the future hole to produce a quantifiable delamination or an occurrence further propagation as the tool continued its movement towards leaving the workpiece was not studied. Capello (2004) hypothesised two main variances in the pattern of delamination. Based on this analysis and in a bid to counter the hypothesised mode of delamination, a new simple prototyped device was designed and built. The effectiveness of this device was verified. From the results obtained, the possibility of significantly decrease of delamination through the proposed device was observed and established.

Additionally, a detailed analysis of influences of some drill geometries, namely; saw, candle stick, core and step drills on delamination has been analytically reported (Hocheng and Tsao 2003), as shown in Figs. 2.10(a)-(d), respectively, and their results were compared with a standard conventional twist drill (Fig. 2.10e). Various critical thrust forces of all the drill types were predicted. This study on occurrence of delamination is necessary to establish drilling parameters and drill geometry governing delamination, predict and establish a suitable and an optimal relationship. From the analytical results obtained, the physical influences of various drill geometry were mathematically represented. Therefore, it was concluded that critical thrust forces of the various drill types can be reduced. When ratio between radius, c of saw drill and the extent of the elliptical delaminated region, a along the major or longer axis equals zero ($s = \frac{c}{a} = 0$), saw drill reduces to the twist drill (Fig. 2.10a). A very high critical thrust force is recorded whenever s approaches 1. Similarly, when ratio between peripheral circular force, P_2 and central concentrated force, P_1 equals zero ($\alpha = \frac{P_2}{P_1} = 0$), candle stick drill reduces to the twist drill (Fig. 2.10b), but candle stick drill reduces to the saw drill when α equals infinity ($\alpha = \frac{P_2}{P_1} = \infty$). In addition, when s equals zero ($s = \frac{c}{a} = 0$) and ratio between thickness, t and radius, c of core drill equals 1 ($\beta = \frac{t}{c} = 1$), core drill (Fig. 2.10c) reduces to the twist drill. Lastly, step drill (Fig. 2.10d) reduces to the twist drill (Fig. 2.10e) when $i = \xi = 0$ and $s = 0$, where $i = 1 - n$, n represents the number of consecutive increase of secondary cutting lips during drilling operation and ξ denotes the separated thickness of the push-out delaminated laminar traced to value of n. However, step drill behaves like core drill type when $\beta = \frac{t}{c} = 1$ and $i = \xi = 0$. These were similarly reported in another study carried out by the same researchers (Hocheng and Tsao 2006).

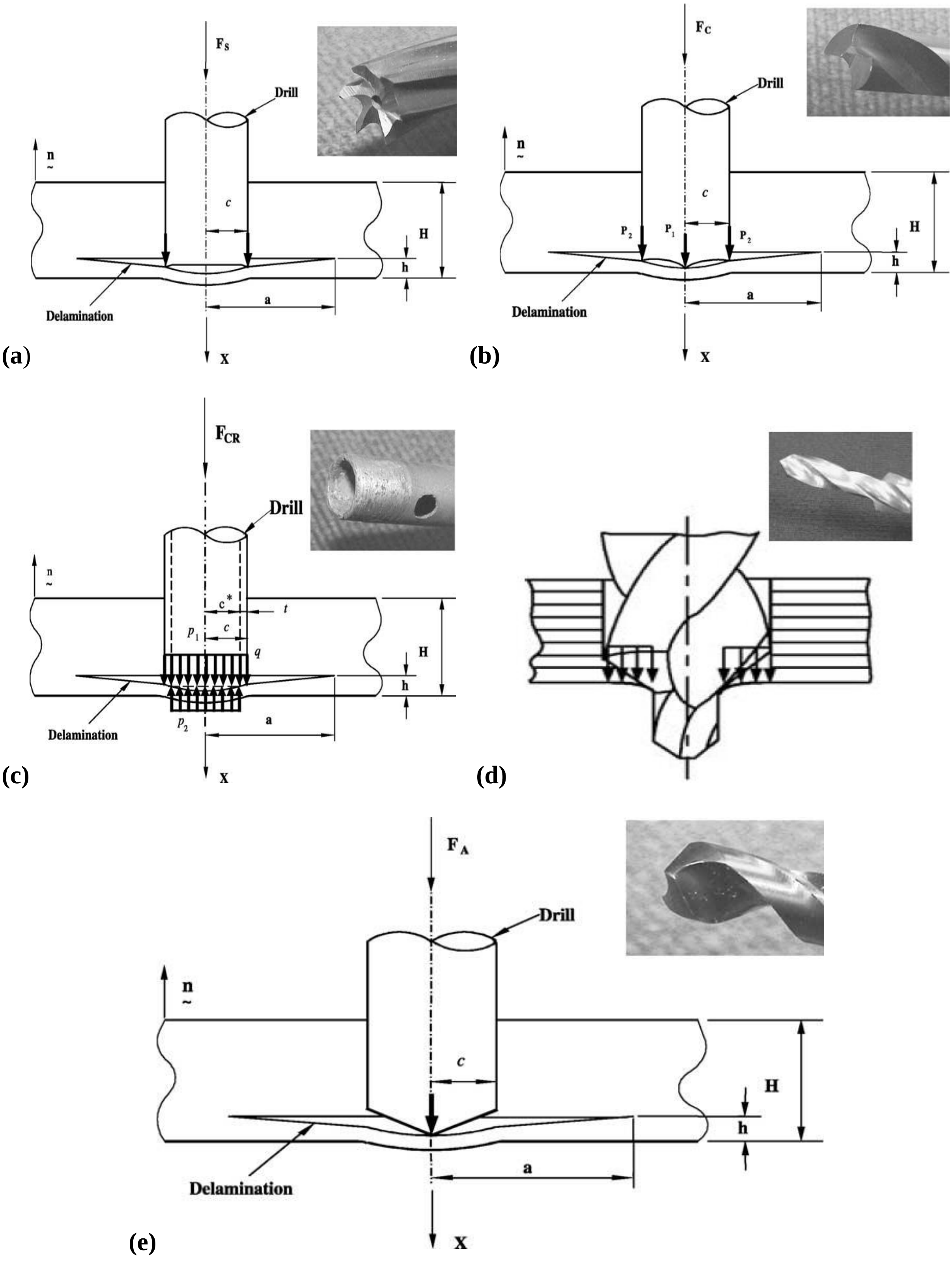


Fig. 2.10 Analysis of push-out delamination in (a) saw, (b) candle stick, (c) core, (d) step drills and (e) twist drill types (Hocheng and Tsao 2003)

Fernandes and Chris (2006) studied the effects of a 'one shot' drill on force and torque developed during drilling of carbon FRP composite material. Also, the influences of tool/drill wear and workpiece thickness on both thrust force and torque were investigated. The drilling process was categorised into various phases and related to associate DID responses. From the results obtained, it was evident that a five-step process with a subsequent step related to various drilling and reaming processes physically from a drilling operation with one-shot drill. An extension and prediction of the tool life as well as enhancement of productivity and quality of drilled holes are established with the empirical model. Similarly, Tsao and Hocheng (2003) investigated into the possibility of achieving a delamination-free drilling, using an analytical method to establish a relationship between chisel edge length and drill diameter. The formulation was based a linear elastic fracture mechanics (LEFM) of FRP composites. A set of holes was obtained, and their optimum set of preliminary hole diameters related to the chisel edge lengths were computed. It was established that drilling of FRP composite laminates with medium to large holes and void of delamination-induced damage are achievable, provided the ratio of the drill chisel edge length is effectively controlled.

2.6 The Influence of Tool Geometry

The influence of tool geometry determines the shape and angle of the projected part of the cutting tool. It affects the type of machining process, materials, efficiency and quality savings of finished parts and tool life.

The factory machining process attracts inclined cutting. Nevertheless, orthogonal cutting has been predominant in the simulation environment of numerical machining studies, because of its ease and usefulness to acquire data about challenging variable measurements. Soldani et al. (2011) supported this notion during experimental studies, stated that an interpretation of results is often proved to be difficult, due to the complexity that may arise from a cutting process as a result of anisotropic nature of the composite materials. Despite this limitation, it is important to further draw necessary information about the morphology of the chip, sub-surface damage, the effect of the orientation of the fibres and the role of the shape (geometry) of the tool/drill. Therefore, Nayak et al. (2005) studied additional development on orthogonal cutting of FRP composite materials and extensively worked on the effects of cutting-edge radius, fibre orientation, slope angle and depth of cut. Accurate validation of several numerical models in many scientific publications have been successful using the experimental results obtained from their work.

2.6.1 Effect of Drill Bit Geometry

The geometry of drill significantly determines the quality and integrity of the holes produced on FRP composite materials during drilling operation. Some researchers have undertaken some studies on the effects of drill geometry on DID responses when cutting FRP composites. For instance, Niketh and Samuel (2016) initiated the surface finishing of a drill flute and edge in a sustainable titanium alloy machining to decrease both friction and torque. Feito et al. (2018) illustrated through experimental investigation that drilling with a step drill produced a lower thrust force and de-bonding or separation in carbon FRP composite materials. Girot and Géhin (2002) found that the shape of a drill decreased the surface temperature of the drill bit used and the adhesion of aluminum during dry drilling of Al2024 alloys. This results may not be too far from the drilling of abrasive carbon FRP composite materials. A one-time shot drill that possessed a continuous saw tooth structure has been adopted to alter the drilling conditions of holes and reduce DID impact on the material used (Jia et al. 2016).

Moving forward, the point geometry of a twist drill has been successfully optimised by Paul et al. (2005). The aim of the study was to minimise drilling forces (thrust and torque) during drilling process. A set of drill grinding parameters obtained from a point geometry parameterisation of three different drills. The drill point geometries included conical, helical and racon. The essential properties of their profiles were maintained. Comparatively, these various kinds of drill profiles recorded the optimal results. Therefore, optimised conical point profiles were manufactured and used to perform experiments for the purpose of obtaining data for validation of the already developed analytical models for drill designed geometry. The simulation results established a conical point as an optimal drill design, as a noticeable decrease in both drilling forces was observed. A decrease of nearly 40% in each of the drilling forces. Additionally, a significant decrease in thrust force was recorded with racon drill, but with a minimal enhancement in torque. The optimised helical drill geometry exhibited a great enhancement above the threshold helical point geometry by decreasing each of the drilling forces above 40%.

Furthermore, modification of a drill point design with plane rake faces has been investigated (Wang and Zhang 2008). Fundamental chisel edge and the lip geometries were modified in an attempt to design a new twist drill. Later, the developed models were validated with two sets of experiments to determine the drilling forces (thrust and torque) as well as the drill-life. From the results obtained, it was evident that up to 46.9% and 13.2% of thrust force and torque can be reduced with an average of 23.8% and and maximum of 24.9%, respectively, when compared with the conventional or traditional twist drills, considering same drilling parameters. The modified drills were more superior to the traditional twist drills, as obtained from their drill-life tests. A better performance of the modified drills was observed, because the workpiece contained pieces of some broken conventional drills, under same drilling parameters and conditions.

Effects of two different geometrically designed drills and cutting parameters on power, delamination and specific cutting pressure have been studied (Davim and Reis 2003). Both helical flute-straight shank and brad-spur drills with diameter of 5 mm each were used experimentally and statistically to study drilling of carbon fibre reinforced plastics. The woven and $0^{o}/90^{o}$ oriented carbon FRP composite laminates were manufactured by autoclaves. The results from the experimental investigation showed that feed rate and cutting velocity had a greatest influence on the delamination of the material at entrance and exit, respectively for both drill types physically and statistically. The entrance/peel-up delamination was higher than the exit/push-out type for both drill types. However, helical flute-straight shank drill exhibited greater peel-up and push-out delamination-induced damage on the carbon FRP composite than the brad-spur drill. In addition, the helical flute-straight shank drill produced lower specific cutting pressure and power than the brad-spur drill, under the same feed rate and cutting speed, as considered cutting parameters. Both drills established that feed rate has a greater influence on the power than cutting speed, both experimentally and statistically. Grilo et al. (2013) conducted a related study, but with different drill tools: spur, four-flute and helicoidal drills, as shown in Fig. 2.11, respectively. From the results obtained, spur drill produced an optimal and delamination-free drilling, with a greater production rate as well as feed rate and spindle speed of 2025 mm/min and 6750 rpm, respectively.

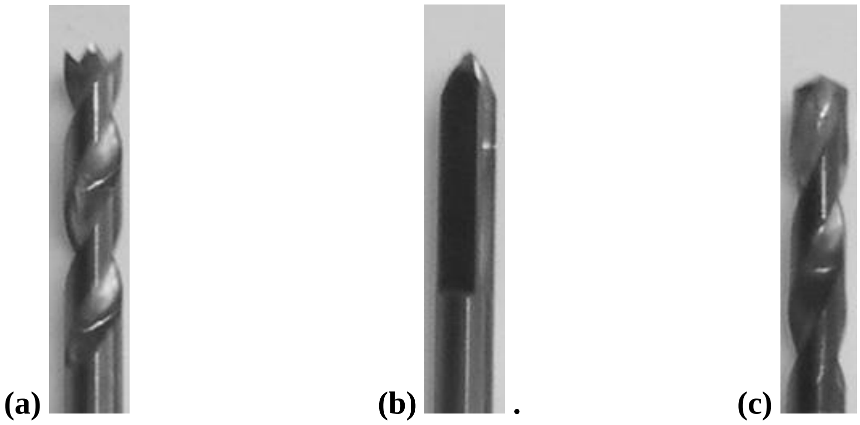


Fig. 2.11 Different types of drill geometries: (a) spur, (b) four-flute and (c) helicoidal (Grilo et al. 2013)

2.6.2 Further Effects of Drill Geometry on Carbon FRP Composite Drilling

An efficient drilling of carbon FRP composites stacked with aluminium has been investigated and reported by Garrick (2007), using polycrystalline diamond (PCD) drill. Though, after 200 holes, a wear land was observed on the cutting edge of the drill, leaving it with an option or resharpening. Also, the operating range of tungsten carbide was observed bigger than the PCD drill. This could be solved with an improved cutting edge by modifying it with k-land. This report did not assess delamination in the carbon reinforced composite and other DID responses. Hence, this report was not a holistic assessment of the new 86 series vein drill. This assessment is necessary to design and optimise the new drill for a better performance. However, Park et al. (2011) took over this challenge and assessed the drilling process of carbon FRP/titanium composite, using PCD drill. Both confocal and scanning electrons microscopes (SEM) were used to monitor the wear mechanism and progression on the drill surface. The performance of the drill was decreased, due to the formation of a micro-chipping or fracture on the drill cutting edges, close to its margin. In addition, the brittle nature of the PCD drill attracted a major chipping on its cutting edges during drilling of titanium. In comparison, PCD recorded a better performance than the tungsten drill type.

Gaitonde et al. (2008) suggested combination of low feed rate values and point angle to reduce DID response on carbon fibre reinforced plastic composites. Importantly, there is need to study the delamination process together with the drilling process in order to come up with a more detailed relationship that will help to understand the delamination mechanism in relationship to the drilling parameters and process. Moreover, the drill wear process is an important variable that could be used to improve the performance of the drill. In addition, the use of other drills apart from the twist drill is recommended.

Tsao (2008) used three different step-core drills: step-core-twist, step-core-saw and step-core-candlestick types (Fig. 2.12) to report the influence of drilling parameters (diameter ratio, feed rate and spindle speed) on drilling-induced delamination of composite materials. The result showed that the three drilling parameters have a significant effect on drilling-induced delamination. The optimal result of combination of drilling parameters was observed with all the step-core drill types, using a higher diameter ratio, lowest feed rate and highest spindle speed of 0.74 mm/mm, 8 mm/min and 1200 rpm, respectively, as depicted in Figs. 2.13 and 2.14. These results were similar to that of Ismail et al. (2016).

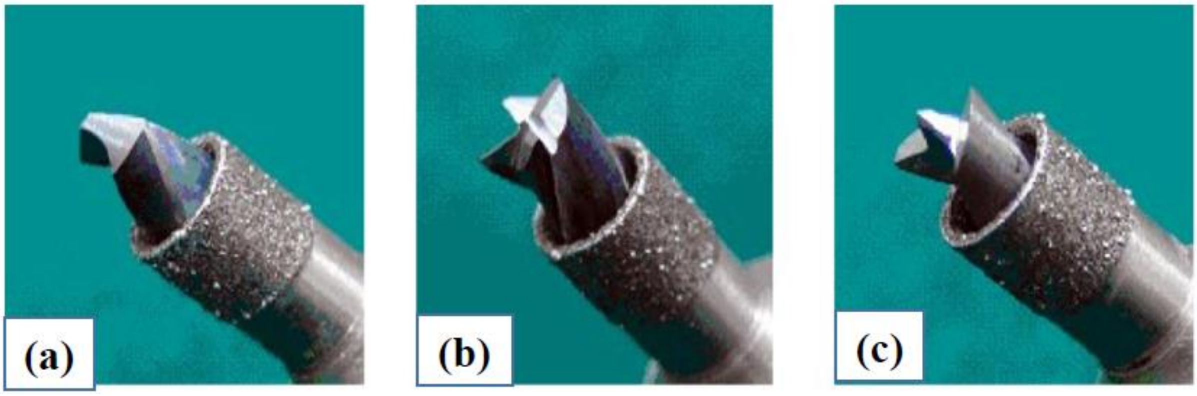


Fig. 2.12 Step-core drills, showing (a) twist, (b) saw and (c) candlestick types (Tsao 2008)

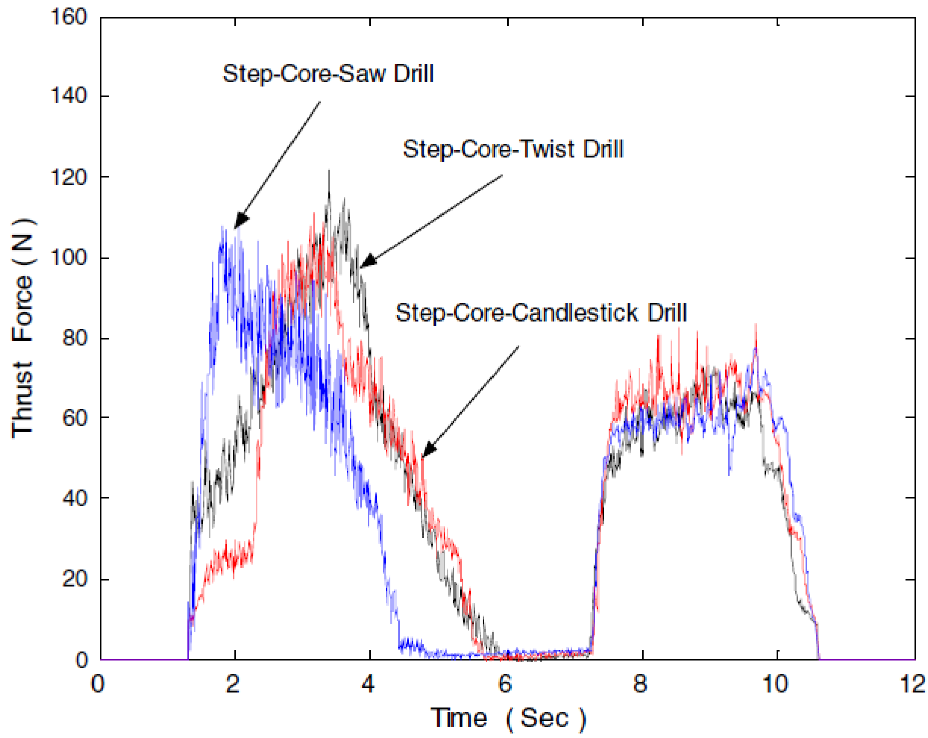


Fig. 2.13 Drilling evolution with different step-core drill types, showing thrust force-time relationship at diameter ratio, feed rate and spindle speed of 0.74 mm/mm, 16 mm/min and 800 rpm, respectively (Tsao 2008)

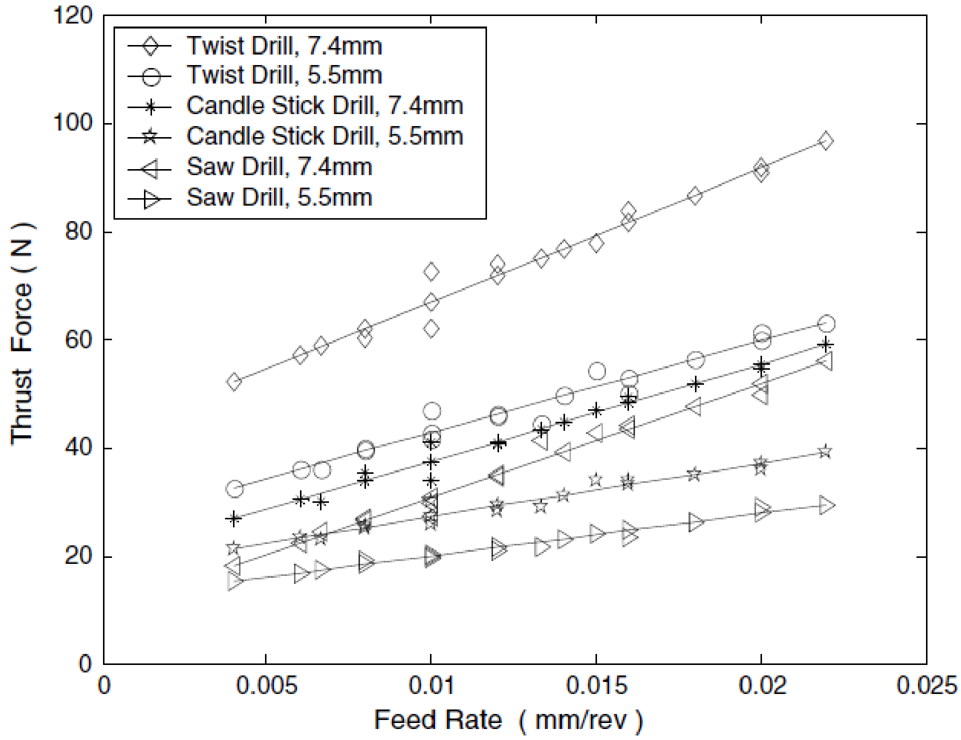


Fig. 2.14 Effects of the drill diameters and feed rates on thrust forces developed by different step-core drill types (Tsao 2008)

These optimal results can be attributed to the following reasons: a lowest feed rate developed a lowest thrust force, which consequently produced a lowest value of delamination response. While, combination of a higher diameter ratio and highest spindle speed probably produced a highest cutting speed that was required for an optimum drilling phenomenon.

2.7 Numerical Simulation and Analytical Analysis

In addition to the aforementioned and discussed simulation and analytical results of DGD, Miao et al. (2009) studied the influences of drill design geometry on the deposition (interface) in a set of solid diamond-coated carbide twist drills, as shown in Fig. 2.15. They were modelled as a two-fluted drill, using a commercially available computer-aided design (CAD) software. The normal and residual stresses developed as a result of the mismatched thermal expansion coefficients during deposition process was simulated with aid of a finite element analysis

(FEA), as illustrated in Fig. 2.16. The model generated was used to design different drill geometries and determine the deposition stresses.

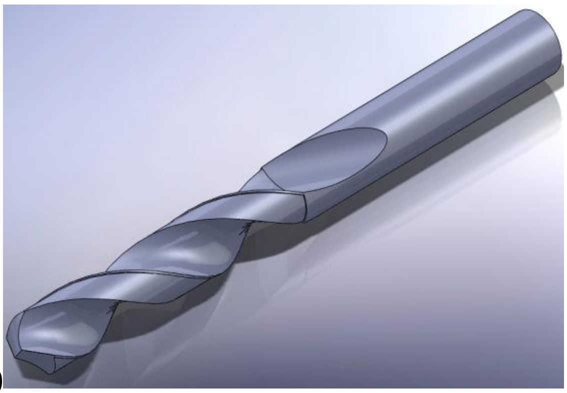
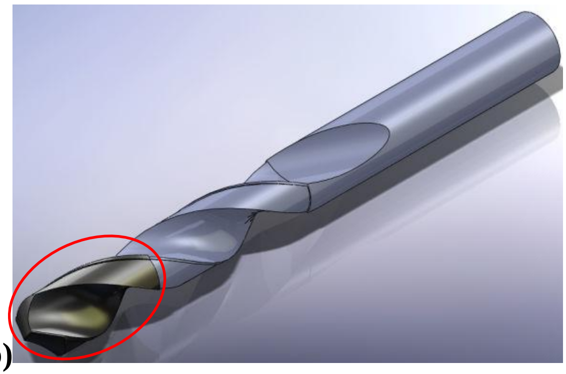
(a)  (b) 

Fig. 2.15 Typical twist drill, showing (a) a solid CAD model and (b) diamond coated head (Miao et al. 2009)

In addition, it was concluded that the model was capable of design various drills with various geometric parameters. Also, the edge radius recorded the highest significant effects on the interface stresses, among the micro-level drill geometry. Other macro-level drill geometries, include point angle, helix and web thickness have tendency of influencing the web angle located at the drill cutting tip from 10^{o} to 20^{o} variances. But, with minor influence on the interface residual magnitudes. This research considered the twist drill with diamond-coated carbide and did not take into consideration the wear process of the tool as well as drilling process of material workpiece, especially carbon FRP composite materials. Although, the influences of coating thickness on interface residual stresses as well as induced mechanical and thermal loads on the deposition residual stress during drilling operation were proposed and recommended for future works.

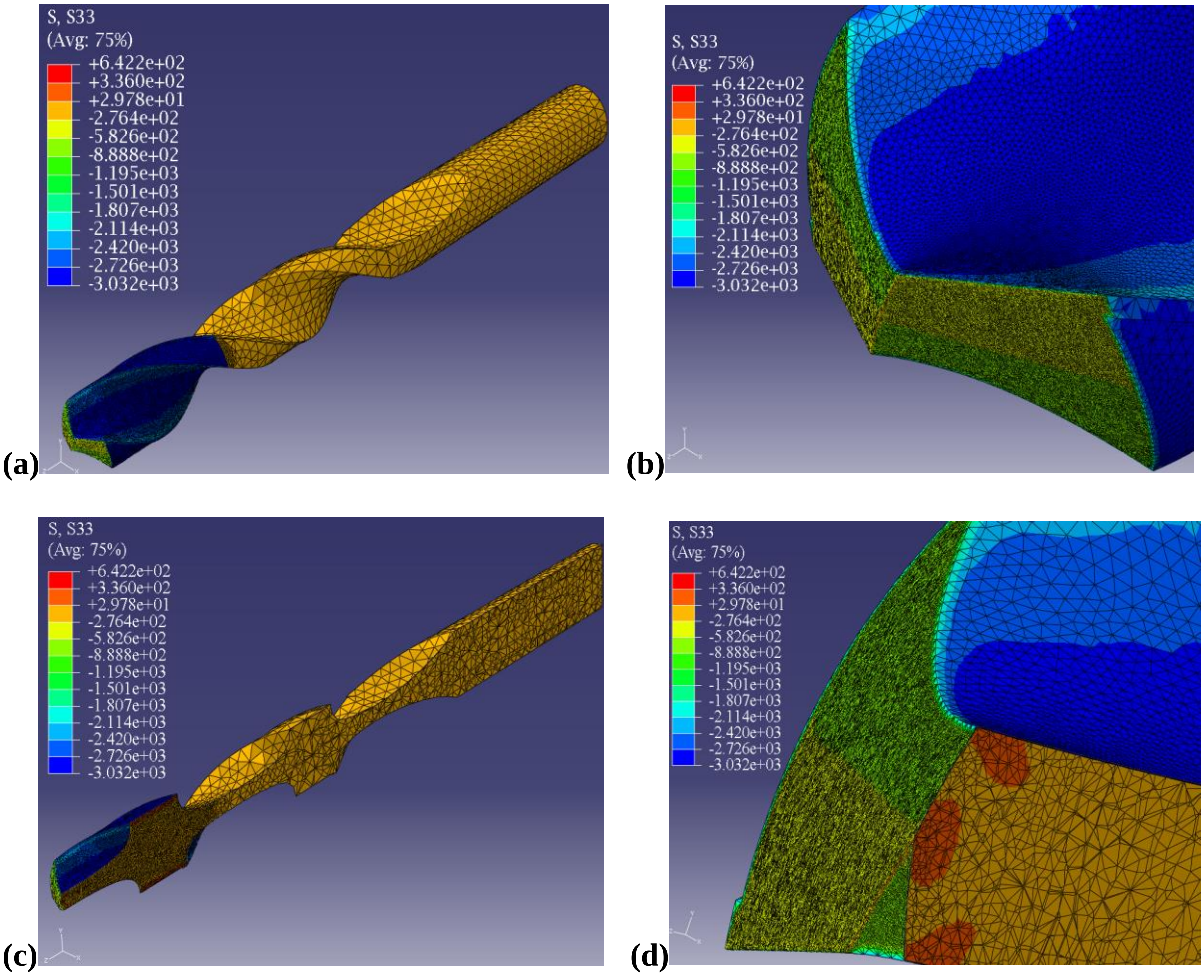
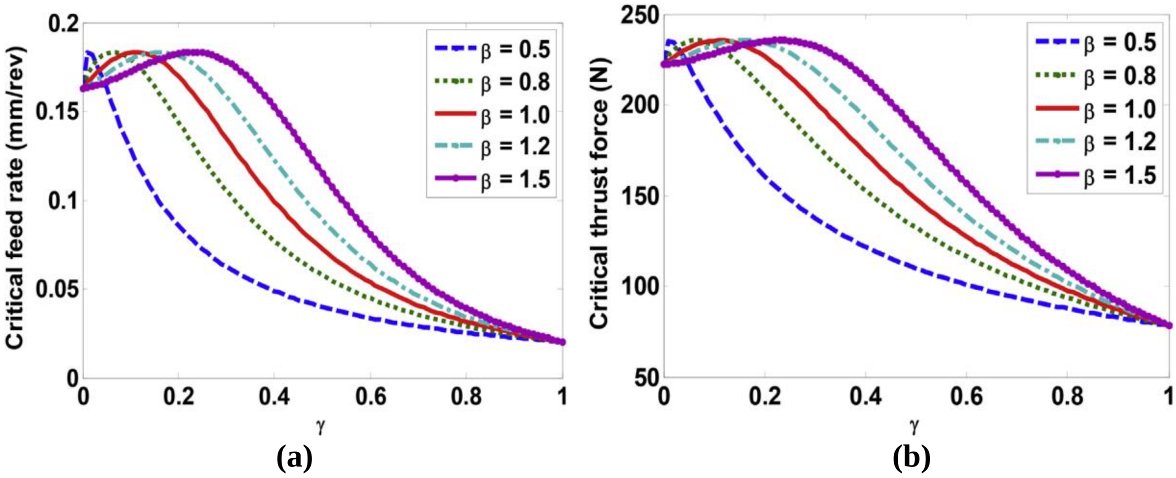


Fig. 2.16 Longitudinal normal stress distribution in a diamond-coated carbide twist drill, showing (a) a complete simulation, (b) a near drill tip, (c) and (d) their sectional views, respectively (Miao et al. 2009)

Moving forward, Ismail et al. (2017b) analytically analysed the influenced of drill chisel edge and point angle ratios on the lowest critical thrust force. It was reported that carbon FRP composite laminates can be drilled without delamination damage through a combination of correct selection and effective monitoring of the drill geometrical parameters; with higher feed rate and thrust force as well as reduced chisel edge and point angle. These are illustrated in Figs. 2.17(a) and (b), where γ denotes chisel edge ratio and β represents ratio between arbitrary and reference point angles.



Figs. 2.17 Influence of chisel edge load on (a) critical feed rate and (b) lowest critical thrust force for various point angles (Ismail et al. 2017b)

The above extensive reviews showed that considerable research have been conducted to comprehend the relationship among DGD, delamination damage and the drilling process. However, little or no work has been done to understand and establish models of relationship among drilling mechanisms (drilling variables), drilling-induced delamination, DGD and the wear process. Moreover, although it has been reported that micro-chipping or micro-fracture occurred on the PCD drill cutting edges close to its margin, which reduced the performance of the PCD drill (Park et al. 2011). Currently, there is no reported study to attempt designing a new PCD drill tool (geometry) that will overcome this problem. Therefore, a deeper knowledge towards further optimisation of the drilling process, resistance to wear and delamination mechanism of FRP composites, using PCD drill is highly required, hence proposed or recommended.

2.8 Recommended Design for Effective Damage Reduction

To reduce the impact of drill-induced damage at exit point of a drill, it is necessary to reverse the cutting direction towards the drilling point. There must be a correct selection of values of drill geometries, such as diameter, angles (point, helix and relief), flutes (two, three or four), shanks (straight, square and taper) and length (web thickness, lip, cutting edge and flute) for a particular drilling of FRP composite. Also, good drill tip geometry and selection of appropriate drilling parameters, especially feed rates are important in reducing delamination. A decrease in feed rate leads to a reduction in thrust force and consequently, both entry/peel-up and exit/push-out drilling-induced delamination are reduced or eliminated.

Additionally, the intermittent saw-tooth structure has proven effective in changing the cutting conditions at the tip of the drill and provides a solution for drilling that avoids damage. The material selection for tooling should be carefully considered. Tool materials have a significant impact on drill-induced delamination and other DID, which have a significant impact on drilling life and structural strength of FRP composite materials.

2.9 Conclusions and Future Perspectives

2.9.1 Conclusions

Machining, especially drilling of FRP composite materials remains an inevitable process in a manufacturing industry, where coupling, assembly or mounting of components is necessary. Hence, this chapter has extensively and comprehensively elucidated the effects of various drill geometries or designs on drilling-induced damage, mainly delamination reduction in different FRP composite laminates.

It was evident that drill geometries significantly determined quality of drilled holes in terms of drilling-induce delamination, among other factors such as drilling parameters (feed rate, cutting speed, depth of cut and rate of material removal), tooling materials (HSS, PCD, carbide –coated and uncoated types) and conditions. It was established that delamination increased with drill diameter, because an increased in drill diameter led to an increase in both thrust force and torque developed when drilling carbon FRP composite laminates.

Furthermore, the drill point angle increased with thrust force, because a decrease in twist drill point angle led to a significant increase in the drill relief angle and consequently, it reduced thrust force and its associated delamination damage. Conversely, a higher helix angle produced a lower drilling forces (thrust and torque). While, a larger drill chisel edge rake angle exhibited a lower drilling forces. A correct choice of a smaller chisel edge web thickness and web-thinning are both required to decrease the thrust force and achieve an optimal or delamination-free drilling process.

Therefore, the aforementioned results are very relevant to select a correct drill geometry for an efficient and optimal drilling of FRP composite material. These results are highly relevant to all drill designers, developers/manufacturers and researchers, as quest to optimise the drilling of FRP composite materials continues.

2.9.2 Future Perspectives

Drilling of FRP composite remains an indispensable machining process, provided holes are required for assembly of components of a system. Also, design and development of an innovative FRP composite materials for several applications in various manufacturing industries have increased the need for continuous improvement in the quality of drills. The efficiency of a drill significantly depends on its geometry design. Therefore, design and manufacturing of more novel or special drilling tools to effectively drill both newly and future developed FRP composite, especially natural/hybrid types remain a continuous and increasing exercises.

Furthermore, the use of computer numerical controlled (CNC) drilling centres has reduced some challenges associated with drilling of abrasive, anisotropic and heterogeneous FRP composite materials. For instance, several and different geometries of drills can be loaded into

CNC drilling machine to perform various drilling processes within a single operation. Also, Special drills with through-holes at their centres have been designed, developed and utilised through the help of CNC drilling machines. The centre holes accommodate coolants, such as compressed/cold air for an effective cooling during drilling operation. There is a tendency of significant improvement on these technologies in the nearest future, especially with the current advent of smart manufacturing and robots in manufacturing technology (robotic arm drilling).

However, moving from subtractive, traditional or conventional manufacturing to additive manufacturing by some engineering industries may reduce the application of drills in the next decade, as drills are fast replacing with print nozzles in additive layer manufacturing technology.

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