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A REVIEW ON DRILLING OF FIBER-REINFORCED POLYMER COMPOSITES

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The drilling is a very important machining process to increase the joining efficiency of assembled parts. In this review, the consolidation of various composite materials with different fibers are discussed. Different drill tools, their materials and geometries, and drilling methods, such as conventional, vibration-assisted, and high-speed ones, are considered, and various numerical models for determining the critical thrust force and delamination are analyzed. It is concluded that unconventional geometries and materials give better results in reducing the thrust force and delamination compared than the traditional materials and geometrical shapes of drill tools

1. Introduction

Nowadays, increasing demands for fiber-reinforced polymer composites in various fields are observed. Various fiber-reinforced composites, such as CFRPs (carbon-fiber-reinforced polymers), GFRPs (glass-fiber-reinforced polymers), KFRPs (Kevlar-fiber-reinforced polymers), and others are used in industry owing to their superior mechanical properties. The fastening of composite laminates to other materials is unavoidable in the structural work. Bolts and rivets are mainly used for joining counterparts in an assembly, because the machining of composite-based parts is more difficult than the conventional materials due to their anisotropy and the presence of reinforcement. Machining creates various faults (such as peel-up and pull-out delaminations) and reduces their strength. The general classification of composite materials is shown in Fig. 1.

The drilling-induced delamination is the major defect faults arising in the drilling process. In the past studies, it was revealed that 60% of aircraft parts were rejected owing to delaminations in holes. To minimize the rejections and to increase the efficiency of joining, delaminations and other defects caused by drilling have to be avoided.

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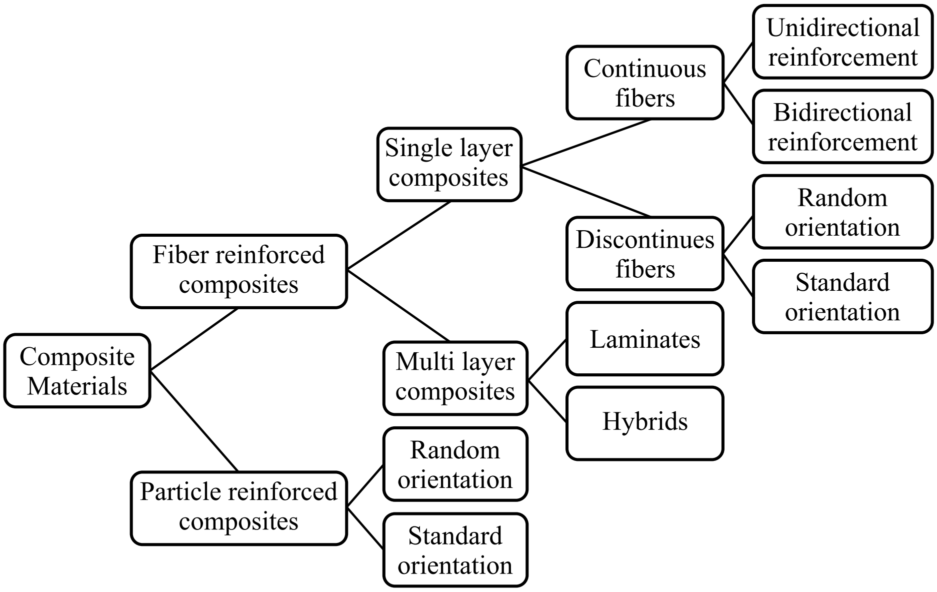

Fig. 1. General classification of composite materials.

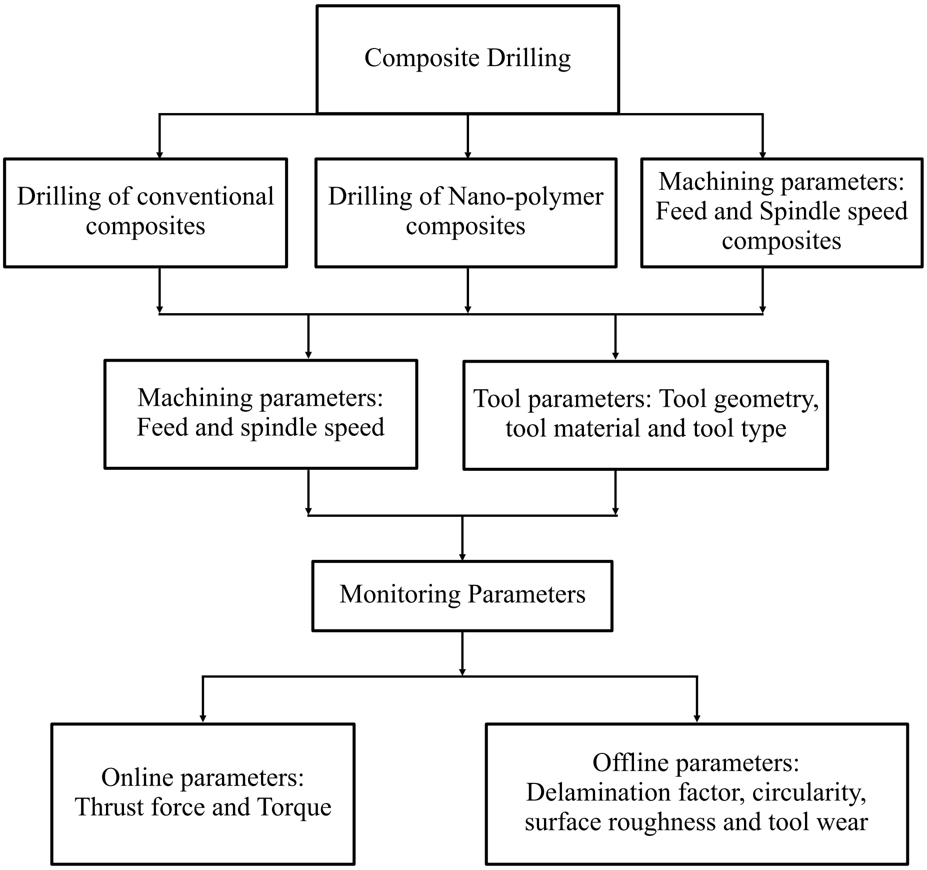

Fig. 2. Different drilling process parameters of composite materials.

Regarding the machining of composite materials, few review papers are available [1-6], but systematically updated reviews are not available. The main drilling parameters of composite materials are shown in Fig. 2.

TABLE 1. Different Composite Materials and Fiber Orientations

Material	Ply/sheet	References
CFRP	Unidirectional	[7, 10—13, 15, 17, 20—32]
	Bidirectional and woven	[7—9, 34—47]
GFRP	Unidirectional	[21, 48—58]
	Woven	[59—70]
	Bidirectional	[35, 65]
	Chopped strand mat	[71, 72]
Metal fiber laminates	CFRP/titanium	[73—76]
	GFRP/GLARE	[77—80]
	CFRP/aluminum	[79, 81—86]
	Aluminum/CFRP/titanium	[87, 88]
KFRP	Kevlar-fiber-reinforced composite /ceramics	[3, 4, 89]
Natural fiber	Sisal, banana, roselle, coir fiber	[6, 18, 90—93]

2. Composite Materials and Fiber Orientations

Different composite materials and their fiber orientations are indicated in Table 1. Shyha et al. [7] investigated the delamination at the entry and exit of CFRPs (unidirectional and woven) in the prepreg form. In this study, a tungsten carbide stepped drill tool was used for drilling, and results showed that the tool life could be increased for woven fiber-based composites when the drilling was performed at a thrust force bellow 125 N and a torque bellow 65 N·mm. Rahme et al. [8] investigated the punching of CFRP specimens by numerical and experimental methods. The number of plies remaining under the punch varied from one to six when the load increased from 360 to 1935 N. Different drill tool materials were used for the drilling process, and the carbide tool was found to produce a higher thrust force than the HSS (high-speed steel) tool. Madhavan and Prabu [9] studied the delamination during drilling of a unidirectional GFRP material and suggested a twist drill with a 90o point angle. Lin and Chen [10] studied how the cutting speed affects the tool wear and thrust force and also analyzed how the flank temperature depends on the feed rate and cutting speed during drilling [11]. Piquet et al. [12] reported that a predrilling is necessary for CFRPs by using a double-twist drill (double-fluted) to neutralize the chisel edge effect. The predrilling was not required for drilling CFRPs by a specific cutting tool. In [13], the drilling of CFRPs with three different tools (two coated and one uncoated) was performed, and neither of them reduced the tool wear or the damage of composite materials. The twist and C-shaped) tools used for drilling unidirectional CFRPs produced a lower thrust force. The finite-element model was also used to predict the thrust force, the uncut thickness at the maximum thrust force, and delamination during the drilling process [14]. A comparison of experimental and numerical models was performed for unidirectional CFRP and GFRP. It was reported that the forces between the fiber and tool caused crushing. Zitoune and Collombet [15] used a numerical method to predict the delamination at the exit of the drill hole in long-fiber composite materials. Rawat and Attia [16] reported that the flank wear increased when a tungsten carbide drill tool was used for drilling woven CFRPs at high spindle speeds and the heavy abrasion of broken fibers and drill tool caused a high temperature and flank wear. The orientation of fibers and rake angles more influenced the cutting force [17, 18]. Kalla et al. [19] investigated the drilling of unidirectional and multidirectional CFRPs by using an end mill tool.

Liu et al. [34] studied the thrust force and torque during drilling of CRFP composites by using half-core carbide drill tool and reported that it produced a minimum thrust force and torque compared to that of the carbide drill. Tsao et al. [37] reported that the delamination of woven composites could be reduced by 60 to 80 % at the exit of the drill tool. Phadnis et al. [38] revealed that the thrust force, torque, and delamination increased with growing feed rate and decreased with increasing spindle speed. Murphy et al. [71] optimized the drilling parameters in the cases GFRP chopped strand mat composites.

TABLE 2 Different Drilling Tools and Materials

Drill bit geometry	Drill tool material	References
Twist drill bit	High-speed steel	[14, 49, 51, 61, 64, 90, 91, 95]
	Coated cemented carbide	[33, 35, 41, 42, 60, 71, 73, 78, 81]
	Coated cemented carbide	[31, 38, 42]
	Polycrystalline diamond (PCD)	[9]
	Tapered drill reamer,8-Faret twin drill, 2-Faret twist drill	[35]
Step drill bit	High-speed steel / cemented carbide	[42, 96]
Brad point drill bit	The same	[39, 65]
Slot drill bit	″ ″	[41, 97—99]
Straight flute drill bit	Cemented carbide	[35, 41, 65, 100]
Core drill bit	Polycrystalline diamond (PCD)	[34, 89]
	Core twist drill, core saw drill, core candle stick, step core twist drill, step core saw drill, step core candle stick drill	[95]
Special drill	Solid carbide nose, HSS nose, PCD ball nose, and Dagger drill	[9, 20]

2.1. Metal fiber laminates

The drilling of metal fiber composites is a tedious process because of different properties of their constituents. Park et al. [73] found that a tungsten carbide tool with a titanium covering had a higher wear factor than a polycrystalline diamond tool with a titanium covering. The variation in the elastic modulus causes diameter variations occurs in the entire depth of metal fiber laminates. To reduce the drilling cost, carbide-coated drill bits were used for making holes in fiber-reinforced materials. Ramulu et al. [74] studied the drilling of graphite/bismaleimide and titanium composites by using high-speed steel, high-speed steel cobalt, and carbide drill bits. The carbide drill tool produced the best results in terms of surface damage, heat-induced damage, and tool life. Shyha et al. [87] reported that the uncoated carbide drill tool had a longer operation life than the hard-metal and diamond-coated drill tools in drilling titanium / unidirectional CFRP / aluminum stack composites.

A helical milling tool was used in [76] for boreholes to reduce the delamination and burr formation occurring in the conventional drilling process of CFRP/titanium composites. Giasin and Ayvar-Soberanis [77, 94] investigated the circularity, entry, and exit errors and the chip formation in a GLARE (glass aluminum-reinforced epoxy) material during the drilling process. It was reported that the spindle speed and feed rate influenced more the burr thickness and height.

3. Drill Geometries and Materials

In Table 2, different drill tools and its materials are listed. Most research work has been carried out by using a twist drill bit alone. Drill tool materials also greatly influence the delamination of composites and life of drill bits. Among the various types of drill bits, high-speed steel and carbide drill bits have gained major attention of investigators.

Karimi et al. [51] investigated the thrust force generated in a GFRP material during the drilling by a 5-mm twist drill tool with a 30o helix angle. To diminish the tool wear the tool was changed in every five experiments. Two different point angles (118o and 135o) and a high speed steel drill tool with a helix angle of 30° of were used for the investigation [49]. Durão et al. [14] studied the delamination in CFRP materials during drilling with twist, brad, and special step drills. The step drill produced the best results in reducing delaminations. Madhavan and Prabu [9] investigated the thrust force during drilling by tools made of high-speed steel, carbide drill, and polycrystalline diamond materials. The HSS drill tools generated the highest thrust force.

TABLE 3 Different Drilling Methods

Drilling operation	References	Remarks
Conventional drilling	[14, 21, 31, 34, 35, 38, 39, 49, 51, 62, 65, 71, 78, 89—91, 95]	Cutting speed < 100 m/min (In general, the spindle rotation speed < 8000 rpm). A standard twist drill, slot drill, and brad point drill bits
Vibration-assisted twist drilling	[25, 61, 86, 102]	Cutting speed < 200 m/min, the highest spindle speed is 22,000 rpm
High-speed drilling	[16, 31, 34, 102]	The cutting speed > 200m/min and a cemented carbide twist drill bit is used

4. Drilling Process Methods

Only few nontraditional machining techniques have been used to make holes in composite laminates. Among them, the water jet machining, electrical discharge machining (EDM), and some others can be mentioned [101]. In the conventional mechanical machining, some of special methods are used to make a hole in composite laminates. This paper mainly focuses on the high-speed mechanical drilling, vibration-assisted drilling, and back-plate drilling. Table 2 lists different drill tools and their materials

4.1. Conventional drilling

Table 3 shows various drilling methods for making hole by using different drill bits, which are classified into four groups — conventional, vibration-assisted twist, and high-speed ones.

4.2. Vibration-assisted twist drilling

During the past few years, the vibration-assisted twist drill (VATD) has mostly been used in academics and industries. The drilling operation combines a low-amplitude vibration and a low frequency feed. The traditional drilling process is a continuous cutting process, whereas the VATD is discontinuous. In the traditional drilling process, a high thrust force develops, but at the same cutting conditions, the thrust force in the VATD drilling is reduced by 20% to 30%.

4.3. High-speed drilling

In recent years, the high-speed drilling process has gained more interest owing to its high production rate. As in the VATD process, the thrust force developing during the drilling process is considerably lower. However, this process is very expensive compared with the traditional drilling. The objective of this work is to decrease the delamination by reducing the of thrust force. The delamination was reduced by combining a high cutting speed, a low feed rate, and specified point angle of hole in the high-speed drilling.

TABLE 4. Numerical Models for the Critical Thrust Force

Authors	Drilling condition	Critical thrust force
1	2	3
Zitoune et al. [81]	CFRP/Al and CFRP, plate thickness 4.2 mm, spindle speed 2020 and 2750, feed rates 0.05, 0.1 and 0.15, twist drill, double cone M1, M2 and M3, drill diameter 6.35 mm	$\left(\frac{G_I}{G_{IC}}\right)^{\alpha}+\left(\frac{G_{II}}{G_{IIC}}\right)^{\alpha}=1.$
Karimi et al. [104]	Flax fiber, thicknesses of plates 1.4, 2.14 and 2.68, feed rates 0.03, 0.06 and 0.12, twist drill with point angles 118, 110, 100, 90, 80, 70 deg, drill diameter 6 mm, cutting speeds 15, 20, and 25 m/min	Concentrated load $T_1=\pi\sqrt{32G_{IC}D'}$, the equivalent uniformly distributed load $T_2=\frac{\pi\sqrt{32G_{IC}D'}}{1-1/2s^2}$, the uniformly distributed load $T_3=\frac{\pi\sqrt{32G_{IC}D'}}{\sqrt{J^2\left(1-\frac{1}{2}S^2\right)^2+\left(1-J\right)^2\left(1-\frac{1}{2}\tau^2S^2\right)^2}}$.
Zhang et al. [105]	CFRP, thicknesses of plates 0.3 to 0.82 mm (1, 2 and 3 plies), feed rate 0.03, spindle speeds 2000, 0.06, and 0.12 rpm, drill tool: inserts of carbide with a drill diameter of 6 mm, drill diameter 6 mm	Zhang model $F_Z=\sqrt{\frac{\pi G_{IC}}{\xi\left(C_3-K\right)}}$, $K=\frac{\pi}{2}\Bigg[\frac{A_{11}}{\xi}\left(3C^2+C_4^2\right)+2A_{12}\left(C_1C_2+C_4C_5\right)+\frac{2A_{16}}{\xi}\left(2\xi C_1C_4+3C_1C_5+C_2C_4\right)$ $+A_{26}\left(3\xi C_2C_4+2C_2C_5+\xi C_1C_5\right)$ $+\frac{16D_{11}}{\xi}\left(3D_{11}+2\xi^2D_{12}+3\xi^4D_{22}+4\xi^2D_{66}\right)$ $+\frac{A_{66}}{\xi}\left[\xi\left(C_1+C_2\right)^2+3\xi^2C_4^2+3C_5^2+2\xi C_4C_5\right]+\frac{2B_{11}}{\xi}C_1C_3+8B_{12}C_3\left(\xi C_1+C_2\right)$ $+24B_{16}C_3\left(C_4+\frac{C_5}{\xi}\right)+24B_{22}\xi^2C_2C_3+24B_{26}C_3\left(C_5+\xi C_4\right)\Bigg]$, Gururaja model $F_G=\sqrt{\frac{\pi G_{IC}}{\xi\left(\frac{C_3}{3}-K\right)}}$, Zhang's model $F=\sqrt{\frac{\pi G_{IC}}{\xi\left[\left(\alpha^2C_3-\left(1-\alpha\right)^2\frac{C_3}{3}\right)-\left(\alpha^2K+\left(1-\alpha\right)^2K\right)\right]}}$.
Zitoune and Collombet [15]	Drill diameter 4.8 mm, cutting speed 1.5 m/min	Isotropic model $F_Z=\pi\left[\frac{8G_{IC}Eh^3}{3\left(1-v^2\right)}\right]^{1/2}$ and orthotropic model $F_Z=8\pi\left(\frac{G_{I_c}D}{\frac{1}{3}-\frac{D'}{8.D}}\right)^{1/2}$,

1	2	3
		where $D=\frac{1}{8}\left(3D_{11}+2D_{12}+4D_{66}+3D_{22}\right)$, $D' =\frac{D_{11}+D_{22}}{2}+\frac{D_{12}+D_{66}}{3}$.
Durao et al. [106]	Material: CC160 ET 443, plate thickness 6 mm, spindle speed 2800 rpm, feed rates 0.02, 0.06, and 0.12 mm/rev, cutting speed 53 m/min, twist drill with point angles of 120 and 85 deg, brad, special step drill and dagger	Isotropic material with concentrated load $F_{crit}=\pi\left[\frac{8G_{iC}E_1h^3}{3\left(1-\upsilon_{12}^2\right)}\right]^{1/2}$, orthotropic materials with a point load $F_{crit}=8\pi\left[\frac{2G_{IC}D}{1-\left(D' /8D\right)}\right]^{1/2}$, orthotropic materials with uniformly distributed load $F_{crit}=8\pi\left[\frac{G_{IC}D}{\left(1/3\right)-D' /8D}\right]^{1/2}$.
Saoudi et al. [107]	CFRP, plate thickness 4.2 m, spindle speed 2000 rpm, feed rate 0.02 mm/rev, twist drill of diameter 6 mm	$F_C\left(\text{Zhang}\right)=\sqrt{\frac{\pi G_{IC}}{\xi\left(C_3-K\right)}}$, $F_C\left(\text{Hocheng}\right)=\pi\sqrt{\frac{8G_{IC}Eh^3}{3\left(1-v^2\right)}}$, $F_C\left(\text{Gururaja}\right)=\sqrt{\frac{\pi G_{IC}}{\xi\left(\left({C_3}/{3}\right)-K\right)}}$, Gururaja model is modified including the temperature effect $F_C=\sqrt{\frac{\pi\left(K^*+G_{IC}\right)}{\xi\left[\left({C_3}/{3}\right)-K\right]}}$.
Hocheng and Tsao [97]	--	Twist drill, $F_A=\pi\sqrt{32G_{IC}M}=\pi\left[\frac{8G_{IC}Eh^3}{3\left(1-v^2\right)}\right]^{1/2}$; saw drill, $F_S=\pi\sqrt{\frac{32G_{IC}M}{1-2s^2+s^4}}$; candlestick drill, $F_C=\pi\left(1+\alpha\right)\sqrt{\frac{32G_{IC}M}{1+\alpha^2\left(1-2s^2+s^4\right)}}$; Core drill $F_{CR}=\pi\beta\left(2-\beta\right)\sqrt{\frac{32G_{IC}M}{\left\{\left[1-\left(1-\beta\right)^4\right]-\left(1/2\right)s^2\left[1-\left(1-\beta\right)^6\right]\right\}}}$; Step drill $\left(F_T\right)_i=\pi\left[1-\left(i\xi\right)^2\right]\sqrt{\frac{32G_{IC}M}{\left\{\left[1-\left(i\xi\right)^4\right]-\left(1/2\right)s^2\left[1-\left(i\xi\right)^6\right]\right\}}}$, $i=1-n$.

1	2	3
Rahme et al. [108]	CFRP unidirectional, plate thickness 20 mm, spindle speed 1492 rpm, twist drill diameter 16 mm, and cutting speed 75 m/min	$\boldsymbol{F}_{1C} = 8\pi\left(1+\nu_{r\theta}\right)\sqrt{\frac{G_{ICI}\,D}{\frac{\left(7+8\nu_{r\theta}+\nu_{r\theta}^{2}\right)}{3}-\frac{D'}{8D}}}$, $D' = \frac{\left(D_{11}+D_{22}\right)\left(9+2\nu_{r\theta}+\nu_{r\theta}^{2}\right)}{2}+\frac{\left(D_{12}\right)\left(25+2\nu_{r\theta}+\nu_{r\theta}^{2}\right)+2D_{66}\left(1+2\nu_{r\theta}+\nu_{r\theta}^{2}\right)}{3}$, $\boldsymbol{F}_{2C} = 32\pi D\left(1-\nu_{r\theta}^{2}\right)\left(a^{2}-b^{2}\right)^{2}\sqrt{\frac{-9G_{ICP}\left(C_{1}+C_{2}+C_{3}\right)}{\left(3C_{1}+C_{2}+C_{3}\right)}}$, $\boldsymbol{C}_1$, $\boldsymbol{C}_2$, and $\boldsymbol{C}_3$ are three variables in terms of a, b, D, and D_{ij} $\boldsymbol{C}_1 = 96\Big[\left(-2D_{11}-2D_{22}+\frac{8}{3}D_{66}-\frac{4}{3}D_{12}\right)\nu_{r\theta}$ $+\frac{16}{3}D-\frac{1}{3}D_{11}-\frac{1}{3}D_{22}-4D_{66}+\frac{10}{3}D_{12}\Big]\left(1+\nu_{r\theta}\right)^{2}b^{6}\left(a^{2}+\frac{1}{2}b^{2}\right)\ln\left(\frac{b}{a}\right)^{2}$ $\boldsymbol{C}_2 = 72\Big[\left(-16D+3D_{11}-3D_{22}+4D_{66}-2D_{12}\right)\nu_{r\theta}^{2}$ $+\frac{32}{3}D-6D_{11}-6D_{22}-8D_{66}-4D_{12}\Big]\nu_{r\theta}$ $+\frac{80}{3}D-\frac{7}{3}D_{11}-\frac{7}{3}D_{22}-\frac{52}{3}D_{66}+\frac{38}{3}D_{12}\Big]b^{2}$ $+a^{2}\Big[\left(-\frac{16}{3}D+D_{11}+D_{22}+\frac{4}{3}D_{66}+\frac{2}{3}D_{12}\right)\nu_{r\theta}^{2}$ $\left(-\frac{32}{3}D-2D_{11}-2D_{22}-\frac{8}{3}D_{66}-\frac{4}{3}D_{12}\right)\Big]\nu_{r\theta}+16D$ $-\frac{5}{3}D_{11}-\frac{5}{3}D_{22}-\frac{28}{3}D_{66}+6D_{12}\Big]\left(1+\nu_{r\theta}\right)^{2}\left(a^{2}-b^{2}\right)b^{4}\ln\left(\frac{b}{a}\right)$ $\boldsymbol{C}_3 = 3\Big[\left(-\frac{208}{3}D+13D_{11}+13D_{22}+\frac{52}{3}D_{66}+\frac{26}{3}D_{12}\right)\nu_{r\theta}^{4}$ $-416D\nu_{r\theta}^{3}+\left(-\frac{640}{3}D-66D_{11}-66D_{22}-\frac{680}{3}D_{66}+\frac{284}{3}D_{12}\right)\nu_{r\theta}^{2}$ $+\left(416D-112D_{11}-112D_{22}-384D_{66}+160D_{12}\right)\nu_{r\theta}$ $+\frac{848}{3}D-27D_{11}-27D_{22}-\frac{524}{3}D_{66}+\frac{362}{3}D_{12}\Big]b^{4}$ $-2\Big[\left(-\frac{16}{3}D+D_{11}+D_{22}+\frac{4}{3}D_{66}+\frac{2}{3}D_{12}\right)\nu_{r\theta}^{2}$

1	2	3
		$\left(-\frac{128}{3}D+2D_{11}+2D_{22}+\frac{8}{3}D_{66}+\frac{4}{3}D_{12}\right)\Big]\nu_{r\theta}-\frac{112}{3}D$ $+9D_{11}-9D_{22}+\frac{4}{3}D_{66}+\frac{50}{3}D_{12}\Big]a^2b^2\left(\nu_{r\theta}-1\right)^2$ $+\Big[\left(-\frac{16}{3}D+D_{11}+D_{22}+\frac{4}{3}D_{66}+\frac{2}{3}D_{12}\right)\nu_{r\theta}^2$ $\left(-\frac{128}{3}D+2D_{11}+2D_{22}+\frac{8}{3}D_{66}+\frac{4}{3}D_{12}\right)\Big]\nu_{r\theta}-\frac{112}{3}D$ $+9D_{11}-9D_{22}+\frac{4}{3}D_{66}+\frac{50}{3}D_{12}\Big]a^4\left(\nu_{r\theta}-1\right)^2\left(a^2-b^2\right)^2$

4.4. Use of the back-up force

The back-up force has been used to give a support to workpiece materials during the drilling of composite laminates. An active back-up force reduces the delamination by 60 to 70%. This method can also increase the manufacturing rate at a high feed rate.

5. Delamination-Induced Damage

Delamination is the debonding of laminates caused by high thrust force induced during their drilling.

5.1. Assessments of delamination

Various methods are employed to assess a delamination, but the commonly method is using the ratio F_d between the maximum D_{max} and nominal D_{nom} diameters.

$$F_d = D_{\text{max}} / D_{\text{nom}}$$

The measuring of delamination by the factor F_d is unclear because few fibers are peeled up and pushed down on a considerable width, as shown in Fig. 3, and it is difficult to determine the delamination area of a drilled hole.

5.2. Methods to reduce the delamination in drilling

It is important to avoid delaminations during the drilling of composite laminates, because the thrust force developed has to be lower than the critical one, which depends on the drill bit geometry, and thickness of uncut plies during machining.

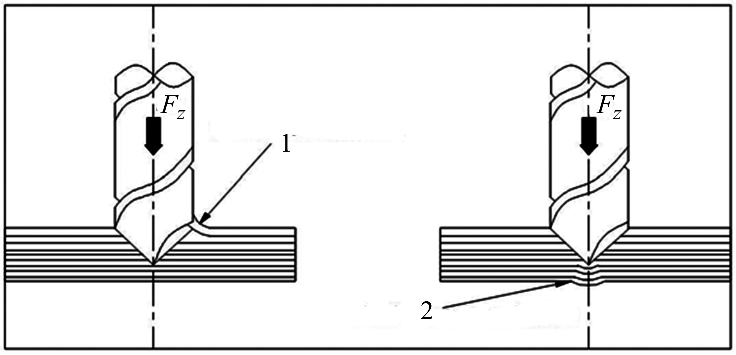

Fig. 3. Delamination during drilling process

6. Thrust Force

It has been revealed that the thrust force arising during drilling composite laminates is the main cause for delamination. This force directly influences on the area of delamination zone, and investigators agree that, below the critical thrust force, this zone has to be minimized [103]. When the thrust force exceeds the critical value, it becomes directly proportional to the induced delamination at its onset.

In [59], it is reported that the cutting speed not much influences the delamination, but the feed rate is directly proportional to the thrust force. The effect of cutting speed on the thrust force in drilling woven GFRP is also studied. When using a fresh drill bit, the cutting speed not much influences the thrust force, but this force considerably increases when using a prewear drill bit. Durao et al. [28] reported that the drill bit point angle greatly affects the thrust force in drilling CFRP and GFRP composite laminates.

The service life of drill tools depends on the thrust force. With decreasing thrust force, it becomes directly proportional to the induced delamination. The delaminations generated in the vibration-assisted twist drilling is by 20 to 30% smaller than in the conventional drilling. It is noted that, at high cutting speeds (exceeding 80 m/min), the feed rate does not much influence the thrust force, but at a normal speed, this force increases with increasing feed rate.

6.1. Numerical model for finding the critical thrust force (TABLE 4)

Zitoune et al. [81] studied the effect of thrust force on the delamination at the hole exit in a stacked CFRP/Al composite during drilling process. In this analysis, two numerical models were used, one of which was applied to the drill tool exit with considered one ply under the tool. The second numerical model was applied between the tool and aluminum. Karimi et al. [104] reported that the feed rate more influenced the thrust force. Three numerical methods were used in this study — the classical theory of plate bending, the elastic facture mechanics, and the mechanics of oblique cutting. This model can be used to eliminate delaminations by the online monitoring of thrust force. Zhang et al. [105] investigated the critical thrust force at different locations of delamination initiation. Durao et al. [106] revealed that the feed rate and the geometry of drill tool tip reduced delamination faults.

7. Conclusion

This paper gives an outlook of different types of drilling, drill tool materials, induced delamination during drilling of fiber materials, and the development of thrust force during drilling. Unconventional drill tools, such as core drill bits, step drill bits, and straight flute drill tool are considered. Among the various types of drilling, the high-speed drilling is highly efficient and gives holes with a good quality. Numerical models of thrust and a delamination factor have been proposed and studied by different investigators. The general conclusion of this paper is that, at low feed rates and high drilling speeds, delaminations are reduced and the service life of tool is increased. Further investigations into the quality evaluation of drilled holes is necessary to clarify the joining strength of assembled parts.

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