Drilling on fiber reinforced polymer/nanopolymercomposite laminates: A review

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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 withcommercialcompositeshasidentifiednumerousparametersduringthedrillingoperation 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 Nano polymer composite laminates. Specifically, the influence of machining parameters, tool geometry, tool materials and tool types on the cutting force generation and delami-nationmechanisms.Basedonthecomprehensiveliteraturesurveyfromthepastfewyears, itisnoticedthatlimitedresearchhasbeenmadeandpublishedconcerningtonanopolymer compositedrillingandhasledtoapartialunderstandingofthecuttingmechanicsactivated inmachining/drilling.Somekeycontributionssuchasexperimentalandnumericalstudies areurgentlydemandedtoaddressaccuratelyvariousprojectionsindrillingofnano-particle reinforced FRP composite laminates.

Keywords:
Drilling, FRPlaminates, Nanopolymer composite laminates Cuttingforces, Delamination

1. Introduction

Composite materials are made-up of least two distinct intended materials which together improve product perfor- mance and lower manufacturing cost [1]. Many materials, continuously designated by other terms are also consid-ered composites including clad, coated metal tools, etc. [2]. Nowadays, FRP composite laminates are the materials of option for many engineering applications; namely, automo- tiveparts,sportinggoods,aerospacecomponents,consumer goods,marineandoilindustries,duetotheirspecialphysical 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 Poly-mer(CFRP)compositelaminatesandnanopolymercomposite 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].

Themostrecentcommercialaircraftdesignsproposeareductioninweightabout50%byreplacingtheprimarystructuralcomponentswithfabricatednanopolymercompos-ites.Usinglightweightandelevatedstrengthcompositesare essential in order to achieve the reduced fuel consumption andbetterpassengercomfortgoalsofthesefuturecom- mercial aircraft design innovations [5]. In generally, all the composite materials will undergo some machining processes intheirfabricationprocedureoritsspecificengineeringappli-cation.Withtheconcernofthecurrentindustry,drillingisthe most frequently used hole making operation for assembly of structuresorcomponents.Variousindustries;suchasauto- motive, aerospace, marine and oil industries, have already started the utilization of nanocomposites in their structures. Thecompositedamagecalleddelaminationisaninter- 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 thenon-homogeneity,multi-phasestructureandanisotropic nature of the composites lead to an inter-ply failure during drilling[7].Withthatreason,about60%ofthedrilledholeson compositesarerejectedattheinitialstageonly[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 spallingare few examples of sub-surface deformations [9,10]. So, in order to improve the product performance and structural integrityofmachinedholes,thematerialdefectssuchassub-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 structuralintegrityisalsostronglydependingonfibermatrix interfacial interactions, fiber orientations, cutting directions and tool wear.

Zhangetal.[13]haveinvestigatedthespalling,fuzzingexit sub-surface deformation defects during drilling of unidirect- ional 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 isusuallyaseveredamageanditisbiggerforUD-CFRPlami- nate as compared to multi-directional CFRP laminate under the same drilling conditions. Khashaba et al. [14]reported that catastrophic shear failure of the composite layers has been done due to the higher feed rates and cutting temper- aturesresultingpoorsurfaceintegrity,lowerbearingstrength ofmachinedholeswhileGFRPcompositedrilling.Heisel et al. [15]investigated the influence of point angle, cutting parameters on cutting forces and drill hole quality i.e. fry-ing,burrformationanddelaminationhavebeeninvestigated while drilling of CFRP laminates. The increase in point angle increasescuttingtemperatureresultingfryingofepoxymatrix with poor quality drilled hole and severe burr formation.

Brinksmeier et al. [16]tried three (Alu- minum/CFRP/Titanium) different materials to investigate thesurfacequalityofboreholesafterorbitalandconventional drilling processes. Compared to the conventional drilling process,orbitaldrillinggivesthefinestboreholesurfaceswith tiny matrix cracks and without fiber breakage under lower cuttingtemperaturesandlargecuttingspeeds.Aruletal.[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 delam- ination, 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 upto 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 result- ing 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 con- sidered 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 struc- tural 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 lay- out 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 com- posite (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 com- posites.

StarostandNjuguna[28]havepreparedareporton the effect of mechanical drilling on nanocompositeslami- nates. The effect and influence of various drilling param- eters on delamination and nano-sized particles have been analyzed. Davis et al. [29]reported that amino func- tionalized 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 normalconventionalthermalcuredcompositewithoutMWC- NTs [30]. The fiber reinforced composite laminates thermal conductivity has been increased drastically with the addi- tion of nano-filler/micro-filler; namely, MWCNTs, DWCNTs [31].

Thepresentworkprovidesadetailedreviewofdrilling on FRP as well as nanopolymer reinforced composite lam- inates. A huge research work has been done on drilling of conventional FRP composites, but there is a need to con- tinueresearchinthefieldofnanocompositedrillingespecially nano-particle (CNF/CNT) reinforced FRP composites where there are limited publications. As specified, nanocomposites arenewlyintroducedmaterialsinthecommercialindustryas wellasunlikepropertiesduetotheirnon-homogeneitystruc- ture;theycanperforminadifferentwayindrilling.Inaddition tothattheidentificationofeffectsofcuttingparameters,tool geometry, tool types and tool materials on the thrust force, torque and delamination in drilling of nanopolymer compos- itesiscompulsoryforbetterunderstandingofmachinability.

1. Drillingoperations

1.1. DrillingonconventionalFRPcomposites

There are several types of drilling operations on compositelaminatesbutconventionaldrillingisthemostfrequentlyused 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 com- posite materials focuses mainly on drilling mechanics, drill tool geometry and material, tool types, delamination mecha- nisms 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 unex- pectedmajordamagewhendrillingcompositelaminates.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 delam- ination on FRP composites. The following observations are noticed from literature survey on drilling in composite lam- inates[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 andstepdrillbit)withlargerfeedrateshowswithoutdelam- ination 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 materialsoccursatlowfeedrateswithhighcutting speeds.

In addition to the cutting parameters, tool geometry, tool types, etc., the work piece constituents, laminate orienta-tion (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 1shows the detailed rangeofcuttingconditionsduringdrillingonCFRPandGFRP compositelaminates.

1.2. *Drillingonnanopolymercomposites*

As polymer nanocomposites are comparatively newly rec- ognized materials, very few studies have been produced on the drilling on nanocomposites. As of the existing literature, limiteddetailsareavailableonthedevelopmentofnanocom-
posites,propertyevaluation,drillingdelamination,processing technologies and thermal damage in polymer nanocompos- ites drilling [38–42].

Li et al. [30]have used microwave curing process to prevent delamination and drilling ablation in drilling of car- bonnanotube/carbonfiberreinforcedepoxycomposites.The revealed experimental results had given decreased drilling induced delamination of microwave cured nanocompositesand increased interlaminar fracture toughness upto 66% com- pared to normal cured composites. Baker et al. [43]have studied the drill tool coatings to minimize the wear resis- tanceduringdrillingonnanocomposites.Pauletal.[44]have employedacousticemissiontechniqueforon-linemonitoring of drilling induced delamination during drilling on CNF rein- forced nanocomposites laminates. The availed literature on drillingofnanocompositelaminatesanditsdrillingconditions are given in Table 2.

2. Needformonitoringdrillingon composites

CommercialFRPcompositematerialshavedefinitecharacter- istics which impel their machining behavior. Consequently, the mechanisms involved while drilling composite mate-rials are specifically different from those observed when drilling homogeneous materials such as metals. Work with commercial composites has recognized numerous param- eters during the drilling operation that can influence the drilling factors and the material damage. Damage particu-larlyrelatedtodrillingoncompositesprimarilyinvestigatesdelamination 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. Otherdefectsinducedbydrillingcomprisespeelupandpush 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 experimen- tal results show that the critical thrust force is increased withgrowingwearwhichinturnsincreasesthedelamination. Drilling delamination of worn twist drill for lower feed rate is verylowcomparedtosharpdrillsandtheseresultsareagreed with industrial experience [10].

3. Drillingfactors

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 rough-nessetc.whicharecalledoutputprocessparameters.So, it is necessary to select the proper process

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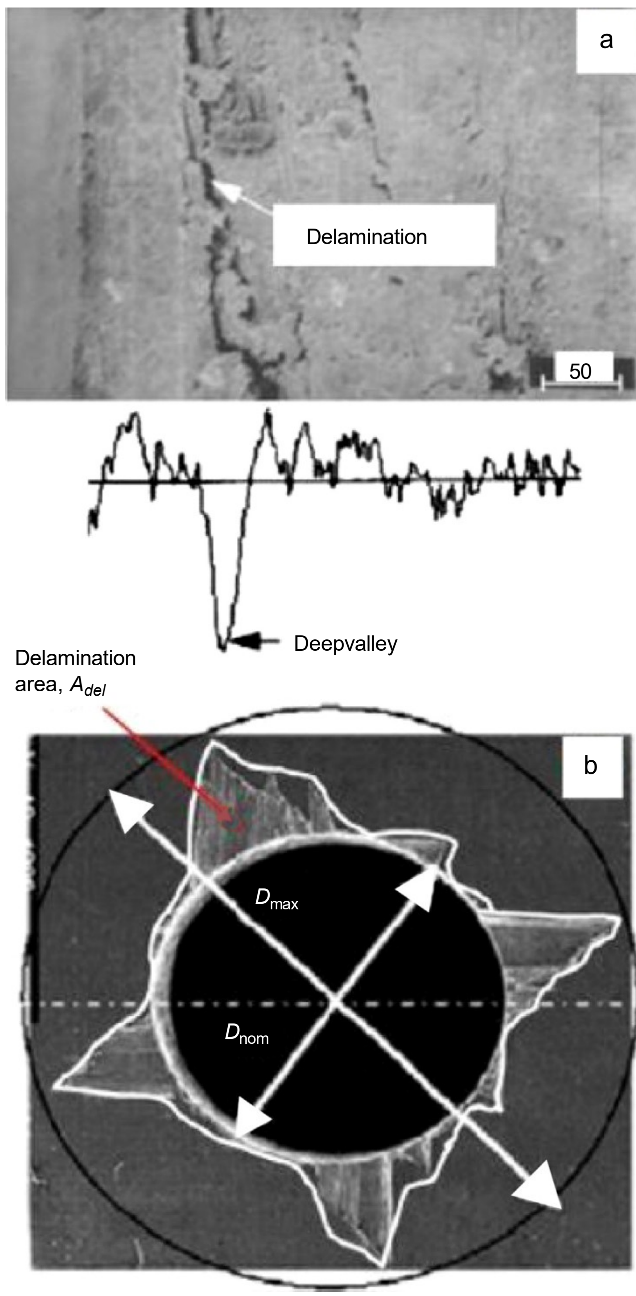
parameters for obtainingthebestperformanceonthedrillingoperation
i.e. best hole quality, which represents minimum damage of the machined components and satisfactory machined sur- face.Fig.3showstheschematicrepresentationofdrillingon composite laminates for the better understanding of drilling studies.

The cutting parameters such as cutting velocity and feed rate,toolgeometry,tooltypesandtoolmaterialshaveshown greater effect on the thrust force, torque and delamination whiledrillingconventionalaswellasnanopolymercomposite laminates.



3.1. *Effect of cutting parameters on thrust force, torque and delamination*

Thedrillingparameterssuchasspindlespeedandfeed 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,thrustforceanddelaminationfactordependsdirectly on the feed rate and tool geometry [21,24].

Phadnis et al. [45]experimental study reported that low feed rates (<1500mm/min) and high cutting speeds (>600rpm) 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 delamina- tion,toolwear,temperatureandholequality.Inaddition to the cutting parameters, the cutting edge of the drill tool has also generates some local feed cutting forces which indi- rectlyinfluencestheholeexitdelaminationonFRPcomposites [46,47].Palanikumar et al. [48]experimental and analytical results indicated that the low feed rate and drill diameter leadstoincreasethethrustforce,whereastheincreaseinthe spindle speed does not show any disparity.

Bello et al. [49]have conducted a series of drilling experi- mentsonadvancedCNThybridcompositesataspindlespeed rangeof 725–1325rpm for optimum cutting conditions. The spindle speed of 1015rpm gives the lower thrust force and torque values. Tan et al. [50]have done some drilling exper- iments on hybrid carbon/glass nanocomposite laminates to optimize the cutting parameters. The experimental results andstatisticalanalysisrevealthatthesecondorderregression model is suitable for prediction of drilling induced delami- nationandsurfaceroughnessresponses.Pauletal.[44]have selected the cutting parameters range of 500–1500rpm in spin- dle speed and 0.02–0.08mm/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 (0.02mm/rev) and higher spin- dlespeed (1500rpm) gives the better thrust force and torque values.

Generally, statistical techniques such as ANOVA, regression analysis etc. were used to establish an empirical relation- ship between the drilling parameters (feed rate, spindle speed,drilldiameterandfibervolumefraction)andcutting

forces in drilling of FRP composites. Optimizing the machin- ability characteristics like feed rate and spindle speed on nanoploymer composite drilling was an essential task, to suppress the drilling defects, thrust force, surface rough- ness and tool life [51,52]. So, the cutting parameters suchas cutting speed and feed are deeply influences the thrust force, torque and delamination during drilling on conven- tional/nanopolymer composite laminates. Gowda et al. [53]have employed Taguchi's orthogonal array technique to optimizethecuttingparametersindrillingonSi_3N_4nanocompositelaminates,byvaryinginputparameterslike%volumeof Si_3N_4 (0, 6, 10), speed (360, 490,680rpm) and feed rate (0.095, 0.19, 0.285mm/rev). The output response variables like circu-larityerror,surfaceroughnessweretabulatedthroughANOVA table.

Therefore,inordertoproducedefectfreeholes,theprocess of drilling on nanopolymer composite laminates needs to be observed.

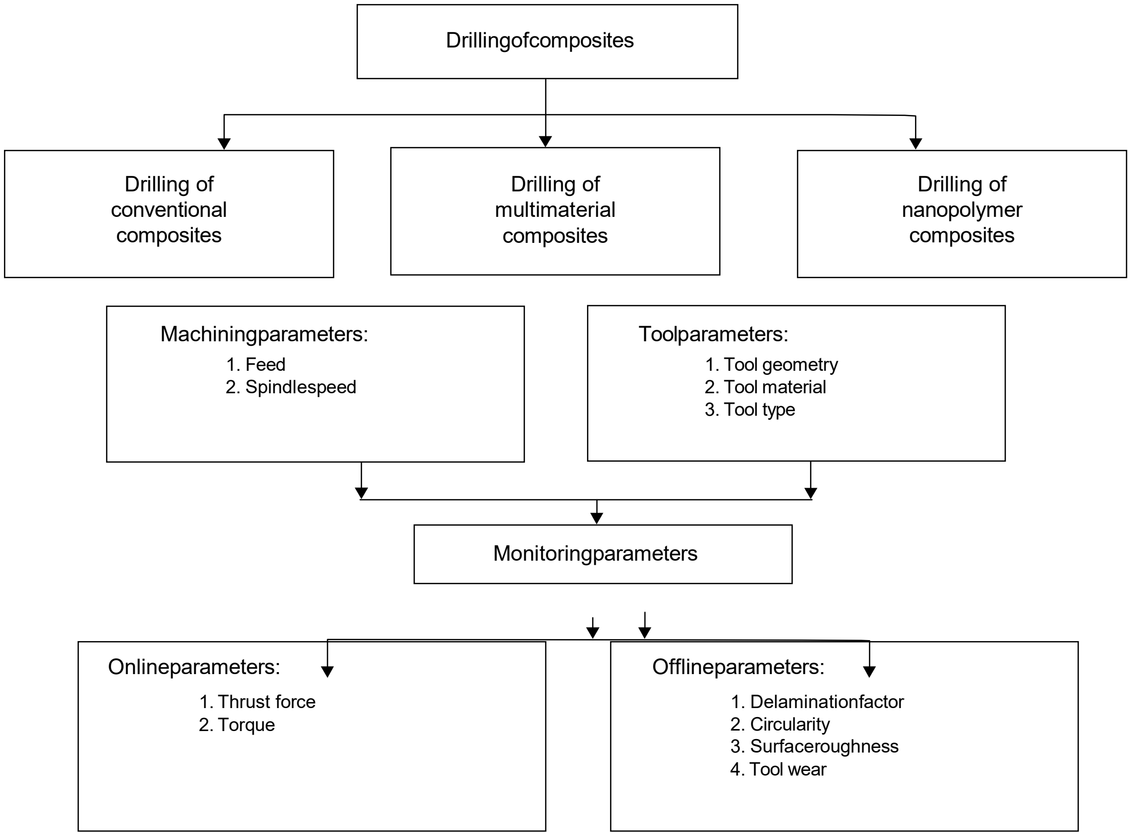


Fig.3–Theschematicrepresentationofdrillingofcompositematerials.

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

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. 4shows the delamination factor value for different drill tool geometries.

Guo et al. [9]have studied carbide twist drills of differ-entdiameters (3–8mm), varying web thicknesses (0.5, 0.55, 0.7,and1.1mm)andpreferreddrilltoolanglesthatprovides theoptimalcuttingparametersandhigh-qualitydrilledholes. The drill tool geometries such as the drill diameter, point angle, helix angle, chisel edge, rake angle and web thickness haveshowngreatereffectonthethrustforce,torqueand bidedrillswithdifferentpointgeometriesonthrustforceand delaminationofpolymericcompositelaminates.Investigation resultsrevealsthattripoddrillperformsbettercuttingforces comparedtootherdrillgeometriesandthecriticalthrustforce observed when feed rate was 0.1mm/rev, above that there was a rapid increase in thrust results.

The drilling experiments using coated tungsten carbide drill(ratiodrill)onGlassFiberReinforcedEpoxy(GFRE)com- posite rods shows better machinability compared to regular twist drill. The new drill geometry called ratio drill was used topredictthemachiningparameters,flankwear,surface roughness and circularity errors [59]. Paul et al. [44]study reportedthattheconventionaltwistdrillwith118°pointangle and6mmdrilldiameterexhibitsthelowerthrustforceand reduceddelaminations in drilling of CFRP nano composite laminates.Sachse et al. [60]have used 10mm diameter drill bitfordrillingonPA6nanocompositesundercontrolledenvi- ronment for the evaluating of emission of particles.

So,theproperselectionofcuttingtoolgeometryand its nomenclature gives the enhanced cutting forces and minimum material damage in drilling of FRP as well as nanocompositeslaminates.

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

Differenttypesofdrillsanddrillmaterialshavegreaterinflu- ence on the thrust force, torque and delamination. Drillingof GFRP composite laminates with distinct and conventional uncoatedcementedcarbidedrillsexhibitsacompleteanalysis 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 com- pared to the conventional drills and also the magnitudes of push-outdelaminationdamagewerenoticeable[61].Adjacent tothetwistdrill,theeffectsofdifferenttypesofdrillssuchas core drill, step drill, saw drill and candle stick drill have exhibitamajorimpactonthecriticalthrustforceanddelamination. 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 zoneisequaltothedrilldiameter,whichistheminimum possible delamination in case of a composite material. Also, whenthediameterofthesawdrillisconsideredtobezero,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,theworkingisthesameasthatofatwistdrillwithapoint load at the centerline of the drill. Also in cases where thedrillcenterlineloadiszero,thisdrillisanalogoustosawdrill. This is as the geometry of a saw drill does not accommodate forcenterlineloads[62–64].Fig.5illustratesthethrustforce 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 thepurposeofdrillingonCNFreinforcedCFRPnanocompositelaminates. The drilling defects called delamination, circular- ity error were minimized at entry as well as exit with solid carbidedrill.Irfanetal.[68]haveemployedaspecialtype of angle drill of 10mm 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 materialsalsoplayakeyroleindrillingofFRPandnanocom-positelaminates.Thecuttingforces,drillingdelaminationand otherinduceddefectswerereducedbytheproperselectionof drill tool types and materials.

4. Summary

Exceptionalmechanicalandphysicalpropertieslikeextraordi-narytensilestrength,modulus,goodcorrosionandchemical resistance, elevated adhesion and dynamic stability have encouraged the use of composites in a variety of applica-tions.Themechanicaldrillingofnanopolymercomposite laminatesdiffersextensivelyinmanyaspectsfromdrillingof conventional composite laminates. The work exhibited hereis an overview of mechanical drilling on FRP/nanopolymer composites laminates, mainly including drilling forces, drill toolgeometry,drilltooltypesandmaterials,drilling-induced delamination and its inhibiting approaches, sub-surface deformation, surface roughness, and tool wear, etc. In addi-tion to that optimization of machining parameters, drill tool geometry and tool types are also investigated.

Thecuttingforceanalysisindrillingofnanopolymercom-positelaminatesbyvaryingmachiningparameters;atarange of500–1500rpminspindlespeedand0.01–0.10mm/revinfeed rate[44]and varying drill sizes (5–10mm diameter) are used intheliteratureforthebetterunderstandingofforcegenera- tion, cutting mechanisms and drilling induced delamination [49,50,53].

Drilling of nanopolymer composite laminates imposes specialrequirementsonthetoolgeometryandthewearmech- anism of the drill bit [59,60]. In addition to uncoated HSS drill, anumberofspecialcoateddrillssuchascarbidetippeddrills, solid carbide drills and special type of angle drills are used fordrillingofnanopolymercompositelaminatestotrimdown 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.

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