Accepted Manuscript

Review

A review on finite element method for machining of composite materials

Nagaraja Shetty, S.M. Shahabaz, S.S. Sharma, S. Divakara Shetty

PII: S0263-8223(16)30277-X
DOI: http://dx.doi.org/10.1016/j.compstruct.2017.06.012
Reference: COST 8599

To appear in: *Composite Structures*

Received Date: 12 April 2016
Revised Date: 5 May 2017
Accepted Date: 6 June 2017

A review on finite element method for machining of composite materials

Nagaraja Shetty[a, 1], Shahabaz S. M.[b, *], S. S. Sharma[a, 1], Divakara Shetty S.[a, 1]

[a]*Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal University, Manipal 576 104, India*

E-mail Addresses: hosadunagaraj@gmail.com; ss.sharma@manipal.edu; shetty.divakar@manipal.edu

[b]*Department of Mechanical Engineering, Manipal University Jaipur, Jaipur 303007, India*

Tel.: +919611822768, +917204572277; E-mail Address: shazz2577@gmail.com

*Corresponding Author

Tel.: +919611822768; E-mail Address: shazz2577@gmail.com

A review on finite element method for machining of composite materials

ABSTRACT

Composite materials are being extensively used in aerospace and automotive industry. The demand for composite materials is increasing due to their superior properties such as high strength to weight ratio, good corrosion resistance and high stiffness. Post machining operations such as drilling, orthogonal cutting, turning are necessary for composite materials to meet the dimensional and functional requirements. Drilling is a major process in manufacturing of holes, required for assembling the components in industrial applications. Drilling of holes in composites leads to a drilling-induced damage called delamination. The researchers have tried to reduce the drilling-induced damage by minimizing the operating variables and tool design. However, the research on delamination analysis using finite element method (FEM) is limited. This paper provides a comprehensive literature review on machining of composites which mainly focuses on conventional methods like turning, milling, trimming and drilling and also on simulation methods including discrete element method and finite element method. A brief and in depth review for drilling of composites using finite element method is delivered, which provides a knowledge on damage of the composites caused during drilling and orthogonal cutting. Comparison of experimental and simulation results shows an overall vision on machining of CFRP using FEM tools.

Keywords: Composite laminates, Drilling, Orthogonal cutting, Delamination, Discrete element method, Finite element method.

1. Introduction

During the past decades the demand for composite laminates such as carbon fibre reinforced polymer (CFRP), glass fibre reinforced polymer (GFRP), fibre metal composite laminates (FMLs), metal matrix composites (MMCs) and ceramic matrix composites (CMCs) [1] is increasing due to their superior mechanical properties such as high strength to weight ratio, high stiffness to weight ratios, high damping capacity, good dimensional stability and good corrosion and fatigue resistances [2-6]. Composite materials are formed by the combination of two or more materials to achieve properties that are superior to those of its constituents. They are abundantly used in various manufacturing sectors such as aircraft, spacecraft, automobile, marine, chemical processing equipment and sporting goods.

Due to their high advantages the metallic materials are getting replaced by composite materials. As a significance of broadening range of applications of fibre composites, the machining of these materials has become an important area for research. Composite materials are fabricated to their near net shape by hand lay-up, autoclave moulding, compression moulding, pultrusion and filament winding processes [7-12]. Turning, milling and drilling are the important post machining operations which are carried out to meet the surface quality and dimensional tolerances [13]. 40% of metal removal is done by drilling operation in aerospace industry [14]. As composite materials are heterogeneous and anisotropic in nature, during machining material damage occurs such as delamination, hole shrinkage and fibre pull out [15,16].

Delamination is the most critical damage occurring during machining which results in heavy losses in industries [17]. Delamination reduces the structural integrity of the material which causes long term performance deterioration of the composite structures [18]. Laser cutting, water-jet cutting, ultrasonic cutting, electro discharge machining are some of the different non-traditional machining process which are performed in making holes in composite materials [19]. A lot of research has been done to investigate and develop optimum tool point geometry for drilling holes in composite materials, but the work done using finite element model for analyzing drilling induced delamination is limited [20]. This paper provides a complete review on the different simulation methods performed on milling, drilling and orthogonal cutting. Brief description on finite element method and discrete element is also provided. A few articles explain the comparison of finite element and experimental methods. Process parameters which influence the surface roughness and delamination during drilling and orthogonal cutting using finite element method and discrete element method have also been discussed.

2. Machining of composites

The machining of composite materials not only depends on the properties of fibre and matrix composition, it also depends on the fibre orientation and volume fraction. Carbon fibre reinforced polymer (CFRP), fibre reinforced plastics (FRPs), glass fibre reinforced polymer (GFRP), metal matrix composites (MMCs), fibre metal composite laminates (FMLs), ceramic matrix composites (CMCs) and natural fibres show similar material properties. They draw research interests from the machining point of view. More number of research work has been done in machining point of view, which includes conventional processes like turning, milling, drilling [27,29,38,40,126-128] and also the unconventional processes such as laser ablation, water-jet cutting [42,48,50,52,132,133]. This section provides a brief description on different conventional processes and also how the process parameters effects the cutting performance and the surface quality on machined area is discussed.

2.1 Conventional process

Composite materials are produced to their near net shapes during manufacturing, but these materials require machining to achieve dimensional accuracy and to produce holes required to attain assemblies. Machining may be performed before or after the curing of material. Machining of composites is carried out by both conventional and non-conventional methods. Conventional processes which are frequently used are turning, milling, drilling, grinding, trimming, countersinking and sawing. Conventional process is carried out by selecting proper tool geometry, cutting speed and feed rate. Table 1, provides different machining operations performed on composite laminates by number of researchers. In this section a brief description of turning, milling, trimming and drilling are explained below.

2.1.1 Turning

In cylindrical components turning operation is carried out to achieve dimensional tolerances. Different tool materials which are used in turning of composite materials are cemented carbides, cubic boron nitride (CBN) and polycrystalline diamond (PCD) [22-24]. Most of the research work emphasizes the challenge to minimize the surface roughness as surface quality depends on the feed rate, depth of cut, cutting speed and also on tool properties such as geometry, material [25, 26].

Face turning operation was performed on CFRP by Santhanakrishnan et al. [27]. Cutting phenomena and tools performance was studied experimentally using sintered carbide tool. Tool performance was evaluated on following parameters such as tool wear, surface roughness and chip formation. The results indicated that uniform surface quality can be obtained using sintered carbide tool during machining. Experiment was carried out by using fuzzy logic algorithms to study the surface roughness in CFRP material by Rajasekaran et al. [25]. Surface roughness was studied based on parameters like feed rate, cutting speed and depth of cut. Tool material used for the study was made of cubic boron nitride (CBN). Conclusion was made that, above all of the parameters mentioned above feed rate had more impact on surface roughness of the material. Surface roughness was determined by Palanikumar et al. [28] using Taguchi and response surface methodologies. The results showed that, high cutting speeds, high depth of cut and low feed rates are the factors that can give a good surface finish during machining of the material. Increase in feed rate increases surface roughness, while cutting speed and depth of cut does not effect the surface roughness was proposed by Lee [29].

2.1.2 Milling and trimming

Milling and trimming operation, as shown in Fig .1(a, c) [21] are used as a material removal process in machining of composites. Trimming operation is carried out in composite materials, to achieve contour shape accuracy. Machining of complex shapes and a high surface finish can be obtained during milling operation [30-32]. High quality surface of composite material depends on the factors such as feed rate, cutting speed, tool nose radius and tool wear [33-36]. Surface roughness of the material increases with increase in feed rate and as the cutting speed increases surface finish decreases. Delamination and burr formation are formed during milling. The main cause behind the material damage is due to the complex interaction which occurs between the ends of the mill and the composite laminate during machining. Accurate prediction of thrust force and axial cutting force are the key factors which can reduce the above mentioned material damage during milling [37]. Denkena et al. [38] proposed helical milling to reduce the delamination and burr formation while machining the metal matrix composites. If surface finishing is to be considered, different process parameters such as axial and tangential feed rate, cutting speed are found to be effective [38,39]. During the investigation of end milling operation on silicon carbide particle reinforced with aluminum alloy composites by Suresh kumar et al.[40], they found that the surface induced damage obtained for aluminum composite was less when compared to that of the milling operation of aluminum metal. Cutting speed, depth of cut and feed rate were considered as the cutting parameters for end milling operation. Influence of feed rate was more compared to that of cutting speed on surface roughness of the composite material during machining operation.

2.1.3 Drilling

Drilling as shown in Fig. 1(b) plays an important machining operation for making riveted or bolted assemblies in CFRP components in industries [41]. Numerous non-traditional machining operations such as laser machining [42-46,132,133], abrasive water jet machining [47-49] and electrical discharge machining [50-54] have been practiced for developing holes in composite laminates. Several researchers have conducted various analytical as well as experimental investigations to study the behaviour of delamination during drilling of composite laminates. Numerous conventional drilling processes using special drill bits such as straight flute drill [55-59], step drill [10,60-66], core drill [65,67,68], step core drill [10,60,69], saw drill [10,70], candlestick drill [10], multi faced drill [71], split drill [72], grinding drilling, vibration assisted twist drilling and high speed drilling have been performed by many researchers [73-76] in order to study the effect of different process parameters causing the delamination in composite materials. The problems which occur during drilling of composite laminates are surface delamination such as peel-up delamination Fig. 2(a) [82], push-out delamination Fig. 2(b) [82] and excessive surface roughness of the hole [15, 77-82]. Fig. 3 [77] shows different parameters that have to be optimized during drilling of composite materials.

Bhattacharya et al. [83] examined that the quality of drilled surface depends on the tool geometry, drilling parameters and tool material. A special non chisel edge and straight flutes drill was developed by Piquet [55] with a zero clearance chamfer to improve the drill quality in composites. Tsao and Chiu [60] conducted an experiment to minimize the thrust force during drilling of CFRP laminates by using compound core special drills. Compound core special drills are the drill composed of the outer drill which is core drill and inner drill is the twist drill, saw drill and candlestick drill as shown in Fig. 4 [60]. Their conclusion was that, the thrust force in drilling of CFRP can be reduced by selecting the proper tools and drilling parameters. Cutting speed ratio, feed rate and inner drill type are the most important variables which influence the thrust force. Compound core special drills were advantageous as lower thrust force, lower delamination, lower chip clogging and higher chip removal was obtained during the experiment.

Hocheng and Tsao [10] investigated delamination by using different types of drills, that is twist drill, saw drill, candle stick drill and step drill. The experiment were conducted for the spindle speed of 900 and 1000 rpm and the feed rate applied were 0.003 to 0.0133 mm/rev. Ultrasonic C-scan technique was used to determine the drilling induced delamination, produced by various drills. A correlation between drilling thrust force and delamination was developed. Error was determined by comparing the theoretical and experimental results, by calculating critical thrust force. The conclusion was made that, core drill, candle stick drill, saw drill and step drill can be operated at larger feed rate without causing any delamination as compared to twist drill, which has highest influence on delamination at higher feed rates.

Palanikumar et al. [11] investigated delamination in drilling of GFRP composites. The experiment was carried out by using high speed steel and 4 flute cutter. Empirical models were developed to study the effect of delamination during drilling. Analysis of variance (ANOVA) and regression analysis was used for analyzing the experiment. By Taguchi's analysis, signal to noise ratio of delamination factor (F_d) was calculated using Eq. (1) which is defined by the ratio of maximum diameter (D_{max}) of damaged region to the nominal hole diameter (D_{nom}) and it was found that delamination increased as the feed rate increases for both cutting tools.

$$F_d = \frac{D_{max}}{D_{nom}} \tag{1}$$

Further analysis was done using ANOVA for same signal to noise ratio of delamination factor and the results indicated that delamination factor was affected by feed rate only. Four flute end mill cutter showed better results compared to twist drill during their investigation.

Tsao [70] studied the effect on thrust force and delamination by using core-saw drill during drilling of CFRP laminates. Taguchi’s method which includes the combination of experiment design theory and quality loss function concept was applied for the analysis. After analysing, the experimental results displayed core-saw drill being effective than the normal core drill. Spindle speed and feed rate influenced more for the thrust force and delamination of composite material.

Thrust force plays an essential role during drilling causing delamination, higher the thrust force higher will be the delamination, lower the thrust force lower will be the delamination [129-131]. In order to resolve this problem Tsao et al. [84] did an experimental research on drilling of composite materials by applying active back up force to reduce delamination. They applied an adjustable active backup force rather than passive backing plate to counter balance the push out delamination caused by the drilling thrust force. They stated that by applying active backup force, delamination reduced by 60-80% at higher feed rates. And also when the backup force was applied more close to the drill bit, there was more minimization of delamination.

Won and Dharan [85] in their work exhibited how the thrust force was affected by the chisel edge during drilling of composite laminates. The experiment was conducted with and without pre drilling of pilot hole in the laminates. The results showed that the thrust force was reduced when drilled using pilot hole and the chisel edge contributed more to the total thrust during drilling of composite laminate.

Sonbaty et al. [86] studied the various factors which effect during the machining of GFRP composites. They concluded that by increasing the cutting speed, torque and force decreased which in turn enhanced the surface roughness of the material. And also by increasing the feed rate, thrust force increased which led to the slight improvement in surface roughness of the composite material. Enemouh et al. [87] developed a method in which Taguchi's method and multi objective optimization criterion were combined in optimum drilling condition to obtain a delamination-free drilling in composite laminates.

Hamzeh et al. [88] investigated on how the machining parameters and tool geometry, effects the machinability of drilling in carbon fibre reinforced thermoset laminates. Cutting speed, feed rate and tool point angle were the process parameters which were considered through the experiment. The conclusion obtained was, by increasing cutting speed and at lower feed rate better surface finish was produced and also lower thrust force were obtained. Delamination factor increased with increasing feed rate and with increase in spindle speed and tool point angle, delamination factor was decreased.

3. Simulation of composites

During machining of composite laminates there is a continuous contact between the tool and the workpiece due to which fast tool wear and poor surface finish is obtained [134,135]. This leads to high costs and challenges in machining of composite materials. To prevent these drawbacks an alternative solution that is numerical simulations have been developed. Finite element method (FEM) and discrete element method (DEM) are the two different types of numerical simulation methods. Although there has been lots of research on drilling induced delamination by experimental methods, FEM method applied and analyzed to the same has been limited. Table 2 provides knowledge on number of researchers, who worked on different machining operations with the application of finite element method. In this section, work done by various researchers on orthogonal cutting and drilling induced delamination by using finite element method and discrete element method has been briefly introduced.

3.1 Discrete element method (DEM)

Cundall and Strack [89] were the first to introduce the discrete element method in the study of behaviour of rock. Discrete element method is a simulation process which is widely used in the study of material behaviour. It establishes a relationship and validation for particulate materials such as soil, rock and ceramics with the particle properties, size and shape [90-92]. This method is very useful in order to understand the granular materials. Various algorithms are developed in this method for different dynamic processes. Many researchers [93-95] have been applying this method as it delivers a clear picture of material behavior during different process and it can also be combined and used with other numerical methods to solve complex problems. Yasir et al. [96] investigated on, how the transverse tension occurs in uni-directional fibre reinforced polymer using discrete element method.

Orthogonal cutting was performed by using DEM technique on fibre orientations of 0˚, 90, 45˚, -45˚ by Iliscu et al [97]. Uni-directional CFRP was used as work material and carbide tool was used for the experimentation. An algorithm was developed to obtain the particle speed and particle position. Two time scales were used, (a) time for step of cut, (b) time linked for oscillation. During the experiment it was found that, for 0˚ fibre orientation high compression, bending and fibre pulling was observed as shown in Fig. 5(a). Fracture of mode I and mode II type was observed in the direction of the tool due to buckling during chip formation. For 90˚orientation mode I type fracture was noted and multi cracking was observed in the material as shown in Fig. 5(b). Fibre stretching and shearing was observed during chip formation in 45˚ fibre orientation as shown in Fig. 5(c). Highest tool wear occurred in this orientation and the reason for the tool wear was due to the small chips obtained during machining. In -45˚ fibre orientation fibre pull out was observed due to shearing of the material which led to the rupture of the matrix as shown in Fig. 5(d). But the tool wear observed was very low and surface finish obtained was comparatively poor to other fibre orientations. Simulated results of cutting force for fibre orientation 0˚ and 45˚ were found to be correspondingly matching with the experimental results whereas for -45˚ and 90˚ cutting force of simulation results was higher compared to the experimental ones. Similarly feed force gave a contrary result when compared to that of the cutting force. During comparison in experimental and DEM valuation, it was found that the resulting cutting force and feed force obtained were found to be in a good agreement.

3.2 Finite element method (FEM)

The different types of FEM modeling approaches include (a) macro-mechanical approach [12,98,101-103,119], (b) micro-mechanical approach [99,100,103] and (c) macro-micro combined approach [12,104]. The composite material is considered to be equivalent homogeneous material in case of macro mechanical approach, this is done to reduce the difficulty in machining simulation but the results obtained will be less accurate.

An experiment on finite element modeling of uni-directional CFRP was done by Rao et al. [98]. 3D macro-mechanical approach was considered. Different range of fibre orientations, depth of cuts and different rake angles were used for the experiment. The results showed that the thrust force and chip formation predicted by finite element simulations matched well with the experimental results. The reinforced fibres and matrix materials of FRP was modeled separately in micro-mechanical approach, due to which accurate predictions can be carried out and it also helps to investigate and analyze the local effect, which is a drawback in macro-mechanical approach. Micro-mechanical approach is complex and the computational cost is high as compared to that of macro-mechanical approach. Macro-micro approach is the combination of macro-mechanical approach and micro-mechanical approach.

Cutting of carbon fibre reinforced plastic by using FEM approach was studied by Rentscha et al. [103]. Milling operation was carried out both experimentally and by simulation approach to compare the results. Macroscopic approach was used for anisotropic material properties with continuous fibre orientation and microscopic approach was developed for explicit matrix representation. 0˚ and 90˚ fibre orientations were used for the investigation. The obtained results as shown in Fig. 6, by simulation showed good agreement with experimental findings, however during material removal mechanism the calculated cutting force and thrust force varied in a small ratio when compared with the experimental ones.

3.2.1 Drilling operation by finite element method

Rakesh et al. [105] investigated delamination on fibre reinforced plastics using FEM approach. The experiment was carried out using three different tools, twist drill, jodrill and trepanning tool. Drilling parameters which were considered during experiment are shown in Table 3. The geometric modeling of different drills was done using Pro-E software and for the simulation purpose ABAQUS software was used. For validating, the results of simulation and experimental were compared for spindle speed of 2250 rpm. They observed that, twist drill caused more drilling induced delamination compared to other drill tools, as shown in Table 4.

Singh et al. [20] carried out an experiment on uni-directional GFRP to find out the factors effecting delamination by finite element model (FEM). Experimental approach was done to compare the results with simulation as shown in Table 4. 27 experimental trials were carried out and the variation of thrust force and torque vs point angle, feed rate and spindle speed were noted. Drill point angle, feed rate and spindle speed are the process parameters which were considered during the study. During the evaluation of experiment it was found that, point angle and the feed rate influenced the thrust force and similarly torque was influenced by the interaction of the point angle and the feed rate. For simulation purpose, modeling of twist drill for 90˚, 104˚ and 118˚ was done in Pro-E software. During analysis Tsai Wu failure plots were drawn as shown in Fig. 7. It was observed that Tsai Wu failure increased as the point angle increased. Validation was done by determining delamination factor by experimental and simulation method. They reported that, as the drill point angle increased delamination factor increased which in turn increased the drilling-induced damage.

Nilanjan Das et al. [101] did an experimental and finite element study on woven glass fibre reinforced plastic. To study the drilling responses, macro-mechanical approach was used. The experiment was carried out by using two different drill types that is (a) high speed steel (HSS) and (b) carbide drill. Several numerical equations were established and calculated for flute geometry of drill and meshing of the workpiece. Experimental run was carried out for different speed feed combinations and a MATLAB program was written for it. The average drilling thrust force was determined by using the program for steady cutting period. For simulation, twist drill was modeled using Pro-E software and finite element analysis was carried out using ANSYS AUTODYN software. Push out and peel up delamination was determined experimentally. For the purpose of validating, the comparison of experimental and finite element results were plotted in graph and it was found that there was a 10-21% deviation for lower cutting speed (Vc) of 45 m/min as shown in Fig. 8(a) for HSS tool, Fig. 8(b) for carbide tool, 6-27% deviation for higher cutting speed (Vc) 65 m/min for both the drill bits as shown in Fig. 8(c) for HSS tool, Fig. 8(d) for carbide tool. Ozden and Elaheh [106, 138] investigated delamination during drilling of CFRP using FEM. Solid works and ABAQUS were used for modeling and analysis of drilling of CFRP. The results showed that step drill was more efficient in reducing thrust force and torque compared to that of the twist drill.

3.2.2 Orthogonal machining by finite element method

Orthogonal machining is commonly carried out for metal matrix composites (MMCs) and the factors which influence for the tough machining are matrix properties and volume fraction of reinforcement phase. Due to increase in volume fraction and average size of the reinforcement phase the increase in tool wear occurs [108-113]. During machining, as the cutting speed, feed rate increases a better surface finish was obtained but with increase in depth of cut poor surface finish is achieved [136,137]. Literature survey [114-118] provides, that the tool materials used for cutting of these composite materials such as polycrystalline diamond (PCD) provides a improved surface finish compared to that of high speed steel (HSS) and tungsten carbide (WC) and the tool wear and surface finish also depends on the grain size of the cutting tool.

Orthogonal cutting was performed by Arola and Ramulu [119] on unidirectional FRP composites, based on maximum stress and Tsai-Hill criteria. The simulation results were compared with the experimental results and it was found that cutting force of simulation matched well with the experiment results however, thrust force were found to be inaccurate with the experimental ones.

Shuji Usui et al. [120] reported a study on the Lagrangian finite element machining model using an explicit time integration scheme for orthogonal machining and drilling. Orthogonal machining was carried out for four orientations of uni-directional CFRP, that is 0˚, 45˚, -45˚ and 90˚. For 0˚ orientation the peel fracture took place along the fibre interface as shown in Fig. 9(a). For 45˚ orientation as shown in Fig. 9(b), the simulation result showed that the chips were separated by mode II fracture at fibre/ matrix interface. For 90˚ orientation small chips were formed and macroscopic cracking was observed as shown in Fig. 9(c). For -45˚ orientation during orthogonal cutting the workpiece was split into half as shown in Fig. 9(d). The simulation results showed that the 90˚ orientation caused more damaged to the workpiece compared to 0˚ orientation which were found to be similar for experimental also. The FEM results obtained were comparatively similar to that of the experimental results.

A macro mechanical model was developed by Carlos Santiuste et al. [102] for numerical analysis of orthogonal cutting of CFRP & GFRP composites. They found that subsurface damage experienced by GFRP was more compared to that of CFRP. Progressive failure occurred during machining of GFRP whereas catastrophic damage was noted in CFRP as shown in Fig. 10. Chip formation during machining of GFRP composite was studied by Takeyama and Iijima [121]. They reported that metal like chip formation was noted during machining the composite and the formation of chip depended on the fibre orientation.

Stress strain relation, tool wear and particle debonding were studied by Pramanik et al. [122] during orthogonal cutting of metal matrix composite (MMC) by finite element method. Debonding at the interface and failure of the particle was observed along the cutting path during experimentation whereas during simulation only debonding of the material was noted as failure criteria were not defined in the material definition. Coupled temperature displacement analysis was carried out by Zhu and Kishawy [123] during orthogonal cutting of Al6061 MMC. The investigation was done for feed rate of 0.1, 0.2 and 0.3 mm/rev at a cutting speed of 85 m/min. It was found that plastic deformation occurred along the chip tool interface due to the friction between the tools rake face and material.

The effect of cutting speed and depth of cut while orthogonal cutting of SiC/Al composite was studied by Zhou et al. [124] using polycrystalline diamond tool. During the experiment, at the initial stage it was noted that the as the tool advances due to less contact area between the chip and tool, high stress concentration was observed as shown in Fig. 11(a) and as the depth of cut increased between the tool and the material, plastic deformation of the material increased this deformation occurred along the rake face of the tool as shown in Fig. 11(b). The results were compared with the experimental results obtained by Kannan et al. [125] who had also conducted the machining on MMC's. The experimental and simulated results showed a slight deviation of less than 20%.

4. Conclusions

This paper has provided a comprehensive literature review on machining of composites, covering achievements of past 30 year in terms of conventional and numerical simulation methods. Some of the conclusions are summarized as follows:

- Composite materials are gaining their attractiveness due to their high mechanical properties. High strength to weight ratio and their resistance to offer for different types of environmental conditions, make them widely used in number of industrial applications.
- Selection of proper cutting tools for their influence on surface finish and machining accuracy, which effect the efficiency of machining performance are reviewed. The parameters which were found to mostly influence the delamination were found to be feed rate and spindle speed.
- For reducing delamination effect during drilling, different approaches such as applying active back up force, introducing pilot hole and using special core drills are reviewed and their effect on reduction in delamination have been found to be very promising.
- Numerical simulation methods (FEM & DEM) offer an alternative way of understanding the tool interaction with the composites. They provide a new approach of machining process which provides promising results when compared with experimental results.

References

[1] Soutis C. Fibre reinforced composite in aircraft construction. Progr Aerosp Sci 2005; 41: 143–51.

[2] Wang XM, Zhang LC. An experimental investigation into the orthogonal cutting of unidirectional fibre reinforced plastics. Int J Mach Tools Manuf 2003; 43: 1015-22.

[3] Campbell FC. Structural composite materials. www.asminternational.org; 2010 [accessed 25. 10. 15].

[4] Karnik SR, Gaitonde VN, Rubio JC, Correia AE, Abrao AM, Davim JP. Delamination analysis in high-speed drilling of carbon fiber reinforced plastics (CFRP) using artificial neural network model. Mater Des 2008; 29: 1768–76.

[5] Singh AP, Sharma M, Singh I. Drilling of fiber reinforced plastic composites: a review. J Manuf Technol 2008; 7: 24–30.

[6] Gaitonde VN, Karnik SR, Rubio JC, Correia AE, Abrao AM, Davim JP. Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites. J Mater Process Technol 2008; 203: 431–9.

[7] Koplev A. Cutting of CFRP with single edge tools. Proceed Adv Compos Mater 1980; 1597-605.

[8] Madhujit Mukhyopadhyay. Mechanics of composite materials and structures. 2nd ed. Hyderabad: India; 2004.

[9] Barbero EJ. Introduction to composite materials design. 2nd ed. London : New York; 2008.

[10] Hocheng H, Tsao CC. Effects of special drill bits on drilling-induced delamination of composite materials. Int J Mach Tools Manuf 2006; 46: 1403–16.

[11] Palanikumar K, Prakash S, Shanmugam K. Evaluation of delamination in drilling GFRP composites. Mater Manuf Process 2008; 23: 858-64.

[12] Demeng C, Ishan S, Peidong H, Ping G, Kornel EF. Machining of carbon fiber reinforced plastics/polymers: a literature review. J Manuf Sci Eng 2014; 136: 034001-22.

[13] Wang DH, Ramulu M, Arola D. Orthogonal cutting mechanisms of graphite/epoxy composite, Part 1: unidirectional laminate. Int J Mach Tools Manuf 1995; 35: 1623-38.

[14] Subramanian K, Cook NH. Sensing of drill wear and prediction of drill life. Trans ASME J Eng Indus 1997; 99: 295–01.

[15] Faraz A, Biermann D, Weinert K. Cutting edge rounding: an innovative tool wear criterion in drilling CFRP composite laminates. Int J Mach Tools Manuf 2009; 49: 1185–96.

[16] Durao LMP, de Moura MFSF, Marques AT. Numerical simulation of the drilling process on carbon/epoxy composite laminates. Compos Part-A: Appl Sci Manuf 2006; 37: 1325–33.

[17] Khashaba UA. Delamination in drilling GFR–thermoset composites. Compos Struct 2004; 63: 313–27.

[18] Caprino G, Tagilaferri V. Damage developments in drilling glass fiber reinforced plastics. Int J Mach Tools Manuf 1995; 35: 817–29.

[19] Tagliaferri V, Caprino G, Diterlizzi A. Effect of drilling parameters on the finish and mechanical properties of GFRP composites. Int J Mach Tools Manuf 1990; 30: 77–84.

[20] Singh I, Bhatnagar N, Viswanath P. Drilling of uni-directional glass fiber reinforced plastics: experimental and finite element study. Mater Des 2011; 29: 546–53.

[21] Sandvik Coromant. Machining carbon fibre materials. http://www.sandvik.coromant.com/sitecollectiondocuments/downloads/global/technical%20guides/en-gb/c2920-30/; 2013 [accessed 27. 11.15].

[22] Ferreira JR, Coppini NL, Miranda GWA. Machining optimisation in carbon fibre reinforced composite materials. J Mater Process Technol 1999; 92: 135-40.

[23] Di Ilio A, Paoletti A. Machinability aspects of metal matrix composites, In: Davim JP (ed) Machining of metal matrix composites. Springer. London; 2012.

[24] Thamizhmanii S, Hasan S. Investigating flank wear and cutting force on hard steels by CBN cutting tool by turning, In: Proceedings of the world congress on engineering WCE. London: UK; 2008.

[25] Rajasekaran T, Palanikumar K, Vinayagam BK. Application of fuzzy logic for modeling surface roughness in turning CFRP composites using CBN tool. Prod Eng Res Dev 2011; 5: 191–9.

[26] Tomac N, Tannessen K, Rasch FO. Machinability of particulate aluminium matrix composites. CIRP Ann Manuf Technol 1992; 41: 55–8.

[27] Santhanakrishnan G, Krishnamurthy R, Malhotra SK. Investigation into the machining of carbon fibre reinforced plastics with cemented carbides. J Mater Process Technol 1992; 30: 263-75.

[28] Palanikumar K. Application of Taguchi and response surface methodologies for surface roughness in machining glass fiber reinforced plastics by PCD tooling. Int J Adv Manuf Technol 2008; 36: 19–7.

[29] Lee ES. Precision machining of glass fibre reinforced plastics with respect to tool characteristics. Int J Adv Manuf Technol 2001; 17: 791–98.

[30] Hocheng H, Puw HY, Huang Y. Preliminary study on milling of unidirectional carbon fibre reinforced plastics. Compos Manuf 1993; 4: 103–8.

[31] Davim JP, Reis P. Damage and dimensional precision on milling carbon fiber reinforced plastics using design experiments. J Mater Process Technol 2005; 160: 160–7.

[32] Cronjager L, Meister D. Machining of fibre and particle-reinforced aluminium. CIRP Ann Manuf Technol 1992; 41: 63-6.

[33] Sheikh AJ, Sirdhar G. Edge trimming of CFRP composites with diamond coated tools: edge wear and surface characteristics, In: Proceedings of the SAE General Aviation Technology Conference and Exhibition. Wichita: KS; 2002.

[34] Ucar M, Wang Y. End-milling machinability of a carbon fiber reinforced laminated composite. J Adv Mater 2005; 34: 46–2.

[35] Janardhan P, Sheikh AJ, Cheraghi H. Edge trimming of CFRP with diamond interlocking tools, In: Proceedings of Aerospace Manufacturing and Automated Fastening Conference. Toulouse: France; 2006.

[36] Davim JP, Reis P. Multiple regression analysis (MRA) in modelling milling of glass fiber reinforced plastics (GFRP). Int J Manuf Technol Mgt 2004; 6: 185–97.

[37] Kalla D, Sheikh-Ahmad J, Twomey J. Prediction of cutting forces in helical end milling fiber reinforced polymers. Int J Mach Tools Manuf 2010; 50: 882–91.

[38] Denkena B, Boehnke D, Dege JH. Helical milling of CFRP–titanium layer compounds. CIRP J Manuf Sci Technol 2008; 1: 64–9.

[39] Nor Khairusshima MK, Che Hassan CH, Jaharah AG, Nurul Amin A. Tool wear and surface roughness on milling carbon fiber reinforced plastic using chilled air. J Asian Sci Res 2012; 2: 593–98.

[40] Suresh KRN, Shin KW, Minyang Yang. Experimental study of surface integrity during end milling of Al/SiC particulate metal matrix composites. J Mater Process Technol 2008; 2: 574–79.

[41] Abrao AM, Rubio JCC, Faria PE, Davim JP. The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite. Mater Des 2008; 29: 508–13.

[42] Lau WS, Yue TM, Lee TC, Lee WB. Unconventional machining of composite materials. J Mater Process Technol 1995; 48: 199–05.

[43] Mathew J, Goswami GL, Ramakrishnan N, Naik NK. Parametric studies on pulsed ND: YAG laser cutting of carbon fibre reinforced plastic composites. J Mater Process Technol 1999; 89: 198–03.

[44] Voisey KT, Fouquet S, Roy D, Clyne TW. Fibre swelling during laser drilling of carbon fibre composites. Opt Lasers Eng 2006; 44: 1185-97.

[45] Herzog D, Jaeschke P, Meier O, Haferkamp H. Investigations on the thermal effect caused by laser cutting with respect to static strength of CFRP. Int J Mach Tools Manuf 2008; 48: 1464–73.

[46] Yao Y, Li D, Yuan Z. Mill-grinding machining for particle reinforced aluminum matrix composites. Proc ICPMT. Seventh International conference on progress of machining technology. Aviation Industry Press. 2004; 258–63.

[47] Lemma E, Chen L, Siores E, Wang J. Study on cutting fiber-reinforced composites by using abrasive water-jet with cutting head oscillation. Compos Struct 2002; 57: 297–03.

[48] Shanmugam DK, Nguyen T, Wang J. A study of delamination on graphite/epoxy composites in abrasive water jet machining. Compos Part A: Appl Sci Manuf 2008; 39: 923–29.

[49] Azmir MA, Ahsan AK. A study of abrasive water jet machining process on glass/epoxy composite laminate. J Mater Process Technol 2009; 209: 6168–73.

[50] Lau WS, Wang M, Lee WB, Electrical discharge machining of carbon fibre composite materials. Int J Mach Tools Manuf 1990; 30: 297–08.

[51] Muller F, Monaghan J. Non-conventional machining of particle reinforced metal matrix composite. Int J Mach Tools Manuf 2000; 40: 1351–66.

[52] Ho KH, Newman ST. State of the art electrical discharge machining (EDM). Int J Mach Tools Manuf 2003; 43: 1287–300.

[53] Ramulu M, Taya M. EDM machinability of SiCw/Al composites. J Mater Sci 1989; 24: 1103–08.

[54] Hocheng H, Lei WT, Hsu HS. Preliminary study of material removal in electrical discharge machining of SiC/Al. J Mater Process Technol 1997; 63: 813–18.

[55] Piquet R, Ferret B, F. Lachaud F. Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills. Compos Part-A: Appl Sci Manuf 2000; 31: 1107–15.

[56] Zitoune R, Vijayan K, Francis C. Study of drilling of composite material and aluminium stack. Compos Struct 2010; 92: 1246–55.

[57] Murphy CBG, Gilchrist MD. The performance of coated tungsten carbide drills when machining carbon fibre reinforced epoxy composite materials. Proc Instn Mech Eng Part B: J Eng Manuf 2002; 216: 143–52.

[58] Fernandes M, Cook C, Drilling of carbon composites using a one shot drill bit, Part I- Five stage representation of drilling and factors affecting maximum force and torque. Int J Mach Tools Manuf 2006; 46: 70–5.

[59] Fernandes M, Cook C. Drilling of carbon composites using a one shot drill bit, Part II- Empirical modeling of maximum thrust force. Int J Mach Tools Manuf 2006; 46: 76–9.

[60] Tsao CC, Chiu YC. Evaluation of drilling parameters on thrust force in drilling carbon fiber reinforced plastic (CFRP) composite laminates using compound core-special drills. Int J Mach Tools Manuf 2011; 51: 740–44.

[61] Shyha I, Soo SL, Aspinwall D, Bradley S. Effect of laminate configuration and feed rate on cutting performance when drilling holes in carbon fibre reinforced plastic composites. J Mater Process Technol 2010; 210: 1023–34.

[62] Durao LMP, Goncalves DJS, Tavares JMRS, de Albuquerque VHC, Aguiar VA, Marques AT. Drilling tool geometry evaluation for reinforced composite laminates. Compos Struct 2010; 92: 1545–50.

[63] Tsao CC, Hocheng H. Computerized tomography and C-scan for measuring delamination in the drilling of composite materials using various drills. Int J Mach Tools Manuf 2005; 45: 1282–87.

[64] Tsao CC. Prediction of thrust force of step drill in drilling composite material by Taguchi method and radial basis function network. Int J Adv Manuf Technol 2008; 36: 1–8.

[65] Hocheng H, Tsao CC. Comprehensive analysis of delamination in drilling of composite materials with various drill bits. J Mater Proc Technol 2003; 140: 335–39.

[66] Marques AT, Durao LM, Magalhaes AG, Silva JF, Tavares JMRS. Delamination analysis of carbon fibre reinforced laminates: evaluation of a special step drill. Compos Sci Technol 2009; 69: 2376–82.

[67] Tsao CC, Hocheng H. Parametric study on thrust force of core drill. J Mater Process Technol 2007; 192: 37–40.

[68] Jain S, Yang DCH. Delamination-free drilling of composite laminates. J Eng Ind 1994; 116: 475–81.

[69] Tsao CC. Experimental study of drilling composite materials with step-core drill. Mater Des 2008; 29: 1740–44.

[70] Tsao CC. Thrust force and delamination of core-saw drill during drilling of carbon fiber reinforced plastics (CFRP). Int J Adv Manuf Techonol 2008; 37: 23–8.

[71] Wu SM, Shen JM. Mathematical model for multifacet drills. J Eng Ind 1983; 104: 173–82.

[72] Friedrich MO, Burant RO, McGinty MJ. Cutting tools/drills: part 5-point styles and applications. Manuf Eng 1979; 83: 29–31.

[73] Ramulu M, Branson T, Kim D. A study on the drilling of composite and titanium stacks. Compos Struct 2001; 54: 67–77.

[74] Khashaba UA, Sonbaty IA, Selmy AI, Megahed AA. Machinability analysis in drilling woven GFR/epoxy composites, Part I–effect of machining parameters. Compos Part-A: Appl Sci Manuf 2010; 41: 391–400.

[75] Brehl DE, Dow TA. Review of vibration-assisted machining. Precis Eng 2008; 32: 153–72.

[76] Wang X, Wang LJ, Tao JP. Investigation on thrust in vibration drilling of fiber-reinforced plastics. J Mater Process Technol 2004; 148: 239–44.

[77] Abrao AM, Faria PE, Rubio JCC, Reis P, Davim JP. Drilling of fiber reinforced plastics: a review. J Mater Process Technol 2007; 186: 1–7.

[78] Konig W, Grab P. Quality definition and assessment in drilling of fiber reinforced thermosets. Ann CIRP 1989; 38: 119–24.

[79] Hocheng H, Dharan CKH. Delamination during drilling in composite laminates. Trans ASME J Eng Ind 1990; 112: 236–39.

[80] Dandekar C, Shin YC, Multiphase finite element modeling of machining unidirectional composites: prediction of debonding and fiber damage. Trans ASME J Manuf Sci Eng 2008; 130: 051016.

[81] Stone R, Krishnamurthy K. A neural network thrust force controller to minimize delamination during drilling of graphite/epoxy laminates. J Mach Tools Manuf 1996; 361: 985-003.

[82] Amrinder PS, Manu S, Inderdeep S. A review of modeling and control during drilling of fiber reinforced plastic composites. Compos Part B Eng 2013; 47: 118–25.

[83] Bhattacharya, Band Sorkhel SK. Investigation for controlled electrochemical machining through response surface methodology based approach. J Mater Process Technol 1999; 86: 200-07.

[84] Tsao CC, Hocheng H, Chen YC. Delamination reduction in drilling composite materials by active backup force. CIRP Annals- Manuf Technol 2012; 61: 91–4.

[85] Won MS, Dharan CKH. Chisel edge and pilot hole effects in drilling composite laminate. J Manuf Sci Eng 2002; 124. 242-47.

[86] Sonbaty IA, Mulgrew V, Khashaba UA, Machaly T. Factors affecting the machinability of GFR/epoxy composites. Compos Struct 2004; 63: 329-38.

[87] Enemuoh EU, Gizawy AS, Okafor AC. An approach for development of damage-free drilling of carbon fiber reinforced thermosets. Int J Mach Tools Manuf 2001; 41: 1795-814.

[88] Hamzeh S, Mostafa H, Masoud F. Experimental investigation of machining parameters on machinability of carbon fiber/epoxy composites. Int J Eng Inn Technol 2012; 2: 30-6.

[89] Cundall PA, Strack ODL. A discrete numerical model for granular assemblies. Geo Abs 1979; 29: 47–65.

[90] Lu M, McDowell GR. Discrete element modelling of railway ballast under triaxial conditions. Geomech Geoeng Int J 2008; 3: 257–70.

[91] McDowell GR, Harireche O. Discrete element modelling of soil particle fracture. Geomech Geoeng Int J 2002; 52: 131–35.

[92] Hentz S, Donze FV, Daudeville L. Discrete element modelling of concrete submitted to dynamic loading at high strain rates. Comput Struct 2004; 82: 2509–24.

[93] Che D, Han P, Guo P, Ehmann K. Issues in polycrystalline diamond compact cutter-rock interaction from a metal machining point of view, Part II-bit performance and rock cutting mechanics. ASME J Manuf Sci Eng 2012; 134: 064002.

[94] Yang D, Sheng Y, Ye J, Tan Y. Discrete element modeling of the microbond test of fiber reinforced composite. Compos Mater Sci 2010; 49: 253–59.

[95] Yaser I, Dongmin Y, Jianqiao Ye. Discrete element method for generating random fibre distributions in micromechanical models of fibre reinforced composite laminates. Compos Part B Eng 2016; 90: 485-92.

[96] Yaser I, Yong Sheng, Dongmin Y, Jianqiao Ye. Discrete element modeling of unidirectional fibre-reinforced polymers under transverse tension. Compos Part B Eng 2015; 73: 118–25.

[97] Iliescu D, Gehin D, Iordanoff I, Girot F, Gutierrez ME. A discrete element method for the simulation of CFRP cutting. Compos Sci Technol 2010; 70: 73–80.

[98] Rao GVG, Mahajan P, Bhatnagar N. Three-dimensional macro mechanical finite element model for machining of uni-directional fiber reinforced polymer composites. Mater Sci Eng Struct 2008; 498: 142–49.

[99] Nayak D, Singh I, Bhatnagar N, Mahajan P, An analysis of machining induced damages in FRP composites-a micromechanics finite element approach. AIP Conf Proceed 2004; 712: 327–31.

[100] Nayak D, Bhatnagar N, Mahajan P. Machining studies of UD-FRP composites part II: finite element analysis. Mach Sci Technol 2005; 9: 503–28.

[101] Nilanjan Das C, Surjya Pal K, Parthasarathi M. Drilling of woven glass fiber reinforced plastic- an experimental and finite element study. Int J Adv Manuf Technol 2012; 58: 267–78.

[102] Carlos Santiuste, Xavier S, Maria Henar M. Machining FEM model of long fiber composites for aeronautical components. Compos Struct 2010; 92: 691–98.

[103] Rentscha R, Pecata O, Brinksmeier E. Macro and micro process modeling of the cutting of carbon fiber reinforced plastics using FEM. Procedia Eng 2011; 10: 1823–8.

[104] Nayak D, Bhatnagar N. Machining studies of uni-directional glass fiber plastic (UD-GFRP) composites, Part 1: effect of geometrical and process parameters. Mach Sci Technol 2005; 9: 481–01.

[105] Rakesh PK, Sharma V, Singh I, Kumar D. Delamination in fiber reinforced plastics: a finite element approach. http://www.SciRP.org/journal/eng/; 2011.

[106] Ozden I, Elaheh G. Numerical investigation of the effects of drill geometry on drilling induced delamination of carbon fiber reinforced composites. Compos Struct 2013; 105: 126–33.

[107] Ozden I, Elaheh G. Finite element analysis of drilling of carbon fibre reinforced composites. Appl Compos Mater 2012; 19: 637–56.

[108] Cheung CF, Chan KC, To S, Lee WB. Effect of reinforcement in ultra-precision machining of Al6061/SiC metal matrix composites. Scr Mater 2002; 47: 77–2.

[109] Ciftci I, Turker M, Seker U. CBN cutting tool wear during machining of particulate reinforced MMCs. Wear 2004; 257: 1041–6.

[110] Sahin Y, Sur G. The effect of Al2O3, TiN and Ti (C, N) based CVD coatings on tool wear in machining metal matrix composites. Sur Coat Technol 2004; 179: 349–5.

[111] Li X, Seah WKH. Tool wear acceleration in relation to workpiece reinforcement percentage in cutting of metal matrix composites. Wear 2001; 247: 161–1.

[112] Weinert K. Consideration of tool wear mechanism when machining metal matrix composites (MMC). Ann CIRP- Manuf Technol 1993; 42: 95–8.

[113] Ozben T, Kilickap E, Cakir O. Investigation of mechanical and machinability properties of SiC particle reinforced Al-MMC. J Mater Process Technol 2008; 198: 220-5.

[114] El-Gallab M, Sklad M. Machining of Al/SiC particulate metal-matrix composites, Part I- tool performance. J Mater Process Technol 1998; 83: 151–8.

[115] El-Gallab M, Sklad M. Machining of Al/SiC particulate metal matrix composites, Part II- workpiece surface integrity. J Mater Process Technol 1998; 83: 277–5.

[116] El-Gallab M, Sklad M. Machining of Al/SiC particulate metal-matrix composites, Part III- comprehensive tool wear model. J Mater Process Technol 2000; 101: 10–20.

[117] Muthukrishnan N, Murugan M, Prahlada Rao P. An investigation on the machinability of Al-SiC metal matrix composites using PCD inserts. Int J Adv Manuf Technol 2008; 38: 447–4.

[118] Bergman F, Jacobson S, Abdel Moneim ME. Comments on tool wear mechanisms in intermittent cutting of metal matrix composites. Wear 1996; 197: 295–6.

[119] Arola D, Ramulu M. Orthogonal cutting of fiber reinforced composites- a finite element analysis. Int J Mech Sci 1997; 39: 597–13.

[120] Shuji U, Jon W, Troy M. Finite element modeling of carbon fiber composite orthogonal cutting and drilling. Procedia CIRP 2014; 14: 211–6.

[121] Takeyama H, Iijima N. Machinability of glass fiber reinforced plastics and application of ultrasonic machining. CIRP Ann Manuf Techonol 1988; 37: 93–6.

[122] Pramanik A, Zhang LC, Arsecularatne JA. An FEM investigation into the behavior of metal matrix composites- tool particle interaction during orthogonal cutting. Int J Mach Tools Manuf 2007; 47: 1497–06.

[123] Zhu Y, Kishawy HA. Influence of alumina particles on the mechanics of machining metal matrix composites. Int J Mach Tools Manuf 2005; 45: 389–8.

[124] Li Zhou, Huang ST, Wang D, Yu XL. Finite element and experimental studies of the cutting process of SiCp/Al composites with PCD tools. Int J Adv Manuf Technol 2011; 52: 619–6.

[125] Kannan S, Kishawy HA, Deiab I, Cutting forces and TEM analysis of the generated surface during machining metal matrix composites. J Mater Process Technol 2009; 209: 2260–9.

[126] DeFu L, YongJun T, Cong WL, A review of mechanical drilling for composite laminates. Compos Struct 2012; 94: 1265–79.

[127] Lazar MB, Xirouchakis P, Experimental analysis of drilling fiber reinforced composites. Int J Mach Tools Manuf 2011; 51: 937–46.

[128] Rajamurugan TV, Shanmugam K, Palanikumar K, Analysis of delamimation in drilling glass fiber reinforced polyester composites. Mater Des 2013; 45: 80–7.

[129] Valarmathi TN, Palanikumar K and Latha B, Measurement and analysis of thrust force in drilling of Particle Board (PB) composite panels. Measurement 2013; 46: 1220–30.

[130] Kivak T, Samtas G and Cicek A, Taguchi method based optimization of drilling parameters in drilling of AlSl 316 steel with PVD monolayer and multilayer coated HSS drills. Measurement 2012; 45: 1547–57.

[131] Faria PE, Campos RF, Abrao AM, Thrust force and wear assessment when drilling glass fiber-reinforced polymeric composite. J Compos Mater 2008; 42: 1401–14.

[132] Negarestani R, Sundar M, Sheikh MA, Mativenga P, Numerical simulation of laser machining of carbon-fibre reinforced composites. Proc Instn Mech Engrs 2009; 224: 1017-27.

[133] Tagliaferri V, Di Ilio A, Visconti IC, Laser cutting of fibre-reinforced polyesters. Composites 1985; 16: 317–25.

[134] Abdul Budan D, Vijayarangan S, Quality assessment and delamination force evaluation in drilling glass fibre-reinforced plastic laminates- a finite element analysis and linear elastic fracture mechanics approach. Proc Instn Mech Engrs 2001; 216: 173-82.

[135] Santiuste C, Dıaz-Alvarez J, Soldani X, Miguelez H, Modelling thermal effects in machining of carbon fiber reinforced polymer composites. J of Reinforced Plastics & Composites 2014; 33: 758-66.

[136] Santiuste C, Olmedo A, Soldani X, Miguelez H, Delamination prediction in orthogonal machining of carbon long fiber-reinforced polymer composites. J of Reinforced Plastics & Composites 2012; 31: 875-85.

[137] Ramesh MV, Seetharamu KN, Ganesan N, Analysis of machining of FRPs using FEM. Int J Mach Tools Manuf 1998; 38: 1531–49.

[138] Ozden I, Elaheh G. Three-dimensional numerical modeling of drilling of carbon fiber-reinforced plastic composites. J of Compos Materials 2014; 48: 1209–19.

List of Tables

Table 1

Conventional machining operations performed on composite materials

Machining operation	Material	Refs.
Turning	CFRP	Rajasekaran et al. [25]; Santhanakrishnan et al. [27]
	GFRP	Palanikumar et al. [28]; Lee [29]
Milling	FRP	Kalla et al. [37]
	CFRP	Hocheng et al. [30]; Davim et al. [31,36]; Khairushshima et al. [39]
	MMC	Denkena et al. [38]; Suresh et al. [40]
Drilling	FRP	Singh et al. [5]; Abrao et al. [77]; Amrinder et al. [82]
	CFRP	Karnik et al. [4]; Gaitonde et al. [6]; Hocheng & Tsao [10]; Faraz et al. [15]; Durao et al. [16]; Piquet et al. [55]; Murphy & Gilchrist [57]; Fernandes & Cook [58,59]; Tsao et al. [60,63,64,67,69,70,84]; Shyha et al. [61]; Marques et al. [66]; Won & Dharan [85]; Hamzeh et al. [88]; Cundall & Strack [89]
	GFRP	Palanikumar et al. [11]; Caprino et al. [18]; Tagliaferri et al. [19]; Abrao et al. [41]; Khashaba et al.[17,74]; Sonbaty et al. [86]
Orthogonal cutting	FRP	Wang & Zhang [2]
	MMC	Ciftci et al. [109]; Li & Seah et al. [111]; Weinert [112]; El-Gallab et al. [114-116]; Muthukrishnan et al. [117]

CFRP- Carbon fibre reinforced polymer; GFRP- Glass fibre reinforced polymer; FRP- Fibre reinforced polymer; MMC- Metal matrix composite

Table 2

Machining operations modeled using finite element method

Machining operation	Material	Refs.
Milling	CFRP	Rentscha et al. [103]
Drilling	FRP	Rakesh et al. [105]
	CFRP	Singh et al. [20]; Ozden & Elaheh [106,107]
	Woven GFRP	Nilanjan Das et al. [101]
Orthogonal cutting	FRP	Arola & Ramulu [119]
	CFRP	Carlos et al. [102]; Shuji et al. [120]
	GFRP	Carlos et al. [102]; Takeyama & Iijima [121]
	MMC	Pramanik et al. [122]; Zhu & Kishawy [123]; Zhou et al. [124]; Kannan et al.[125]

CFRP- Carbon fibre reinforced polymer; GFRP- Glass fibre reinforced polymer; FRP- Fibre reinforced polymer; MMC- Metal matrix composite

Table 3

Drilling conditions applied during investigation of drilling-induced delamination by finite element approach

Material	Geometry of drill bit	Diameter	Feed Rate	Spindle Speed	Refs.
UD-GFRP	Twist drill	6 (mm)	0.075,0.188,0.300 (mm/rev)	375,938,1500 (rpm)	Singh et al. [20]
Woven GFRP	Twist drill	5 (mm)	0.25,0.5,0.75,1 (mm/rev)	45,65 (m/min)	Nilanjan Das et al. [101]
UD-GFRP	Jodrill Twist drill Trepanning tool	8 (mm)	20 (mm/min)	2250 (rpm)	Rakesh et al. [105]
UD-CFRP	Twist drill Step drill	8 (mm)	457 (mm/min)	4500 (rpm)	Ozden & Elaheh [106]
UD-CFRP	Twist drill	8(mm)	355,457,584,685 (mm/min)	3000,4500,6000,9000 (rpm)	Ozden & Elaheh [107]

UD- Uni-directional; CFRP- Carbon fibre reinforced polymer; GFRP- Glass fibre reinforced polymer

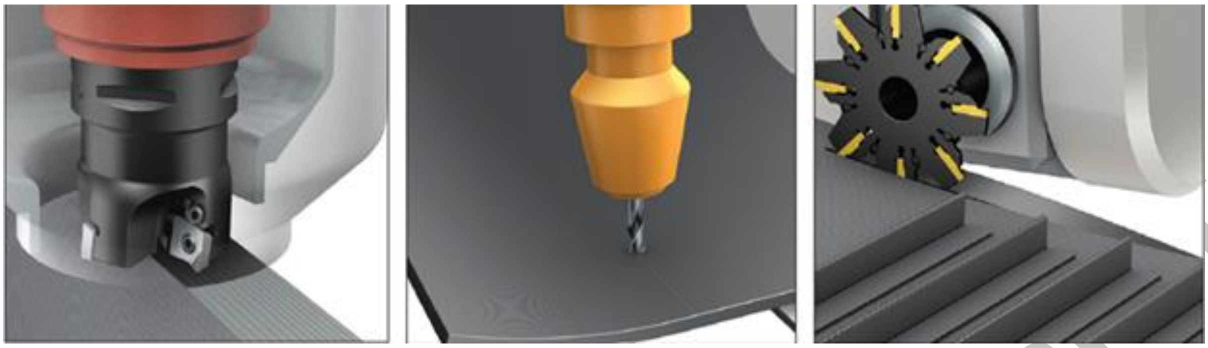
Table 4

Comparison of experimental results with simulation results in drilling

Experimental results	Simulation results	Remarks	Refs.
ANOVA	Results observed according to Tsai Wu Failure criteria	The results observed from the experimental and simulation were good agreement with each other	Singh et al.[20]
Thrust Force	Deviations were within the limit	Deviation of 10-21% for lower cutting speeds. Deviation of 6-27% for higher cutting speeds.	Nilanjan Das et al.[101]
230 N	225 N	Thrust force is directly related to delamination	Ozden & Elaheh[106]
Torque			
0.29 N-m	0.3 N-m	Experimental and simulation results were found to be fairly match each other	Ozden & Elaheh[107]
Delamination Factor			
Twist drill- 2.86	4.43	Trepanning tool is the best tool compare to Twist and Jodrill for minimum delamination	Rakesh et al.[105]
Jodrill- 2.53	3.79		
Trepanning tool- 2.03	3.08		

Delamination Factor is the ratio of maximum diameter (D_{max}) of damaged region to the nominal hole diameter (D_{nom})

List of Figures



(a) (b) (c)

Fig. 1. Machining of composite laminates (a) Milling (b) Drilling (c) Trimming [12] (From, Demeng C, Ishan S, Peidong H, Ping G, Kornel EF. Machining of carbon fiber reinforced plastics/polymers: a literature review. J Manuf Sci Eng 2014; 136: 034001-22. Reproduced with permission of ASME)

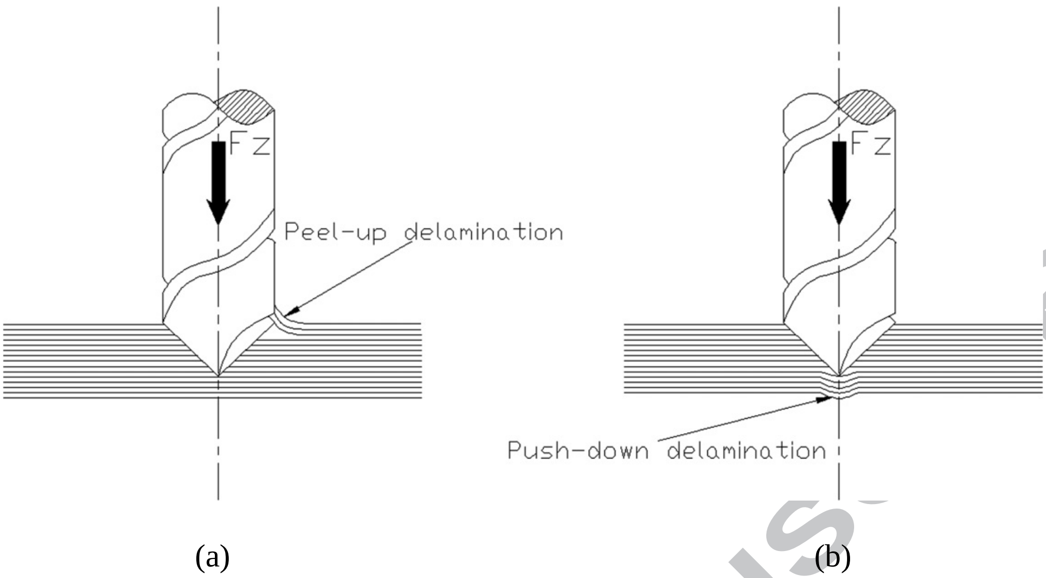


Fig. 2. (a) Peel-up delamination (b) Push-down delamination [82] **(**From, Amrinder PS, Manu S, Inderdeep S. A review of modeling and control during drilling of fiber reinforced plastic composites. Compos Part B Eng 2013; 47: 118–25. Reproduced with permission of Elsevier)

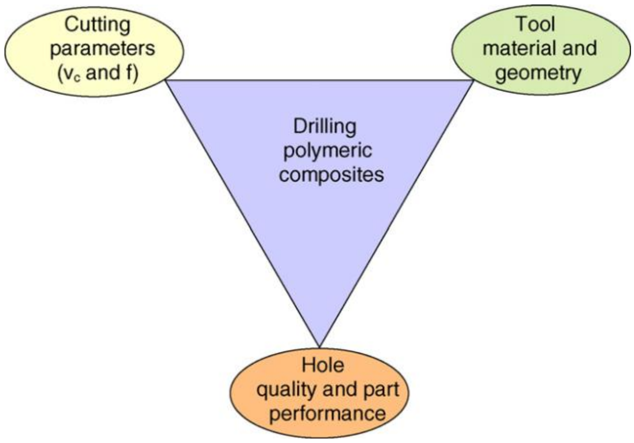
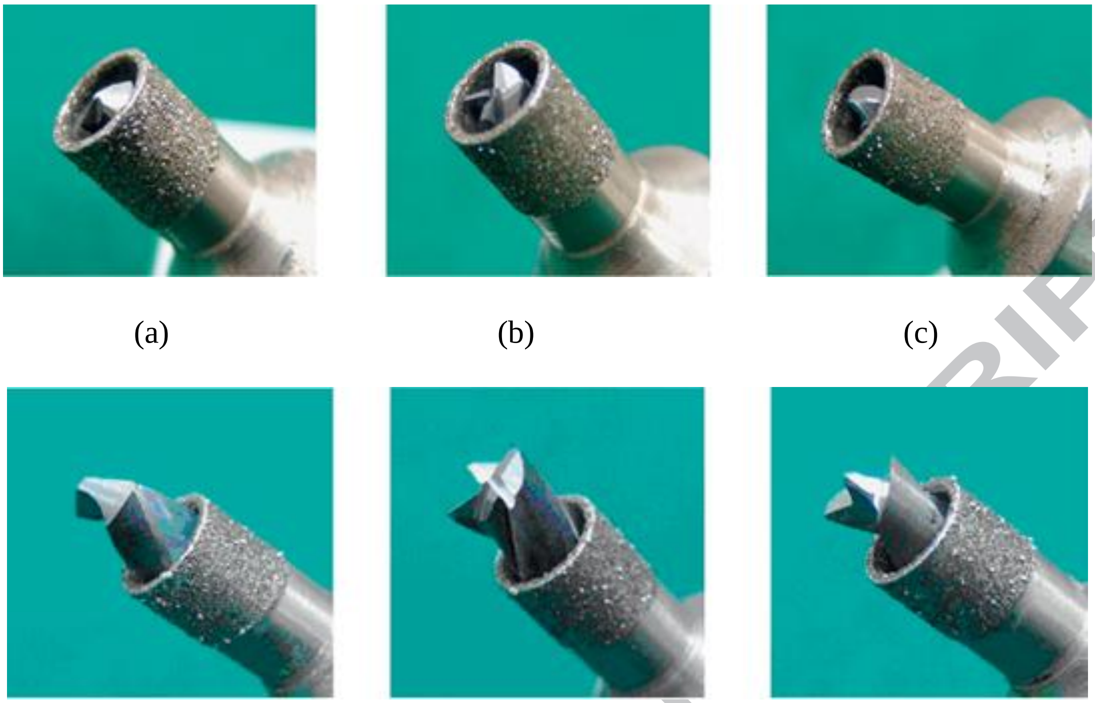


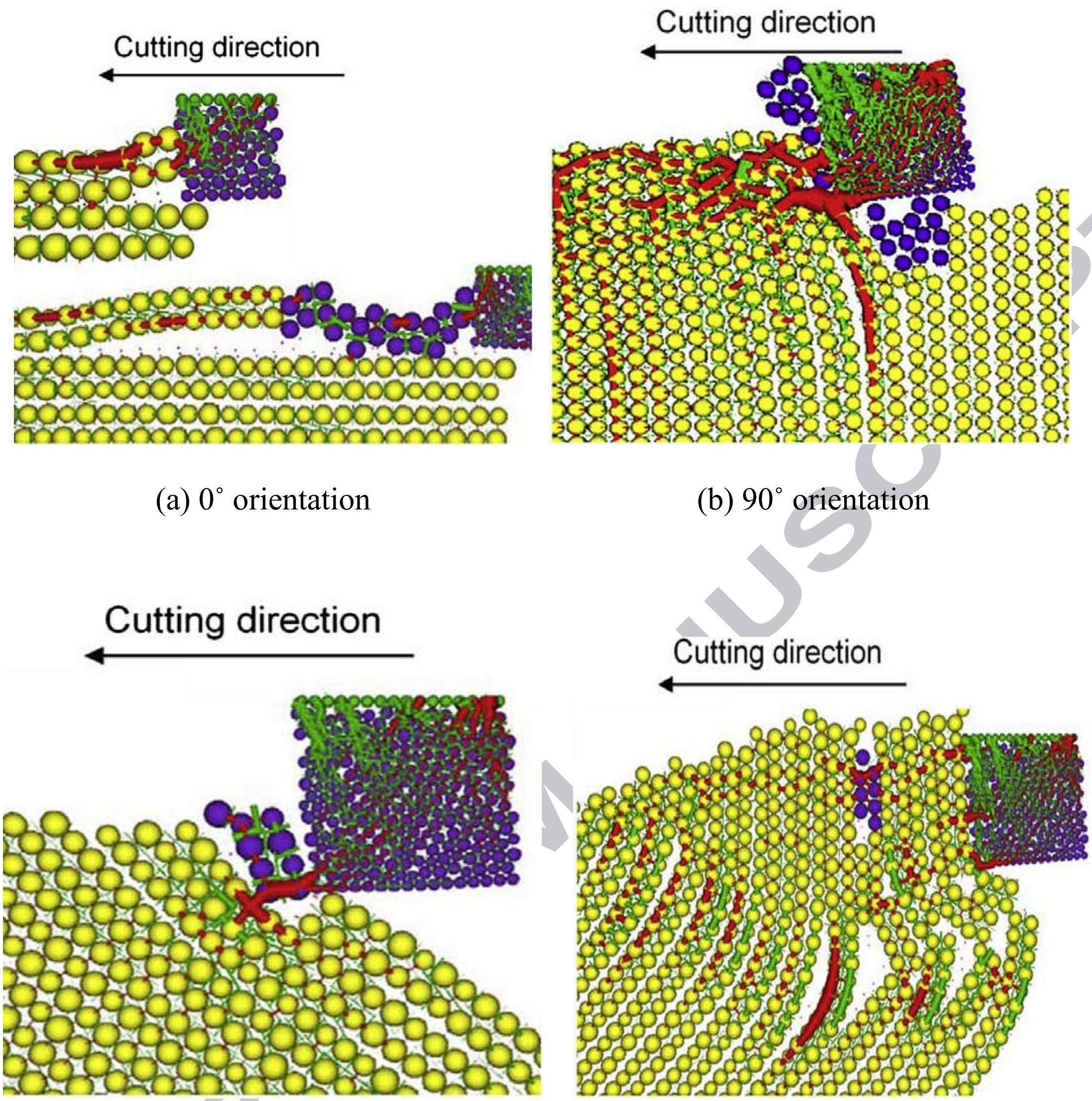
Fig. 3. Principal parameters that needs to be considered during drilling of composites [77] (From Abrao AM, Faria PE, Rubio JCC, Reis P, Davim JP. Drilling of fiber reinforced plastics: a review. J Mater Process Technol 2007; 186: 1–7. Reproduced with permission of Elsevier)



(a) (b) (c)

(d) (e) (f)

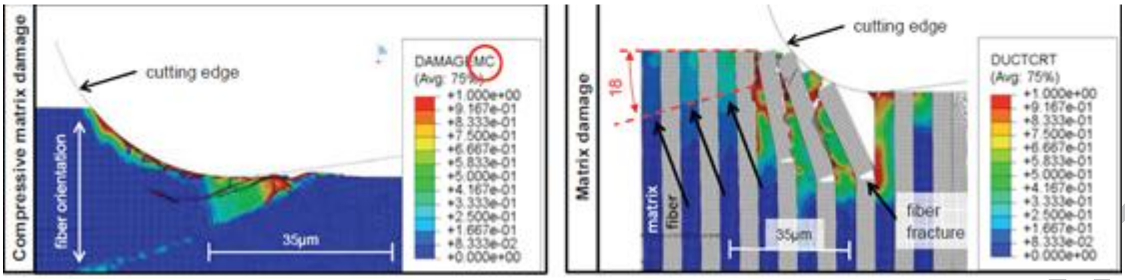
Fig. 4. Special type of core drills (a) Core-twist drill, (b) Core-saw drill, (c) Core-candlestick drill, (d) Step-core-twist drill, (e) Step-core-saw drill and (f) Step-core-candlestick drill [60] (From, Tsao CC, Chiu YC. Evaluation of drilling parameters on thrust force in drilling carbon fiber reinforced plastic (CFRP) composite laminates using compound core-special drills. Int J Mach Tools Manuf 2011; 51: 740–44. Reproduced with permission of Elsevier)



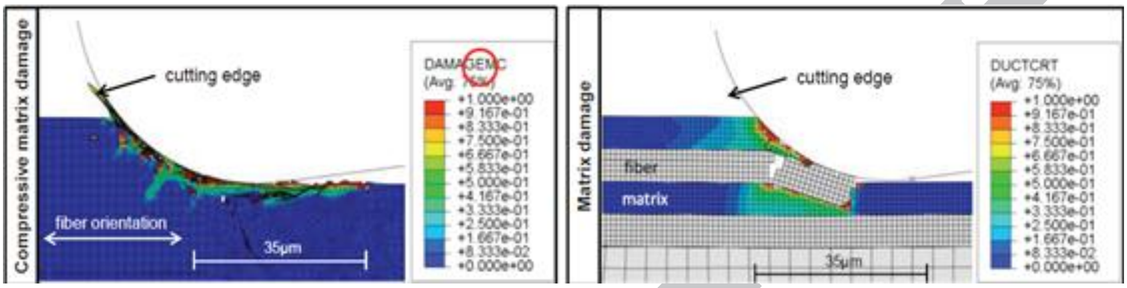
(a) 0˚ orientation (b) 90˚ orientation

(c) 45˚ orientation (d) -45˚ orientation

Fig. 5. Formation of chip during orthogonal cutting by discrete element simulation for different fibre orientation [97] (From, Iliescu D, Gehin D, Iordanoff I, Girot F, Gutierrez ME. A discrete element method for the simulation of CFRP cutting. Compos Sci Technol 2010; 70: 73–80. Reproduced with permission of Elsevier)

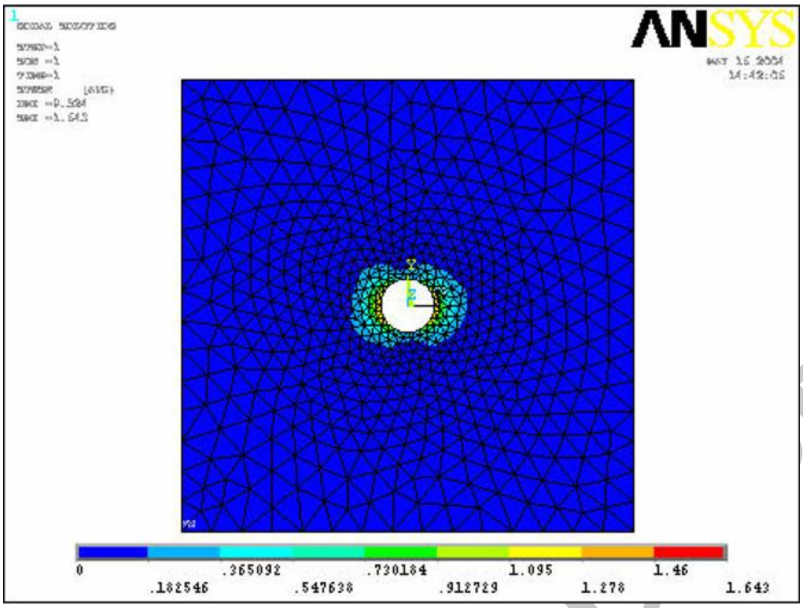


(a)

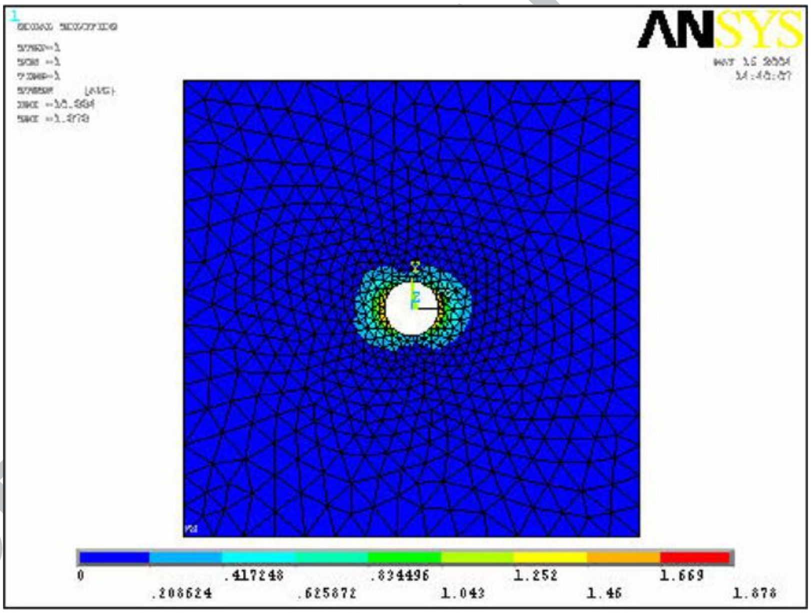


(b)

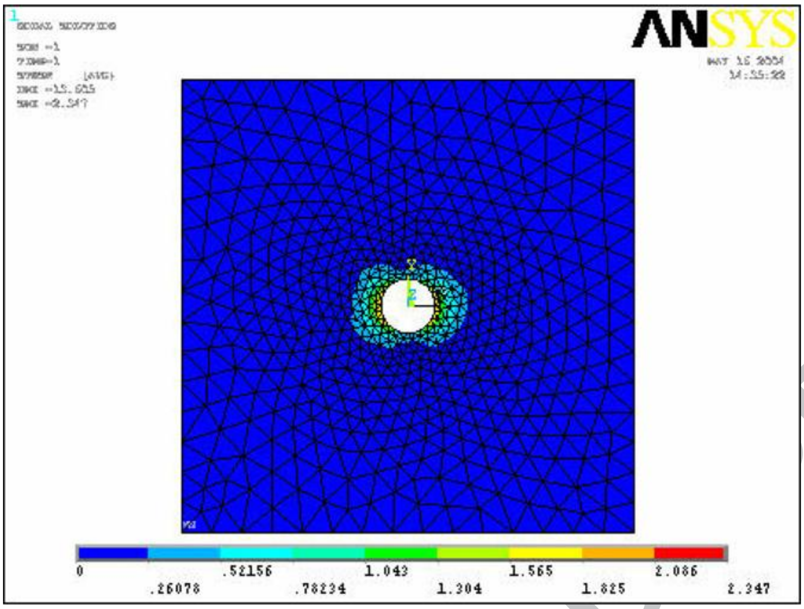
Fig. 6. (a) Macroscopic and Microscopic level damage distribution for 90˚ fibre orientation and (b) Macroscopic and Microscopic level damage distribution for 0˚ fibre orientation [103] (From, Rentscha R, Pecata O, Brinksmeier E. Macro and micro process modeling of the cutting of carbon fiber reinforced plastics using FEM. Procedia Eng 2011; 10: 1823–8. Reproduced with permission of Elsevier)



(a) For 90˚



(b) For 104˚



(c) For 118˚

Fig. 7. Tsai Wu failure plots for different point angles [20] (From, Singh I, Bhatnagar N, Viswanath P. Drilling of uni-directional glass fiber reinforced plastics: experimental and finite element study. Mater Des 2011; 29: 546–53. Reproduced with permission of Elsevier)

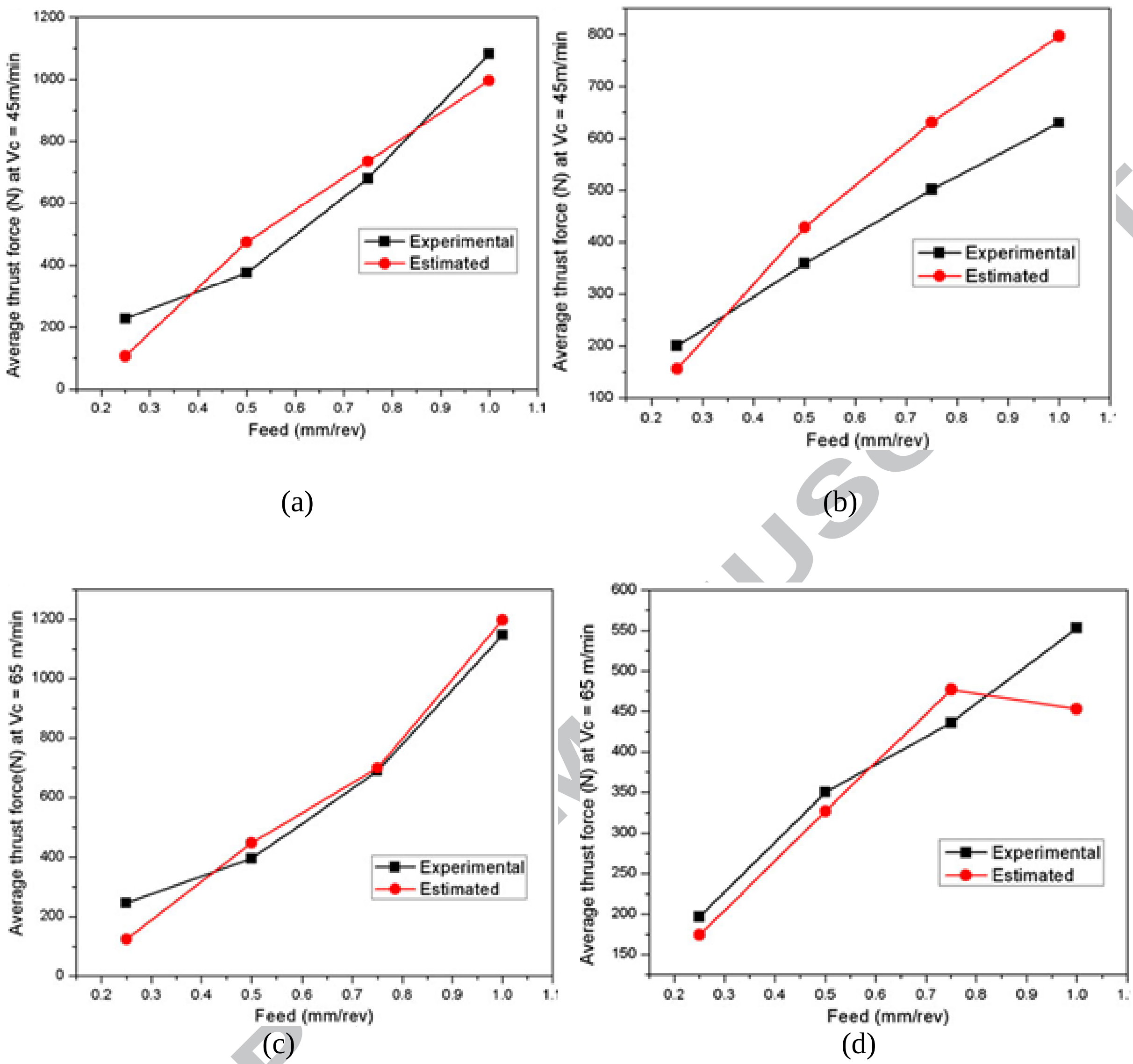
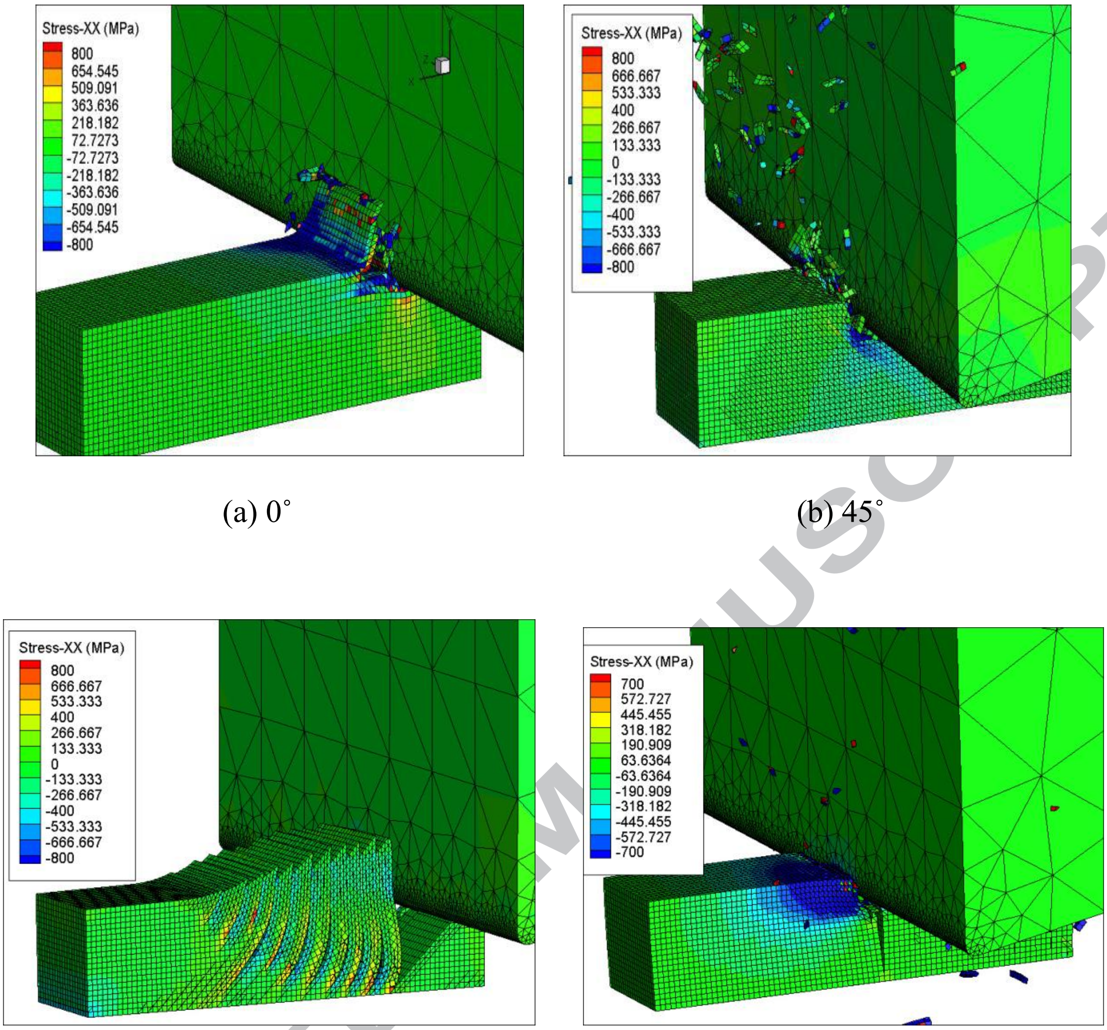


Fig. 8. Thrust force comparison of experimental results and estimated finite element results for Vc= 45 m/min (a) for HSS drill bit, (b) for Carbide drill bit and for Vc= 65 m/min (c) for HSS drill bit, (d) for Carbide drill bit [101] (From, Nilanjan Das C, Surjya Pal K, Parthasarathi M. Drilling of woven glass fiber reinforced plastic- an experimental and finite element study. Int J Adv Manuf Technol 2012; 58: 267–78. Reproduced with permission of Springer)



(a) 0˚ (b) 45˚

(c) 90˚ (d) -45˚

Fig. 9. Orthogonal cutting performed for four different orientations [120] (From, Shuji U, Jon W, Troy M. Finite element modeling of carbon fiber composite orthogonal cutting and drilling. Procedia CIRP 2014; 14: 211–6. Reproduced with permission of Elsevier)

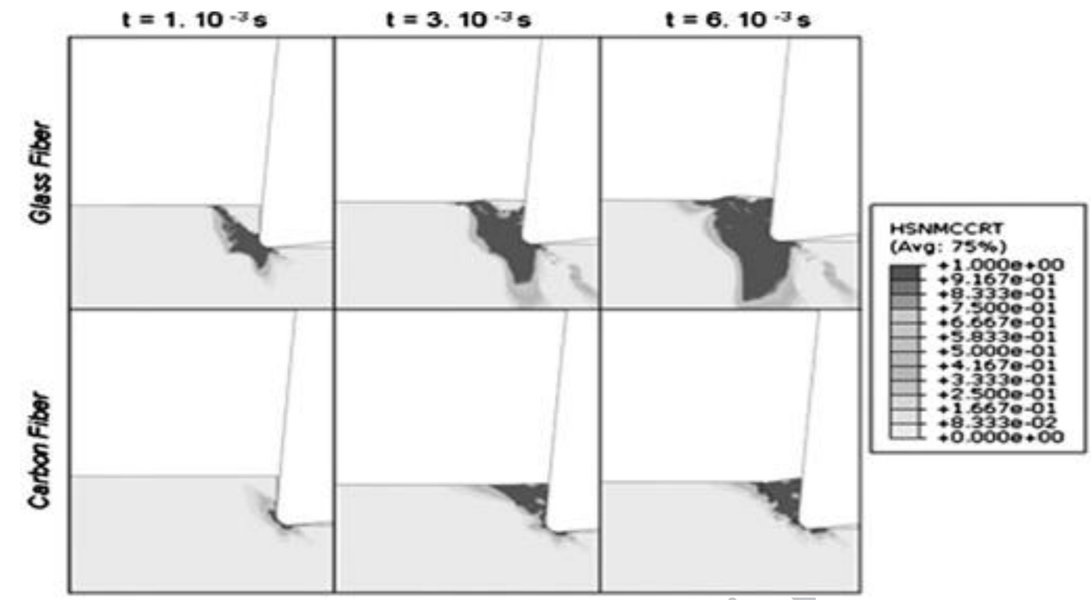
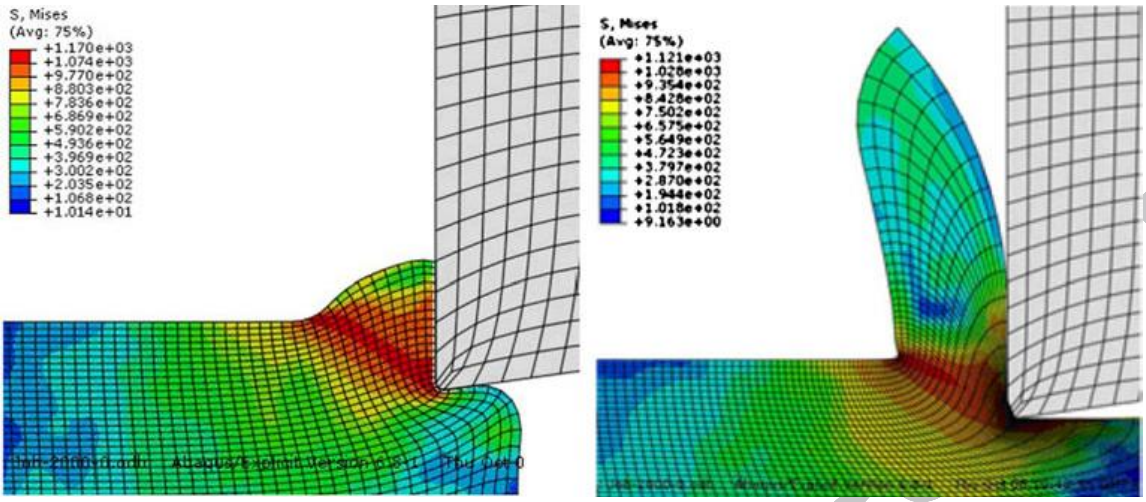


Fig. 10. Comparison of matrix damage occurring in CFRP and GFRP composite [102] (From, Carlos Santiuste, Xavier S, Maria Henar M. Machining FEM model of long fiber composites for aeronautical components. Compos Struct 2010; 92: 691–98. Reproduced with permission of Elsevier)



(a) (b)

Fig. 11. Formation of chip (a) initial stage (b) when depth of cut is increased [124] (From, Li Zhou, Huang ST, Wang D, Yu XL. Finite element and experimental studies of the cutting process of SiCp/Al composites with PCD tools. Int J Adv Manuf Technol 2011; 52: 619–6. Reproduced with permission of Springer)