Review Article

Drilling on fiber reinforced polymer/nanopolymer composite laminates: a review

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\textbf{ABSTRACT}

Among various machining operations, drilling is the most commonly employed machining operation for polymer composite laminates owing to the need for joining structures. Work with commercial composites has identified numerous parameters during the drilling operation that can influence the drilling factors and the material damage. The present paper gives a precise review of drilling on current state of fiber reinforced polymer as well as nanopolymer composite laminates. Specifically, the influence of machining parameters, tool geometry, tool materials and tool types on the cutting force generation and delamination mechanisms. Based on the comprehensive literature survey from the past few years, it is noticed that limited research has been made and published concerning to nanopolymer composite drilling and has led to a partial understanding of the cutting mechanics activated in machining/drilling. Some key contributions such as experimental and numerical studies are urgently demanded to address accurately various projections in drilling of nano-particle reinforced FRP composite laminates.

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1. Introduction

Composite materials are made-up of at least two distinct intended materials which together improve product performance and lower manufacturing cost [1]. Many materials, continuously designated by other terms are also considered composites including clad, coated metal tools, etc. [2]. Nowadays, FRP composite laminates are the materials of option for many engineering applications; namely, automotive parts, sporting goods, aerospace components, consumer goods, marine and oil industries, due to their special physical and mechanical properties [3].

The basic initiative behind the learning of FRP composite laminates mainly comprise Glass Fiber Reinforced Polymer (GFRP) composite laminates, Carbon Fiber Reinforced Polymer (CFRP) composite laminates and nanopolymer composite laminates and their applications are based on the possibility of using materials with definite characteristics and ultimate properties that are not found in any of the raw materials [4].

The most recent commercial aircraft designs propose a reduction in weight about 50% by replacing the primary
structural components with fabricated nanopolymer composites. Using light weight and elevated strength composites are essential in order to achieve the reduced fuel consumption and better passenger comfort goals of these future commercial aircraft design innovations [5]. In generally, all the composite materials will undergo some machining processes in their fabrication procedure or its specific engineering application. With the concern of the current industry, drilling is the most frequently used hole making operation for assembly of structures or components. Various industries, such as automotive, aerospace, marine and oil industries, have already started the utilization of nanocomposites in their structures.

The composite damage called delamination is an inter-ply failure phenomenon induced by drilling, which is a very serious problem and has been recognized as an unexpected major damage when drilling composite laminates [6]. Due to the non-homogeneity, multi-phase structure and anisotropic nature of the composites lead to an inter-ply failure during drilling [7]. With that reason, about 60% of the drilled holes on composites are rejected at the initial stage only [8].

In addition to delamination, sub-surface deformation is another important drilling induced damage while composite machining. Interfacial debonding, matrix deformation, fiber pullouts, matrix crazing, cracking, hole shrinkage and spalling are few examples of sub-surface deformations [9,10]. So, in order to improve the product performance and structural integrity of machined holes, the material defects such as sub-surface deformation and delamination has to be trim-down by proper selection of cutting parameters, tool geometries, tool types and cutting conditions [11,12]. Nevertheless, the structural integrity is also strongly depending on fiber matrix interfacial interactions, fiber orientations, cutting directions and tool wear.

Zhang et al. [13] have investigated the spalling, fuzzing exit sub-surface deformation defects during drilling of unidirectional as well as multi-directional CFRP laminates with HSS twist drill. Spalling and fuzzing are considered as the major exit damage mechanisms during drilling of FRP composite laminates and these damages increase with an increase in feed rate and decrease in spindle speed. Spalling at hole exit is usually a severe damage and it is bigger for UD-CFRP laminate as compared to multi-directional CFRP laminate under the same drilling conditions. Khahaba et al. [14] reported that catastrophic shear failure of the composite layers has been done due to the higher feed rates and cutting temperatures resulting poor surface integrity, lower bearing strength of machined holes while GFRP composite drilling. Heisel et al. [15] investigated the influence of point angle, cutting parameters on cutting forces and drill hole quality i.e. faying, burr formation and delamination have been investigated while drilling of CFRP laminates. The increase in point angle increases cutting temperature resulting faying of epoxy matrix with poor quality drilled hole and severe burr formation.

Brinksmeier et al. [16] tried three (Aluminum/CFRP/Titanium) different materials to investigate the surface quality of boresholes after orbital and conventional drilling processes. Compared to the conventional drilling process, orbital drilling gives the finest borehole surfaces with tiny matrix cracks and without fiber breakage under lower cutting temperatures and large cutting speeds. Arul et al. [17] have utilized acoustic emission technique to improve the quality and surface integrity of the machined hole during drilling on woven glass fabric/epoxy composite laminates. The effect of cutting parameters on axial force, flank wear and their influence on the hole shrinkage was monitored and correlated with AE parameters. Abhishek et al. [18] employed PCA-fuzzy integrated with Taguchi’s philosophy technique to optimize the cutting parameters for trim down the delamination, sub-surface damage defects while drilling of CFRP composites. Eneyew and Ramulu [19] have studied the effect of cutting parameters, cutting direction and fiber orientation on the drilled hole surface quality in the UD-CFRP composite laminate. The lower value of thrust force was identified at a rotational angle of 135° and 315°, fiber pullouts are observed at two cutting regions where the cutting direction and fiber orientation interface angle is from 135° to 175° and 315° to 355°. The examined sub-surface damages i.e. delamination, surface roughness, fiber pull outs are captured through SEM.

Generally, when the drill tool is commerce with the FRP laminate, the drill chisel edge generates a nominal thrust force in the axial direction and subsequently initiates the surface deformation due to the frictional rubbing action of tool and work-piece [20,21]. This deformation can remain the same up to the last two piles of composite laminates and increases drastically for further drill extent due to the smaller uncut chip thickness, lower resistance to deformation and stiffness. At this instant, the exit side of the laminate undergoes severe damage of matrix and initiation of crack propagation resulting poor surface integrity [22,23]. Tool-work piece Tribological interactions are also reasons for sub-surface deformation of the composites and these thermo-mechanical mechanisms can be reported in the form of tool wear [24]. Abrasion is considered as chief tool wear mechanism during drilling on FRP as well as nano composite laminates and it can be occurred mainly on rake and flank face of the tool cutting edge causing severe abrasive wear on the flank face resulting poor structural integrity and long-term performance deterioration of the machined surface [25]. Inoue et al. [26] inspected the effect of tool wear on the sub-surface deformation in drilling of small diameter holes of GFRP composites. Based on experimental results, it was concluded that higher flank wear occurs at lower feed rates and larger cutting speeds.

So, in order to eradicate the defects induced during drilling on conventional composites such as GFRP and CFRP, these composites are modified with secondary reinforcements called nano-fillers; namely carbon nano-fibers (CNFs), carbon nanotubes (CNTs), polyamide 6, Polypropylene-Silicon for the property enhancement of composite laminates. A typical layout of classification of composite materials is shown in Fig. 1.

Abrao et al. [27] have made an extensive literature on drilling of FRP composites. Aspects such as tool geometry, machining parameters and their influence on thrust force, torque and delamination are examined in the review. Liu et al. [4] provided a review on mechanical drilling of composite materials such as FRP (CFRP, GFRP) as well as fiber metal composite (FML) laminates. This review paper also encloses with grinding drilling, Vibration-assisted twist drilling (VATD) and high speed drilling (HSD) operations of both FRP and FML composites.
Starost and Njuguna [28] have prepared a report on the effect of mechanical drilling on nanocomposites laminates. The effect and influence of various drilling parameters on delamination and nano-sized particles have been analyzed. Davis et al. [29] reported that amino functionalized single-walled CNTs/CFRPs and fluorine doped single-walled CNTs/CFRP nanocomposite laminates exhibit good improvement in tensile strength, stiffness and fatigue durability compared to non-functionalized composites under tension–tension and tension–compression loadings. The multi-walled CNTs/CFRP composite laminates cured by microwave process was prepared to prevent delamination and drilling ablation and have been compared against normal conventional thermal cured composite without MWCNTs [30]. The fiber reinforced composite laminates thermal conductivity has been increased drastically with the addition of nano-filler/micro-filler; namely, MWCNTs, DWCNTs [31].

The present work provides a detailed review of drilling on FRP as well as nanopolymer reinforced composite laminates. A huge research work has been done on drilling of conventional FRP composites, but there is a need to continue research in the field of nanocomposite drilling especially nano-particle (CNF/CNT) reinforced FRP composites where there are limited publications. As specified, nanocomposites are newly introduced materials in the commercial industry as well as unlike properties due to their non-homogeneity structure; they can perform in a different way in drilling. In addition to that the identification of effects of cutting parameters, tool geometry, tool types and tool materials on the thrust force, torque and delamination in drilling of nanopolymer composites is compulsory for better understanding of machinability.

2. Drilling operations

2.1. Drilling on conventional FRP composites

There are several types of drilling operations on composite laminates but conventional drilling is the most frequently used drilling operation and other operations like vibration assisted drilling, high speed drilling are also used and provides superior quality of drilled holes as well as high efficiency [4]. The research on development of mechanical drilling on composite materials focuses mainly on drilling mechanics, drill tool geometry and material, tool types, delamination mechanisms and its preventing approaches, cutting force, and tool wear, etc. The composite damage called delamination is an inter-ply failure phenomenon induced by drilling, which is a very serious problem and has been recognized as an unexpected major damage when drilling composite laminates. The SEM images of delamination of GFRP and CFRP were as shown in Fig. 2.

Based on the review on experimental analysis, it is found that the input parameters such as cutting speed, feed and point angle of twist drill, tool types, tool materials, type of drilling operation directly affect the drilling induced delamination on FRP composites. The following observations are noticed from literature survey on drilling in composite laminates [32–35]:

Delamination at exit is more severe than at entry. Delamination tendency increased with the increase of twist drill point angle. Special drill bits (straight-flute drill bit, brad point drill bit and step drill bit) with larger feed rate shows without delamination compared with the twist drill bit. Carbide coated and diamond coated tools give up better results in terms of tool wear and tool life during drilling on composites. Generally, the minimum delamination defect on composite materials occurs at low feed rates with high cutting speeds.

In addition to the cutting parameters, tool geometry, tool types, etc., the work piece constituents, laminate orientation (0°/0°/0°/0°, 45°/45°/−45°/45°, 0°/45°/0°/45°, 45°/0°/45°/0°, 0°/0°/45°/−45° and 45°/−45°/0°/0°) also effect the delamination in drilling of composites [36,37]. Table 1 shows the detailed range of cutting conditions during drilling on CFRP and GFRP composite laminates.
2.2. Drilling on nanopolymer composites

As polymer nanocomposites are comparatively newly recognized materials, very few studies have been produced on the drilling on nanocomposites. As of the existing literature, limited details are available on the development of nanocomposites, property evaluation, drilling delamination, processing technologies and thermal damage in polymer nanocomposites drilling [38–42].

Li et al. [30] have used microwave curing process to prevent delamination and drilling ablation in drilling of carbon nanotube/carbon fiber reinforced epoxy composites. The revealed experimental results had given decreased drilling induced delamination of microwave cured nanocomposites and increased interlaminar fracture toughness upto 66% compared to normal cured composites. Baker et al. [43] have studied the drill tool coatings to minimize the wear resistance during drilling on nanocomposites. Paul et al. [44] have employed acoustic emission technique for on-line monitoring of drilling induced delamination during drilling on CNF reinforced nanocomposites laminates. The available literature on drilling of nanocomposite laminates and its drilling conditions are given in Table 2.

3. Need for monitoring drilling on composites

Commercial FRP composite materials have definite characteristics which impel their machining behavior. Consequently, the mechanisms involved while drilling composite materials are specifically different from those observed when drilling homogeneous materials such as metals. Work with commercial composites has recognized numerous parameters during the drilling operation that can influence the drilling factors and the material damage. Damage particularly related to drilling on composites primarily investigates delamination mechanisms, as this is the foremost and most important cause of component rejection as a result restricts the use of composite laminates for structural applications. Other defects induced by drilling comprises peel up and push out delaminations, circularity error, tiny cracks are likely to occur.

Drilling induced delamination was also caused by drill tool wear when drilling on FRP composites. The experimental results show that the critical thrust force is increased with growing wear which in turns increases the delamination. Drilling delamination of worn twist drill for lower feed rate is very low compared to sharp drills and these results are agreed with industrial experience [10].

4. Drilling factors

The input process parameters like cutting parameters, tool geometries, tool types and tool materials show the effect on thrust force, torque, tool wear, delamination, surface roughness etc. which are called output process parameters. So, it is necessary to select the proper process parameters for obtaining the best performance on the drilling operation i.e. best hole quality, which represents minimum damage of the machined components and satisfactory machined surface. Fig. 3 shows the schematic representation of drilling on composite laminates for the better understanding of drilling studies.

5. Cutting parameters

The cutting parameters such as cutting velocity and feed rate, tool geometry, tool types and tool materials have shown greater effect on the thrust force, torque and delamination while drilling conventional as well as nanopolymer composite laminates.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ply/sheet</th>
<th>References</th>
<th>Drilling conditions</th>
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<tbody>
<tr>
<td>CFRP laminates</td>
<td>UD-ply</td>
<td>Park et al. [69]; Bhatnagar et al. [70]; Lin and Chen [71]; Chen [72]; Piquet et al. [73].</td>
<td>Spindle speed: 800–1600 rpm Feed rate: 0.05–0.20 mm/rev Diameter (d): 4–6 mm Point angle (h): 90–118° Laminate thickness (T): 2–3 mm</td>
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<td></td>
<td>Woven ply</td>
<td>Gaitonde et al. [74]; Karnik et al. [75]; Faraz et al. [76]; Shyha et al. [77]; Lazar and Xiouchakia [63].</td>
<td>Spindle speed: 60–600 rpm Feed rate: 0.01–0.06 mm/rev Diameter (d): 6–9 mm Point angle (h): 85–130° Laminate thickness (T): 2–3 mm</td>
</tr>
<tr>
<td>GFRP laminates</td>
<td>UD-ply</td>
<td>Mathew et al. [78]; Ramkumar et al. [79,80]; Capello [81]; Rao et al. [82]; Mkaddem et al. [83]; Lasti et al. [94]; Kilickap [85].</td>
<td>Spindle speed: 375–1500 rpm Feed rate: 0.075–0.3 mm/rev Diameter (d): 6 mm Point angle (h): 90–118° Laminate thickness (T): 2–4 mm</td>
</tr>
<tr>
<td></td>
<td>Woven ply</td>
<td>Khashaba et al. [86,87]; Velayudham et al. [88,89]; Arul et al. [90,91]; Rubio et al. [92]; Isik and Ekici [10]</td>
<td>Spindle speed: 60–500 rpm Feed rate: 0.05–0.45 mm/rev Diameter (d): 6–10 mm Point angle (h): 90–118° Laminate thickness (T): 6–9 mm</td>
</tr>
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Table 1 – Available literature in drilling on FRP composite laminates.
5.1. Effect of cutting parameters on thrust force, torque and delamination

The drilling parameters such as spindle speed and feed rate highly influence the cutting forces and delamination in drilling of FRP as well as nanocomposites laminates. The cutting forces decrease with the higher cutting speed and increase with the escalating feed rate, drill size and fiber volume fractions. In drilling of carbon/epoxy composites the torque, thrust force and delamination factor depends directly on the feed rate and tool geometry [21,24].

Phadnis et al. [45] experimental study reported that low feed rates (<1500 mm/min) and high cutting speeds (>600 rpm) are the best cutting parameters for drilling on carbon/epoxy laminates. An exceeded experiment have been done on FRP drilling by varying the machining conditions to investigate the correlations between cutting forces, drilling delamination, tool wear, temperature and hole quality. In addition to the cutting parameters, the cutting edge of the drill tool has also generates some local feed cutting forces which indirectly influences the hole exit delamination on FRP composites [46,47]. Palanikumar et al. [48] experimental and analytical results indicated that the low feed rate and drill diameter leads to increase the thrust force, whereas the increase in the spindle speed does not show any disparity.

Bello et al. [49] have conducted a series of drilling experiments on advanced CNT hybrid composites at a spindle speed range of 725–1325 rpm for optimum cutting conditions. The spindle speed of 1015 rpm gives the lower thrust force and torque values. Tan et al. [50] have done some drilling experiments on hybrid carbon/glass nanocomposite laminates to optimize the cutting parameters. The experimental results and statistical analysis reveal that the second order regression model is suitable for prediction of drilling induced delamination and surface roughness responses. Paul et al. [44] have selected the cutting parameters range of 500–1500 rpm in spindle speed and 0.02–0.08 mm/rev in feed rate for minimum drilling induced delamination and surface roughness during drilling on CNF reinforced CFRP nanocomposite laminates. Specifically, the lower feed rate (0.02 mm/rev) and higher spindle speed (1500 rpm) gives the better thrust force and torque values.

Generally, statistical techniques such as ANOVA, regression analysis etc. were used to establish an empirical relationship between the drilling parameters (feed rate, spindle speed, drill diameter and fiber volume fraction) and cutting parameters. These techniques were found to be very effective in optimization of cutting parameters.
forces in drilling of FRP composites. Optimizing the machinability characteristics like feed rate and spindle speed on nanopolymer composite drilling was an essential task, to suppress the drilling defects, thrust force, surface roughness and tool life [51,52]. So, the cutting parameters such as cutting speed and feed are deeply influences the thrust force, torque and delamination during drilling on conventional/nanopolymer composite laminates. Gowda et al. [53] have employed Taguchi’s orthogonal array technique to optimize the cutting parameters in drilling on Si$_3$N$_4$ nanocomposite laminates, by varying input parameters like %volume of Si$_3$N$_4$ (0, 6, 10), speed (360, 490, 680 rpm) and feed rate (0.095, 0.19, 0.285 mm/rev). The output response variables like circularity error, surface roughness were tabulated through ANOVA table.

Therefore, in order to produce defect free holes, the process of drilling on nanopolymer composite laminates needs to be observed.

5.2. Effect of tool geometry on thrust force, torque and delamination

The drill tool geometries such as the drill diameter, point angle, helix angle, chisel edge, rake angle and web thickness have shown greater effect on the thrust force, torque and delamination while drilling FRP laminates [54–56]. The point angle of a drill tool highly affects the machining forces and drill whole quality (delamination, fraying, and burr formation) on drilling of CFRP composites. The increasing of point angles (155°, 175°, 178° and 185°) increases the feed force, drilling torque and delamination factor also [15]. Fig. 4 shows the delamination factor value for different drill tool geometries.

Guo et al. [9] have studied carbide twist drills of different diameters (3–8 mm), varying web thicknesses (0.5, 0.55, 0.7, and 1.1 mm) and preferred drill tool angles that provides the optimal cutting parameters and high-quality drilled holes.
on CFRP composite laminates. Based on simulated data, the thrust force and torque values generated by using 8 mm drill diameter are four times higher than that of 4 mm drill diameter and thrust force increases with the increase of point angle. The thrust force and torque values increases by 88% and 400% respectively as the web thickness increases from 0.5 to 1.1 mm. Eneyew and Ramulu [19] conducted some preliminary experiments on UD-CFRP composites using PCD tipped eight facet drill to find out the surface quality and material damage in drilling. During drilling of GFRP/Epoxy composites, the drill tool geometry and tool material highly influences the cutting forces and material damage. Four drills (EDP27199, A1141, A1163 and A1167A) with different drill geometries and materials and various cutting parameters were used to test the composite for defect free holes in drilling [57].

Velayudham and Krishnamurthy [58] have carried out a sequence of drilling experiments to study the influence of carbide drills with different point geometries on thrust force and delamination of polymeric composite laminates. Investigation results reveals that tripod drill performs better cutting forces compared to other drill geometries and the critical thrust force observed when feed rate was 0.1 mm/rev, above that there was a rapid increase in thrust results.

The drilling experiments using coated tungsten carbide drill (ratio drill) on Glass Fiber Reinforced Epoxy (GFRE) composite rods shows better machinability compared to regular twist drill. The new drill geometry called ratio drill was used to predict the machining parameters, flank wear, surface roughness and circularity errors [59]. Paul et al. [44] study reported that the conventional twist drill with 118° point angle and 6 mm drill diameter exhibits the lower thrust force and reduced delaminations in drilling of CFRP nano composite laminates. Sachse et al. [60] have used 10 mm diameter drill bit for drilling on PA6 nanocomposites under controlled environment for the evaluation of emission of particles.

So, the proper selection of cutting tool geometry and its nomenclature gives the enhanced cutting forces and minimum material damage in drilling of FRP as well as nanocomposites laminates.

5.3. Effect of tool types and tool materials on thrust force, torque and delamination

Different types of drills and drill materials have greater influence on the thrust force, torque and delamination. Drilling of GFRP composite laminates with distinct and conventional uncoated cemented carbide drills exhibits a complete analysis of push-out delamination and drilling load profiles.

Based on the experimental and analytical results, it was concluded that specialized drill tools reduced the drilling thrusts for the whole range of machining parameters compared to the conventional drills and also the magnitudes of push-out delamination damage were noticeable [61]. Adjacent to the twist drill, the effects of different types of drills such as core drill, step drill, saw drill and candle stick drill have exhibit a major impact on the critical thrust force and delamination. In case of a saw drill, the size of the delamination zone is dependent on the thrust force applied on the FRP composite laminate. At high thrust forces, the size of the delamination zone is equal to the drill diameter, which is the minimum possible delamination in case of a composite material. Also, when the diameter of the saw drill is considered to be zero, its behavior is analogous to twist drill with zero drill diameters or with infinite delamination zone. In case of a candle stick drill with zero circular load, i.e. no torsional load on the drill bit, the working is the same as that of a twist drill with a point load at the centerline of the drill. Also in cases where the drill centerline load is zero, this drill is analogous to saw drill. This is as the geometry of a saw drill does not accommodate for centerline loads [62–64]. Fig. 5 illustrates the thrust force variation related to the feed rate for different drill tools.

In addition to the standard drill tools, the newly micro coated tools such as PCD tools, CBN coated tools, diamond like coated tools coated tools, etc. were also used to acquire good surface finish of the drilled holes with less damage [65–67]. Paul et al. [44] have selected three different types of drills; namely, HSS drill, carbide tipped drill and solid carbide drill for the purpose of drilling on CNF reinforced CFRP nanocomposite laminates. The drilling defects called delamination, circularity error were minimized at entry as well as exit with solid carbide drill. Irfan et al. [68] have employed a special type of angle drill of 10 mm diameter in drilling of Polyamide 6- and Polypropylene-Silicon Composites for the estimation of release of nanoparticles.

In addition to the tool geometry, the tool types and tool materials also play a key role in drilling of FRP and nanocomposite laminates. The cutting forces, drilling delamination and other induced defects were reduced by the proper selection of drill tool types and materials.

6. Summary

Exceptional mechanical and physical properties like extraordinary tensile strength, modulus, good corrosion and chemical resistance, elevated adhesion and dynamic stability have encouraged the use of composites in a variety of applications. The mechanical drilling of nanopolymer composite
laminates differs extensively in many aspects from drilling of conventional composite laminates. The work exhibited here is an overview of mechanical drilling on FRP/nanopolymer composites laminates, mainly including drilling forces, drill tool geometry, drill tool types and materials, drilling-induced delamination and its inhibiting approaches, sub-surface deformation, surface roughness, and tool wear, etc. In addition to that optimization of machining parameters, drill tool geometry and tool types are also investigated.

The cutting force analysis in drilling of nanopolymer composite laminates by varying machining parameters; at a range of 500–1500 rpm in spindle speed and 0.01–0.10 mm/rev in feed rate [44] and varying drill sizes (5–10 mm diameter) are used in the literature for the better understanding of force generation, cutting mechanisms and drilling induced delamination [49,50,53].

Drilling of nanopolymer composite laminates imposes special requirements on the tool geometry and the wear mechanism of the drill bit [59,60]. In addition to uncoated HSS drill, a number of special coated drills such as carbide tipped drills, solid carbide drills and special type of angle drills are used for drilling of nanopolymer composite laminates to trim down delamination damage [44].

Therefore, in order to produce defect free holes and mechanical joining of composite structures, the process of drilling on FRP as well as nanopolymer composite laminates needs to be monitored.

REFERENCES


