A review on strengthening, delamination formation and suppression techniques during drilling of CFRP composites

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Abstract: Carbon fiber-reinforced composite laminates are progressively appealing for several applications in various manufacturing sectors such as aeronautical and automobile, because of their amazingly predominant mechanical properties. This has subsequently led to an increase in research of various machinability techniques emphasizing on both conventional and non-conventional methods. Typically, conventional drilling is one of the most significant machining processes for most kinds of fiber composite laminates. The most unsolicited damage termed as delamination during drilling has recently become one of the most influential research subjects as numerous engineers in manufacturing sector have been trying to prevent this problem over decades. This review paper briefly discusses about the incorporation of different types of fillers in carbon fiber-reinforced composites. The paper also summarizes the steady progress in drilling-induced delamination of carbon fiber laminates. It covers the delamination formation mechanism, delamination suppression strategies, and the optimization of various drilling parameters to reduce the delamination damage. The present article provides researchers an opportunity to deepen their knowledge on specific aspects by exploring different methods for reducing delamination in CFRP composites.

Subjects: Aerospace Engineering; Mechanical Engineering; Composites; Surface Engineering-Materials Science

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PUBLIC INTEREST STATEMENT
Composite materials are gaining importance in today's industrial manufacturing sector as they possess superior mechanical properties compared to metals. In the vast area of composites, carbon fibre-reinforced polymer (CFRP) are used extremely for fabrication of different parts in automobile, aerospace, and marine sector. Drilling of these CFRP composites is always a challenging task as it leads to machining defects such as delamination, producing permanent damage. Hence, this article will provide the researchers with a better understanding of improving the strength of composites by adding different types of fillers. Also, readers will expand their knowledge on delamination mechanisms and different techniques to prevent these drilling defects.
Keywords: Carbon fiber reinforced polymer; inorganic fillers; natural fillers; drilling; delamination suppression

1. Introduction

Composite materials are a mixture of two or more distinct materials constituting matrix and reinforcement. In comparison with many metals and non-metals, mechanical properties such as combination of strength, stiffness, toughness, and corrosion resistance are significantly found in composites (Chandramohan, 2020; Singh et al., 2013; Tsao & Chiu, 2011). Fiber-reinforced polymer composites involving fiber phase provide strength to the composite, whereas the reinforcement phase absorbs energy resulting in increase in toughness. Due to the robust properties of these composite materials, their demand for the use has been increased in the recent decades (Geng et al., 2019; Rybicka et al., 2016; Shahabaz et al., 2020; Shetty et al., 2017). Aircraft named Boeing Dreamliner 787 consumes minimum fuel compared to any other heavy aircraft, as its primary structure consists of 57% of composite materials parts (Geier, 2020; Singh et al., 2013). Similarly, the new age engines of General Electric aviation industry, consisting of fan cases and blades in the cooler section of the compressor, are fabricated from composites. Also in case of automobile sector, several parts manufactured using metals are switched to carbon fiber composites (I Shyha et al., 2010).

Different types of micro- and nanofillers are used to enhance specific properties of the composites (Samal, 2020; Shettar, Kini et al., 2020; Shettar, Kowshik et al., 2020). Incorporating nanoparticles into epoxy resin enhances thermal and mechanical properties in addition with providing excellent strength and dimensional stability (Behniafar & Nazemi, 2017; Demirci et al., 2017; Taşyürek & Tarakçıoğlu, 2017). Researchers reported that the enhancement of mechanical properties by blending alumina (Al₂O₃) nanoparticles into different types of polymers, including polystyrene, polyether ketone, epoxy resin, and polyamide (Y Wang et al., 2006; H Zhang et al., 2006; H Zheng et al., 2006). In the study of Shi et al. (Shi et al., 2004) impact strength was found to be slightly increased along with the flexural modulus and flexural strength with the addition of Al₂O₃ fillers into neat epoxy resin. Similar study by Zhai et al. (Li et al., 2008) stated the drastic increase in adhesion strength by adding 2 wt.% of nano-Al₂O₃ into epoxy. Increase of 84% in impact strength, 29% in flexural modulus and upto 18% increase of flexural strength was reported by Zheng et al. (Y-P Zheng et al., 2009) with addition of nano-Al₂O₃ fillers. Wang et al. (Z Wang et al., 2016) carried out a study to investigate the integration of microalumina (Al₂O₃) fillers and their effects on the mechanical properties of carbon fiber-reinforced polymer (CFRP) composites. They
focused on investigating mode 2 type of interlaminar fracture toughness, flexural properties, impact strength, and initial modulus. They noticed that addition of microalumina fillers to the CFRP improved the above properties significantly, due to the resistance offered by micro-Al₂O₃ particles on crack growth.

Krishnamoorthy et al. (Krishnamoorthy et al., 2019) performed a study on drilling of unidirectional CFRP, using an eight-facet drill with a polycrystalline diamond tip as shown in Figure 1. The results showcased an increase in the thrust force as the feed rate increased. Also, it was found that delamination decreased, and the surface quality increased with a mixture of higher cutting speed and lower feed rate, as a result reduction in thrust force was observed. Using response surface methodology (RSM) and analysis of variance (ANOVA) technique, the effect of feed rate and cutting speed on drilling of unidirectional CFRP (UD-CFRP) was investigated by Geier et al. (Geier, Szalay et al., 2019). The results proved that cutting speed has more effect on UD-CFRP when non-conventional drilling angles are used as compared to using conventional drilling angles. Also, the specific feed force in the non-conventional drilling direction was observed three times higher than the value of the specific feed force in conventional drilling directions.

Drilling of holes in CFRP composites is a necessary machining operation to assemble different parts in many structures (Geier, Póka et al., 2019; Geier & Szalay, 2017). However, during drilling of composites, delamination and fiber pull out lead to rejection of parts at the quality inspection, also increasing the manufacturing cost (Aveen et al., 2021; DF Liu et al., 2012). These above drawbacks also affect the long-term performance of the composite. Delamination depends on various cutting conditions of drilling and hence studying these conditions and optimizing them results in minimizing the delamination in composites. This paper systematically reviews the strengthening of CFRP composites with inorganic and natural fillers. Later, the effects of drilling and drilling induced-delamination are briefly discussed and to prevent the defects during drilling, a section termed as delamination suppression techniques, where the recent technologies adapted in the current years for overcoming the defects are explained in a systematic manner.

2. Composites with fillers

Fillers are classified into two types: they are conductive and extender fillers (Y Liu et al., 2013). Electrical and thermal conductivity properties are improved in composites by adding conductive fillers, whereas usage of extender filler is done to reduce material costs. Some of the fillers used in composites are alumina (Al₂O₃) (Sarkar et al., 2018), silica (SiO₂) (Jo & Lee, 2017), graphite (Gr) (Garcia et al., 2018), calcium carbonate (CaCO₃) (Şahin et al., 2018), and natural fillers are of various types (Prasad et al., 2018). Synthetic fibers have certain advantages that cannot be reciprocated by natural fibers. Some of the drawbacks of natural fibers are high moisture absorption, low thermal stability, and irregular surface quality. These drawbacks of natural fibers can be improved by the addition of the above inorganic fillers.

The usage of natural fillers has also increased in past decade, even though they do not provide the same performance as synthetic composites (Shekar & Ramachandra, 2018). The following reason being the hazardous nature of some of the inorganic fillers effecting the environment. Therefore, the researchers are investigating to improve the performance of composites using natural fillers (Dittenber & GangaRao, 2012).

2.1. Inorganic fillers

Inorganic fillers, as mentioned in the above section, improve the properties of composites by altering specific characteristics depending on the application requirements. Various research has been carried out to determine the scope of improvement in the composite instigated by the incorporation of the fillers (Thakur & Singh, 2021). Hussain et al. (Hussain et al., 1996) examined the mechanical properties of CFRP composites with the addition of nano, microsized Al₂O₃ fillers. The results indicated that the integration of the Al₂O₃ filler into the matrix improved the toughness property of the composites. The interfacial bonding at the fiber-matrix interfaces was the reason for improvement.
Table 1. Effects of various inorganic fillers on composite materials

| Material | Filler   | Filler wt. % | Remarks                                                                 | Refs                  |
|----------|----------|--------------|------------------------------------------------------------------------|-----------------------|
| CFRP     | Al₂O₃    | 10           | The addition of the filler improves the mechanical properties of the composite, such as flexural strength and interlaminar shear strength. | Hussain et al. (Y-P Zheng et al., 2009) |
| FRP      | CaCO₃, Silica | 5    | Silica led to an improvement in flexural, compressive modulus, and strength, and tensile strength improved. | Bagherzadeh et al. (Krishnamoorthy et al., 2019) |
| CFRP GFRP| Al₂O₃    | 1,2,3,4,5    | Tensile strength and tensile modulus increased more in CFRP than GFRP | Akash et al. (Geier & Szalay, 2017) |

Singh et al. (Singh & Singh, 2019) investigated the effect of different sizes of fillers on mechanical properties, incorporated in natural fiber hybrid composites. Bagherzadeh et al. (Bagherzadeh et al., 2020) studied the mixing of different sizes of silica microparticles affecting the properties of epoxy resins. The adhesion and mechanical properties of the mixture of epoxy and silica microparticles to steel and concrete bars were used to test the mechanical performance of the mixture. The results indicated that the increase in compressive modulus for epoxy with fillers compared to without. The authors also stated that lessening the molecule size of fillers lead to an increase in compressive modulus. As the surface area increases, higher interaction of the particles was seen with the epoxy.

In the review article by Ganesh et al. (Chavhan & Wankhade, 2020), different types of hybrid composites were comprehensively reviewed based on the numerous industrial applications. The authors stated the elastic modulus and tensile strength of the hybrid composites increases by addition of fillers.

Mohanty et al. (Mohanty et al., 2014) carried out the mechanical characterization of Al₂O₃ nano-fillers on CFRP composites and GFRP composites. Four kinds of samples were fabricated by mixing Al₂O₃ in 1-5% of volume. The density of the composite increased as the percentage by volume of fillers was increased as represented in Table 1. Reduction in failure strain was observed, the most significant in case of Al₂O₃ fillers added to CFRP composites. Also, longitudinal modulus and tensile strength showed much improvement due to the filler addition.

CFRP- Carbon Fiber-Reinforced Polymer, FRP-Fiber-Reinforced Polymer, GFRP- Glass Fiber-Reinforced Polymer, Al₂O₃ - Aluminium Oxide, CaCO₃ - Calcium Carbonate

2.2. Natural fillers

Natural fillers used in composites are advantageous as they least effect the environment, also they require less energy for manufacturing and in comparison with synthetic type they are economical (Mendes & Cestari, 2011). Suthan et al. (Suthan et al., 2020) studied the wear, and morphological analysis of treated and un-treated bio-filler reinforced polymer composites. Four types of bio-fillers, such as rice husks, groundnut shell powder, coconut shell powder, and hybrid fillers, were used. Hand lay-up method for fabrication and pin-on-disc setup was adapted to perform the wear tests. Wear resistance was found to be enhanced with the treatment of hybrid bio-filler composites as compared to neat.
To study the water uptake characteristics and mechanical properties in composites by using wood flour, wastepaper, and purified cellulose, the authors conducted water absorption and tensile test. They specified with the increasing filler content water absorption was maximum. However, there was no significant improvement observed in tensile strength with the fillers added to epoxy (Tajvidi & Ebrahimi, 2003).

Naheed Saba et al. (Saba et al., 2014) reviewed several research articles to provide information on natural fibers, nanofillers, natural fiber composites, and nanocomposites with their applications. They also studied papers informing on new technological developments in usage of natural fibers and nanocomposites. Outcome described by authors indicated, use of nano-sized fillers improved the mechanical properties of composites. Similarly, in the study of Yang et al. (H-S Yang et al., 2005), thermal stability of composites filled with rice husk flour and wood flour was experimented by varying filler content of 10, 20, 30, and 40% as shown in Table 2. The thermogravimetric curves of each filler and composite mixture showed mass loss due to the evaporation and loss in moisture content. Also, it was noted that as the filler content increased, thermal expansion of the composite also increased.

3. Drilling of composites
Drilling of composites has been very challenging machining operation and from past two decades the research has been continuously thriving in order to obtain a uniform hole quality in composites. Various non-traditional methods of machining are carried out on composites such as abrasive water jet machining (Hejjaji et al., 2017; Kumaran, Ko, Uthayakumar et al., 2017; Tripathi et al., 2020), laser machining (Akman et al., 2019; Gautam & Singh, 2018; Jaeschke et al., 2018; Park et al., 2019), and electrical discharge machining (Islam et al., 2017; Lau et al., 1990; Mazarbhuinya et al., 2020). Drilling and other machining techniques determine the significant role of composites in applications such as automobile, aerospace, and other industries (Cavalier et al., 2006; Godara & Nagar, 2020; Pervaiz et al., 2016; Prolongo et al., 2009; Rezaei et al., 2008). Different types of damage occur in composites during drilling, these damages are at a high risk in case of aerospace industry, as a small crack initiation will lead to a catastrophic failure (Kumar & Jayakumar, 2018).

Many studies are carried out to find the effect of drilling parameters on composites as it leads to fiber pull out, delamination, matrix cracking, poor hole quality, burr formation, and other failure damages (Aurich & Dornfeld, 2009; Frankl et al., 2019; GAF & Al-Jarrah, 2018; Heisel & Pfeifroth, 2012; Pereszlai et al., 2021; Ş & Turgut, 2020). There are several methods to avert above damages, such as the inclusion of fillers, optimizing the machining parameters, using different types of drills and so on (Othman et al., 2018).

| Material | Filler | Filler Wt. % | Remarks | Refs. |
|----------|--------|--------------|---------|-------|
| FRP      | Rice-husks, groundnut shell powder, coconut shell powder and hybrid fillers | 10, 20 & 30 | Filler and matrix interaction improved, and wear properties also improve. | Suthan et al. (DF Liu et al., 2012) |
| PPC      | Cellulose fibers, wastepaper, and wood flour | 15, 25 & 35 | Wastepaper showed the highest water absorption, followed by wood flour and, lastly, cellulose fibers. | Mehdi Tajvidi et al. (Aveen et al., 2021) |
| PPC      | Rice-husk and wood flour | 10, 20, 30 & 40 | Thermal stability improved, and thermal expansion reduced. | Yang et al. (H-S Yang et al., 2005) |
During the manufacturing of an aircraft using composites, many complex parts are assembled by fasteners that are inserted into drilled holes. These drilling operations are carried out at a repetition rate, as the nature of these composites are inhomogeneous and anisotropic. Due to this sole reason the drilling operation induces surface damages into these structural members. Drilling-induced delamination is one of the most challenging failure mode resulting in heavy losses in the aerospace industry (Al-wandi et al., 2017; Fleischer et al., 2018; Wang, Melly, Li et al., 2018). Rejection of parts are as high as 60% due to the drilling-induced delamination caused in the composite laminates during the final assembly (Stone & Krishnamurthy, 1996; Wong, 1981). Therefore, there is a requirement of improving hole quality by not compromising the strength characteristics of composites (Eneyew & Ramulu, 2014; Ramulu, 1997).

To investigate the exit damage such as spalling and fuzzing, while drilling of uni-directional (UD) CFRP and multi-directional CFRP by HSS twist drill. Zhang et al. (HJ Zhang et al., 2001) reported maximum damage observed for increasing feed rate and decreasing spindle speed. Also, for the same drilling parameters, spalling was more and higher for UD-CFRP laminates as compared to multi-directional CFRP. Similarly, in the study of Eneyew and Ramulu (Eneyew & Ramulu, 2014), influence of fiber orientation, drilling parameters, and cutting directions on drilling of UD-CFRP composite revealed that the lowest value of thrust force was determined at a rotational angle of 135° and 315°. At the cutting direction and fiber orientation interface angle of 135° to 175° and 315° to 355°, maximum fiber pull outs were detected. Surface quality of bore holes was inspected on sandwiched composite material of aluminum/CFRP/titanium by orbital drilling method and conventional drilling process. Orbital drilling exhibited improved borehole surface at higher cutting speeds and under lower cutting temperature, as compared to conventional drilling (Brinksmeier et al., 2011).

Abrasive water jet drilling, vibration assisted drilling and laser drilling are some of the non-traditional machining methods employed to reduce delamination in drilling of CFRP composites. The experimental setup of abrasive water jet drilling, vibration-assisted drilling, and laser drilling are shown in Figure 2.

Laser beam drilling provides tool wear free and excellent flexibility in drilling of composites (El-Hofy & El-Hofy, 2019; Tamrin et al., 2019). In laser drilling, the material removal is performed by high-intensity stationary laser beam focused on surface to be drilled. Material removal takes place due to phase change leading to higher magnitude of heat-affected zone (HAZ). Thermal and mechanical properties of composites are mainly affected due to HAZ (Herzog et al., 2008). To cut CFRP plates, continuous CO₂ laser was used and the minimum HAZ value obtained was 540 nm (Riveiro et al., 2012). Similarly, IR and UV laser were used in cutting CFRP of 2 mm thickness by Takahashi et al. (Takahashi et al., 2016). They found that UV laser was more effective in cutting compared to IR laser.
Shanmugan et al. (Shanmugam et al., 2008) observed that delamination can be minimized by reducing jet diameter or by decreasing water pressure during drilling of composites. Phapale et al. (Phapale et al., 2016) studied different delamination control techniques by using back-up plates and pre-drilling of holes during drilling of CFRP by abrasive water jet drilling technique. The authors stated that delamination was significantly reduced by using back-up plates followed by pre-drilling of holes. Better surface finish of holes was observed by lowering the abrasive flow rate, water pressure, and minimizing the stand-off distance.

Based on frequency type, vibration-assisted drilling is categorized into two types, low-frequency vibration-assisted drilling and ultrasonic vibration-assisted drilling. Frequency range of less than 1000 Hz is termed as low-frequency vibration-assisted drilling and frequency with more than 20 kHz is ultrasonic vibration-assisted drilling (Brehl & Dow, 2008). Low-frequency vibration-assisted drilling provides better results in reducing delamination with improved tool life and surface integrity of hole (Linbo et al., 2003). Thrust force was found to be reduced by adopting low-frequency vibration-assisted drilling in drilling of CFRP with constant and hybrid variation parameters (Wang et al., 2004). During vibration-assisted drilling of composites, the thrust, as well as torque, can be decreased by 20 to 30%, respectively, when compared to conventional drilling (J Xu & Ei Mansori, 2016).

3.1. Drilling parameters

In drilling of FRP composites, spindle speed and feed rate show a significant influence on thrust force, torque, and delamination. In case of CFRP/epoxy drilling, the above factors are highly effected by feed rate and drill geometry (El-Sonbaty et al., 2004; Ramirez et al., 2014). Panchagnula and Palaniyandi (Panchagnula & Palaniyandi, 2018) in their review state that, with increasing cutting speed, feed rate, drill size, and fiber volume fractions, cutting forces decreases. Therefore, right selection of drilling parameters is utmost necessary for reducing delamination.

With the increasing cutting speed, delamination factor was increased in the study reported by Feito et al. (Feito et al., 2018) and Sorrentino et al. (Sorrentino et al., 2018) during drilling of CFRP and GFRP laminates. Similarly, Krishnaraj et al. (Krishnaraj et al., 2012) claimed that delamination is initiated at lower forces as the stiffness of matrix reduces because of heating occurring at the tool and composite interface at high speed drilling. They also reported that by analysis of variance (ANOVA), the major factor responsible for drilling induced delamination was feed rate as the contribution of feed rate was maximum (51.4%) as compared to the spindle speed (35.42%). Feed rate lower than 1500 mm/min...
and spindle speed higher than 600 rpm have provided the best results during drilling of CFRP/epoxy composites (Phadnis et al., 2013). Davim et al. (Davim & Reis, 2003) investigated on selection of different cutting parameters for drilling on CFRP composites using high-speed steel drill bits and cemented carbide drill bits. Two techniques adopted during their study were ANOVA and Taguchi's technique. They established a relationship between feed rate and the cutting velocity with delamination in composites. Bora et al. (Bora et al., 2010) studied different orientation of fiber on scratch resistance of unidirectional CFRP composites. Testing was performed using CSM microscratch tester machine. The relation between scratch direction and orientation of the fiber was inspected as a function of scratch hardness, coefficient of friction, and penetration depth. Optimizing the drilling parameters will highly contribute in suppressing the drilling defects, thrust force, surface roughness by also increasing tool life.

3.2. Types of delamination
The anisotropic and heterogenous behavior of CFRP produces defects during drilling like delamination, matrix cracking, thermal ablation, tool wear, fiber pullout, and fuzzing at the hole periphery and uncut fibers (Zitoune et al., 2016). The most common damage in CFRP composites during drilling is delamination failure, which leads to most of the rejection almost 60% of complex assembled composite structures (Al-wandi et al., 2017; Fleischer et al., 2018; Wang, Melly, Li et al., 2018). Delamination depends on factors such as process parameters like the material thickness, drill diameter and cone angle, etc. as experimentally recorded by the Taguchi method (Babu & Philip, 2014; Palanikumar et al., 2008). Delamination in the composites are of two types, peel up delamination at the initial layer of the composite and pushout delamination occurring at the bottom layer of the composite as represented in Figure 3.

During drilling operation, the drill generates a peeling force separating the laminate layers in top layer of the composite due to fracture generated by mode III (but the fibers undergo inefficient tearing shear due to the vibration of the drill). Fibers are pulled during the process as crack opening takes place in the laminate due to mode I failure. Peel up delamination occurs due to combined mode I and mode III failure as shown in Figure 4(a) (Girot et al., 2017).

Similarly, in pushout delamination as the tool reaches the bottom-most layers in the composite, the intact plies under the drill are easily delaminated and undergo bending with the decreasing thickness of the composite. Push out delamination due to combined mode I and mode II failure is represented in Figure 4(b) (Anand & Patra, 2017; Curiel-Sosa et al., 2018; Geier, Davim et al., 2019; Rahme et al., 2015).
Figure 5. Types of drill a) twist drill; b) step drill; c) brad spur; d) one shot; e) multi-faceted; f) trepanning (Hocheng & Tsao, 2006)

The stress-induced between the layers transcends to the bond strength between the layers. The chisel edge of the tool applies an abrasive force on the plies at this stage. As the process further progresses, the chips exit the laminate along the slope of the flute. Thus, a vertical pulling force is applied axially upwards due to the cutting action, which separates the top plies of the composite. In contrast, the tool applies a thrust force in the opposite direction on the intact layers at the bottom. Delamination is caused due to the force induced by the cutting motion at the boundary of the hole. Hence, delamination mainly depends on thrust force and distribution of force on the cutting edges and the interlaminar strength.

Pushout delamination is more hazardous in comparison with peel-up delamination due to the absence of sufficient backing force to counter the thrust force produced by the tool on the composite (Khashaba et al., 2010; I Shyha et al., 2010).

3.3. Delamination suppression techniques

3.3.1. Drill geometry
Delamination varies mainly due to the thrust force, feed rate, and the cone/point angle of the tool (Koenig et al., 1985; Komanduri, 1993; Raj & Karunamoorthy, 2018; Taglioferrari et al., 1990). With the increasing cone angle of twist drill, extrusion area increases on the laminate, amplifying the thrust force and consequently adds to the pushout delamination. It was observed that the delamination was reduced by 45% at the hole exit when a lower point angle of 85° twist drill, was used for the process (Gaitonde et al., 2008; Heisel & Pfeifroth, 2012). However, in case of peel-up delamination, minimum delamination was observed for 140° point angle when compared to point angle of 118° (IS Shyha et al., 2009). Recent studies showcase geometry of tool having a significant impact on the delamination of CFRP composites (Pereszlai & Geier, 2020; Tsao & Hocheng, 2004; Wang et al., 2013; Xu et al., 2021). The effect of six different geometry drills as shown in Figure 5, including twist, core, saw, candlestick, and stepped drill on the delamination and the thrust force applied was compared. It was noted that the highest feed rate with minimum delamination was obtained for core drill. In contrast, the lowest feed rate for minimum delamination was observed using conventional twist drill (Hocheng & Tsao, 2006; Phapale et al., 2020). Among one shot, brad-spur, and twist drill, the brad-spur drill bit showed minimum delamination and the better surface finish was obtained. Whereas in case of core drill, inadequate chip removal leads to the excessive delamination (Tsao, 2006). Furthermore, delamination of a twist drill with a larger cone angle 120° was obtained lower in comparison with a brad spur drill. It was also reported that brad spur, step, and dagger type tools do not have significant delamination reduction in comparison with a twist drill used for drilling with pilot holes (Marques et al., 2009). Drilling with a brad-spur geometry displayed a reduction in thrust force, damage produced as compared to stub drill. Using a step drill, consisting of two steps, where the first step is a typical twist drill bit with a smaller diameter, and next step is for boring the drilled hole to the needed dimensions with the help of edged steps. The first step helps in reducing delamination by minimal thrust force due...
to reduced area and the second step machines the hole periphery by providing a better surface finish.

Double cone tool geometry gives superior machining of the hole in comparison to twist, brad, and spur drill in CFRP laminates (Zitoune et al., 2013). Stub tool geometry produces a more significant thrust force than the brad-spur tool. A trepanning or U-shape geometry provides the smoothest machining characteristics as they have the lowest extrusion area, which in turn produces the smallest thrust (Mathew et al., 1999). From, Figure 6. thrust force of trepanning drill was 50% lower as in comparison with twist drill. The authors declare that trepanning tool cuts the last fibers without any abrupt, with the momentary increase in feed rate and produced good and acceptable quality of holes.

It was observed that the tool geometries that give minimum delamination for synthetic composites differ from those for naturally reinforced composites. It was concluded that among the brad-spur, end mill, and conventional twist tool geometries with 120° point angle, the lattermost gives optimum characteristics and lowest damage (Azuan et al., 2012; Debnath et al., 2014).

The most effective way to achieve better-machined holes for FRP’s is to reduce thrust and torque by using trepanning tools. Additional advantages of using the hollowed-out tool are the low production cost as well as regrinding because of its simple geometry. A trepanning tool has dual edges to facilitate shear, which is situated on opposite sides of the tool body. It was observed that the trepanning tool induces a 50% lower thrust as well as a 10% lower torque in contrast to traditional twist geometry.

Thrust force developed by the different geometries declines from twist, saw, candlestick, and stepped, respectively. When compared to candlestick, the stepped drill seems to be more promising in terms of life, whereas candlestick drill seems to be a better choice in terms of delamination (Krishnaraj et al., 2010).

A new drill bit was designed by Su et al. (Su et al., 2018), combining the fundamental design principles of one shot and candlestick drill. The new designed drill as shown in Figure 7, cuts the fibers along the edge of the hole quickly and penetrates the last layer of the composite with the
help of pulling-shearing and the cut-push effect. Drill bits with nano-coatings like nc-CrAlN/a-Si$_3$N$_4$ produce smoother hole peripheries in the laminates, and the thrust forces undergo a reduction of 30% and 20% during drilling of CFRP/Al (Mathew et al., 1999). A comparison between the results of the Kungl Tekniska Hogskolan method, PCD (PolyCrystalline Diamond), and dagger type drill tools was made. Holes drilled by the KTH method yielded the highest strength and fatigue life with better machining quality in comparison with the holes done by polycrystalline diamond and dagger tools (Krishnaraj et al., 2010).

Various researchers, in order to study the surface characteristics such as delamination, surface roughness, uncut fibers, fiber pull out, have performed analysis on chip removal mechanism, during machining of CFRP composites (Jia et al., 2016; Usui et al., 2014; F Wang et al., 2017). Based on the analysis performed researchers assert that fiber-cutting angle display dominant effect on chip-removal mechanism (An et al., 2015; Sheikh-Ahmad, 2009). Similarly, during drilling of CFRP composites, uncut fibers are seen around the machined edges. These uncut fibers...
characterize the burr area $A_1$ and $A_2$ as seen in Figure 8. To minimize the burr formation around the cutting edges, Xu et al. (Xu et al., 2013) proposed increasing feed rate being the significant factor in enhancing the burr formation. Same conclusion was provided at the entry of hole by Heisel and Pfeifroth (Heisel & Pfeifroth, 2012) during dry drilling of CFRP, in contrast they also observed no burr at the exit side of the hole with increasing feed rate.

3.3.2. Use of support plates
More often in industries drilling using support plates is performed to reduce the delamination despite the higher cycle time and more significant production cost associated with it (Capello, 2004). It was reported that the delamination of the last bottom-most layer along with the neighboring layer of the composite is lowered by 13% and 7%, respectively, when the area of the last ply is reduced from 14 to 6.5 mm. To minimize pushout delamination further, an adjustable active-backup force was set up with the help of an electromagnetic solenoid device to counter the pushout due to thrust force applied by the drill instead of a simple support plate (Tsao et al., 2012). When more complex structures other than a plate are to be manufactured, an
electromagnet and a deformable chip colloidal solution of magnetic iron powder is used in tube type parts in industries, which reduces the delamination by about 60–80% (Hocheng et al., 2014).

A more environmentally safe procedure was developed, which uses the expansive internal force of water while freezing is used to provide back-up as shown in Figure 9, during drilling of tubes to avoid delamination, which was reportedly reduced by 40% (Hocheng et al., 2016). When an aluminium plate is used as backing material at the bottom plies of the laminates, the pushout delamination at the hole exit in CFRP laminates reduces (Davim & Reis, 2003).

3.3.3. Cryogenic cooling
Cryogenic cooling is used for composites because of undesirable moisture absorption in the FRP while wet machining due to its hazardous effect on shear fracture toughness of the laminates (Joshi et al., 2019). It was observed that hole surface quality and tool life was improved along with delamination reduction for cryogenic cooling of the composite as shown in Figure 10 (Ahmed, 2006; Joshi et al., 2018; Kumaran, Ko, Li et al., 2017; Morkavuk et al., 2018). When liquid nitrogen was used in drilling, it was reported that delamination factor is less in cryogenic drilling in contrast to traditional drilling because of change in failure mechanism was observed from bending fracture to shear fracture. However, by using rotary ultrasonic machining technique in a cryogenic setup, the peel up delamination was found to be reduced, due to increase in shear modulus as well as transverse strength in the laminate (Kumaran, Ko, Li et al., 2017).

3.3.4. Optimization of drilling parameters
In addition to different types of drill bit as mentioned above, thrust force, torque, and delamination are also influenced by drill diameter, rake angle, chisel edge angle, web thickness, and helix angle (Abrao et al., 2008; Murthy et al., 2010). For obtaining optimal delamination, several researchers have studied optimizing drilling parameters by Taguchi’s method (Babu & Philip, 2014; Geng et al., 2019; Sardiñas et al., 2006). Linear regression analysis was used to establish relationship between input parameters (point angle, feed rate, cutting speed, drill diameter) and drilling-induced delamination (Geng et al., 2019). Other optimization methods include response surface methodology (RSM), analytical, numerical, deep learning (Genna et al., 2017; Jung & Chang, 2021; Krishnamoorthy et al., 2009; Rao et al., 2017; Saeed et al., 2019). Studies with varying drilling parameters are represented in Table 3.

It was found experimentally that by enhancing the speed of cutting tools in the drilling of CFRP composites, delamination was also found to be enhanced (Feito et al., 2018; Sorrentino et al., 2018). At the same time, it was observed that the pushout delamination is initiated in a shorter amount of time at higher cutting speed because of heat generated, which makes the matrix softer and less stiff (Krishnaraj et al., 2012). It is also observed that due to the low feed rate and high speed, a temperature rise occurs, which in turn enhances the delamination in the composite (Geng et al., 2017; Loja et al., 2018). In contrast, Gaitonde observed that delamination was minimized by enhancing the cutting speed of the tool in traditional machining of carbon fiber composites (Gaitonde et al., 2008). A high ratio of cutting speed and feed is optimal to minimize delamination.

It was observed that a large portion of the thrust induced due to the drill is because of the chisel edge and the cone angle of the drill. Increasing the chisel edge length results in an increase in thrust force, at the same time, decreasing the edge width of the chisel leads to a decrease in the extrusion area, which in turn decreases the thrust applied (Jain & Yang, 1993; Won & Dharan, 2002).

At most times, a high cutting speed (150–200 m/min) and lower feed (0.01–0.05 mm/rev) is used in machining fiber-reinforced structures within industries to reduce delamination as well as maintain process efficiency and reduce cycle time (Mkaddem et al., 2013). But cutting speed is usually limited up until 4000 m/min because after that temperature increase is significant, which damages the composite. The lower the speed-feed ratio, the poorer will be the quality. The failure mode for
### Table 3. Studies dealing with drilling-induced delamination of CFRP laminates

| Composite & composite thickness | Cutting tool specification | Cutting parameters | Remarks | Refs. |
|---------------------------------|---------------------------|--------------------|---------|-------|
| CFRP Thickness: 9.16 mm         | (1) CVD diamond-coated brad spur drill | Spindle Speed: 1000, 1500, 2000, 2500 rpm; Feed: 0.010, 0.015, 0.020, 0.025 mm/rev | The brad spur drill bit revealed the most suitably satisfying performance showing the least delamination compared to the twist and dagger drill about drilling force, hole grade and tool wear. | (Xu et al., 2019) |
|                                 | (2) Uncoated tungsten carbide twist drill | | | |
|                                 | (3) Uncoated solid carbide dagger drill | | | |
| CFRP Thickness: 4 mm            | (1) TiAIN coated solid carbide micro drill | Spindle Speed: 8000, 10,000 rpm; Feed Rate: 200 mm/min | The drilling diameters in steps of 50 holes up to 200 holes for each spindle speed. Spindle speed does not provide significant impressions on hole precision with feed rate less than 0.10 mm/rev. Delamination occurred after 50 holes and as the quantity of holes to be drilled increases the hole diameter decreases due to tool wear. | (Nasir et al., 2019) |
|                                 | (2) WC-TiAIN coated twist drill | | | |
|                                 | (3) WC-Diamond coated twist drill | | | |
| CFRP Thickness: 10 mm           | (1) Tungsten Carbide (WC) uncoated twist drill | Cutting Speed: 60, 100, 140 m/min; Constant Feed: 0.05, 0.1, 0.15 mm/rev; Variable Feed: 0.025, 0.05, 0.075 mm/rev | Thrust force ($F_t$), Delamination factor ($F_d$) and Average surface roughness ($R_a$) values with the variable feed rates are compared to those of constant feed rates. It was found that it is viable to decrease delamination factor to the lowest with variable feed rate when drilling CFRP composites. The hole sizes drifted from the nominal value with increasing cutting speed. | (Yaşar & Günay, 2019) |
|                                 | (2) WC-TiAIN coated twist drill | | | |
|                                 | (3) WC-Diamond coated twist drill | | | |
| UD-CFRP Thickness: 4.9 mm       | (1) Stepped drill | Spindle Speed: 1500, 3500, 5500 rpm; Feed: 0.01, 0.02, 0.03, 0.04, 0.05 mm/rev | Stepped drill with pilot diameters had greater performance than the twist drill in terms of hole wall damage (delamination). Delamination damage reduces as feed rate increases under the same spindle speed conditions. The damaged area reduces as the feed rate is increased. | (Qiu et al., 2018) |
|                                 | (2) Ultrafine grain carbide drill | | | |
high feed consists of damage because of high impact, cracks between the adjacent layers in the composite, delamination in a stepped pattern, and formation of a large number of microfailure zones (Caprino & Tagliaferri, 1995). It was also noticed that by thinning the web, it is possible to reduce the axial thrust by 30 to 35% (Krishnaraj et al., 2010). From literature, based on optimizing drilling parameters, minimum peel up and push out delamination was obtained at minimum feed rate (Abrão et al., 2007; Aveen et al., 2021; Dandekar & Shin, 2012).

CFRP- Carbon Fiber Reinforced Polymer, UD-CFRP- Uni-directional Carbon Fiber Reinforced Polymer

3.3.5. Special tool paths
With addition to optimizing the machining parameters as discussed in the above section, new machining techniques that improve the hole quality have been investigated and applied for producing holes in CFRP composites. The methods include helical milling and wobble milling (Haiyan et al., 2013; Shan et al., 2011; Tonshoff et al., 2000).
To produce high accuracy holes, helical milling process is one of the precise methods, where the holes to be fabricated are larger than the cutting tool diameter and during the process, the cutting tool moves in a spiral path as shown in Figure 11 (Amini et al., 2019). Advantages of helical milling compared to conventional drilling include lower thrust force, smooth cutting operation, and higher precision holes (B Wang et al., 2018). Also, better lubrication and cooling take place as more free space is obtained resulting in less expelled chips due to eccentricity and helical path of cutting tool (Wang, Melly et al., 2018).

During helical milling of CFRP/Ti composite, Wang et al. (Wang, Suntoo et al., 2018) observed reduction in thrust force. Similarly, during the investigation of temperature influence in helical milling of CFRP, only 5% error was observed with good agreement between the experimental output and cutting force model data. Also, with increasing spindle speed of 3000-5000 rpm, the workpiece temperature increased only up to 15%. This temperature reduction causes lowering the coefficient of friction at cutting area which in turn lowered the adhesion between tool and the workpiece (J Liu et al., 2014). Delamination reduction was observed for high spindle speed, suitable helical pitch and lower feed rate, during helical milling of CFRP by Qin et al. (Qin et al., 2014). A correlation between delamination and process parameters were developed using MATLAB ANN toolbox.

Wobble milling is another recent and most effective advanced technology for producing holes in composite materials, where the cutting tool is tilted that decreases the axial cutting force at the hole entry (Peresztlai & Geier, 2020). Due to tilting of cutting tool, peel up and push out delamination is minimized as the acting cutting force compresses the top and bottom layer of the composites as represented in Figure 12.

Schulze and Beke (Schulze & Becke, 2011) studied the influence of process parameters on resultant machining force vectors by wobble milling method. They observed that there was no effect on tool wear due to wobble milling. To calculate chip geometry and specific forces, a mechanistic model was developed. They stated that only tool inclination angle had a significant influence on effective force angle as compared to feed rate and cutting-edge radius. In the other study of Schulze et al. (Schulze et al., 2011, 2012), machining-induced damage was reduced by adopting complex machining strategies (five-axial advanced machining) in comparison to conventional drilling. In the recent article of Csongor Peresztlai & Norbert Geier (Peresztlai & Geier, 2020), comparing the wobble milling, helical milling with conventional drilling on CFRP, authors stated that wobble milling technique was more effective in minimizing the amount of uncut fibers.

4. Conclusion and future scope

Based on the above literature, the following conclusion and future opportunities are represented as follows:

- Carbon Fiber-Reinforced Polymers (CFRP) are gaining their allure in the industry primarily due to certain properties (Strength and its lightweight). High strength to weight ratio and their ability to withstand various conditions that affect a materials ability to function in an optimum manner, make them broadly utilized in several modern applications.
- Laser drilling of CFRP composites provides excellent hole characteristics for thickness less than 3 mm, whereas with thickness above 10 mm produces plume (large amount of plasma and evaporated materials) and the feasibility of obtaining dimensional accuracy and efficiency are still unknown. More studies are essential to apply the non-conventional method for thickness above 3 mm.
- Delamination effecting CFRP materials is always a mix of two modes, mode I/II and mode I/III. As noticed mode I failure is seen in both peel-up and pushout types of delamination.
- Feed-rate and spindle speed have a significant impact on the delamination induced in CFRP’s during drilling. Also, different drill bit geometry tend to cause minimum delamination as compared to twist drill bits. Drilling area temperatures that are extremely high or extremely
low have a significant impact on delamination and hole quality, therefore a suitable range of temperatures must be established for CFRP’s to obtain good quality holes during drilling.

- Specially developed drill bits have shown a significant promise in reducing drilling induced delamination of CFRPs. More study needs to be performed on designing novel drill bits to significantly suppress delamination.

- Employing support plates has shown a promising results in reducing push-out delamination; however, support plates are only applicable for simple and plain geometry CFRP. Therefore, more further studies are required on reducing push-out delamination on complex geometries.

- Helical milling and wobble milling provide excellent surface integrity of hole with minimum defect; however, both the methods are expensive and further research is required for optimization of parameters during drilling of CFRP composites.

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