

# A Review on Finite Element Method for Machining of Composite Materials

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**Abstract:-** Composite materials are formed by combination of two or more materials to achieve properties such as high strength to weight ratio, good corrosion resistance and high stiffness that are superior to those of its constituents. Composites are one of the widely used materials because of their adaptability to different situations and relative ease of combination with other materials to serve specific purpose. Composites are used in a wide range of fields including aerospace, architecture, automotive, energy, infrastructure, marine, military, sports and recreation. The machining of these materials is always being an important area for research. It was found that, during machining of composites surface induced damage occurs such as delamination, hole shrinkage and fiber pull out. This paper provides a complete review on the different simulation methods performed on milling, drilling and orthogonal cutting. Finite Element Methods 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.

**Keywords:** Composite Material, Delamination, FEM, FRP

## 1. INTRODUCTION

During the past decades the demand for composite laminates such as carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), fiber 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 fiber 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 molding, compression molding, 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 fiber 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 is 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.

## 2. MACHINING OF COMPOSITES

The machining of composite materials not only depends on the properties of fiber and matrix composition, it also depends on the fiber orientation and volume fraction. Carbon fiber reinforced polymer (CFRP), fiber reinforced plastics (FRPs), glass fiber reinforced polymer (GFRP), metal matrix composites (MMCs), fiber metal composite laminates (FMLs), ceramic matrix composites (CMCs) and natural fibers 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] and also the unconventional processes such as laser ablation, water-jet cutting [42,48,50,52]. 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.

### *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. In this section a brief description of turning, milling, trimming and drilling are explained below

#### *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 affect the surface roughness was proposed by Lee [29].

#### *Milling and trimming*

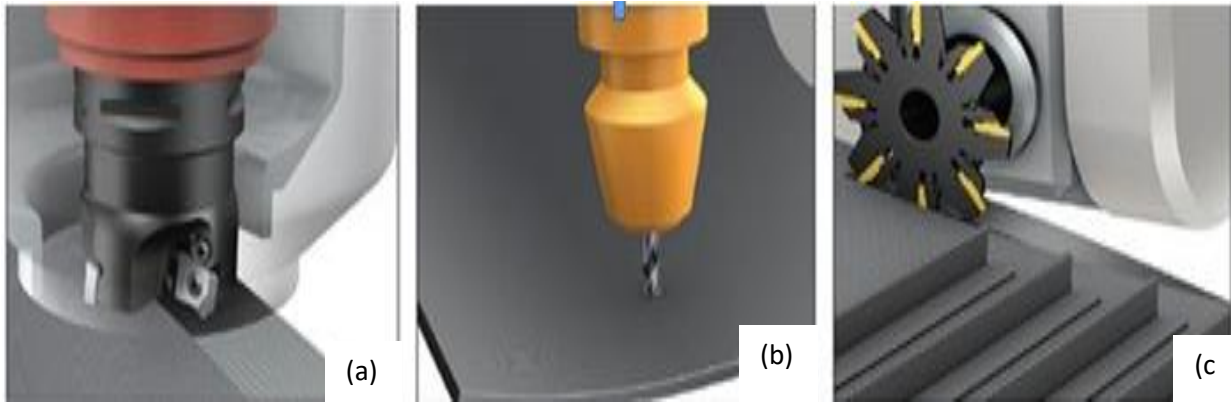
Milling and trimming operation, as shown in Fig. 1(a, c) [21] are used as a material removal process in machining of composites. Trimming operation is carried out in composite materials, to achieve contour shape accuracy. Machining of complex shapes and a high surface finish can be obtained during milling 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.

#### *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], 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 behavior of delamination during drilling of composite laminates. Numerous conventional drilling processes using special drill bits such as straight flute drill [55], step drill [10], core drill, step core drill [10], saw drill [10], candlestick drill [10], multi faced drill, split drill, grinding drilling, vibration assisted twist drilling and high speed drilling have been performed by many researchers 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), push-out delamination Fig. 2(b) and excessive surface roughness of the hole [15]. Fig. 3 shows different parameters that have to be optimized during drilling of composite materials.

Bhattacharya et al. 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 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. 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.



**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)

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. 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.



**Fig. 2.** (a) Peel-up delamination (b) Push-down delamination (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)

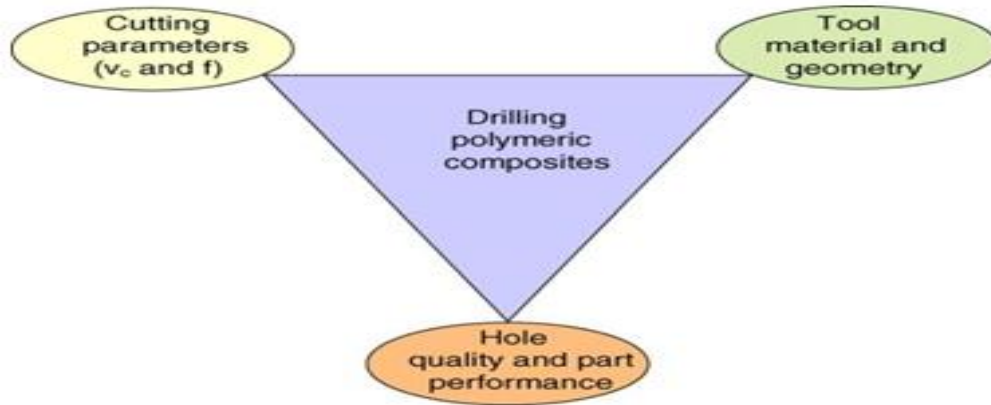


Fig. 3. Principal parameters that needs to be considered during drilling of composites (From Abrao AM, Faria PE, Rubio JCC, Reis P, Davim JP. Drilling of fiber reinforced plastics: a review. J Mater Process Technol 2007; 186: 1–7. Reproduced with permission of Elsevier)

Tsao 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 analyzing, 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. In order to resolve this problem Tsao et al. 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 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. 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

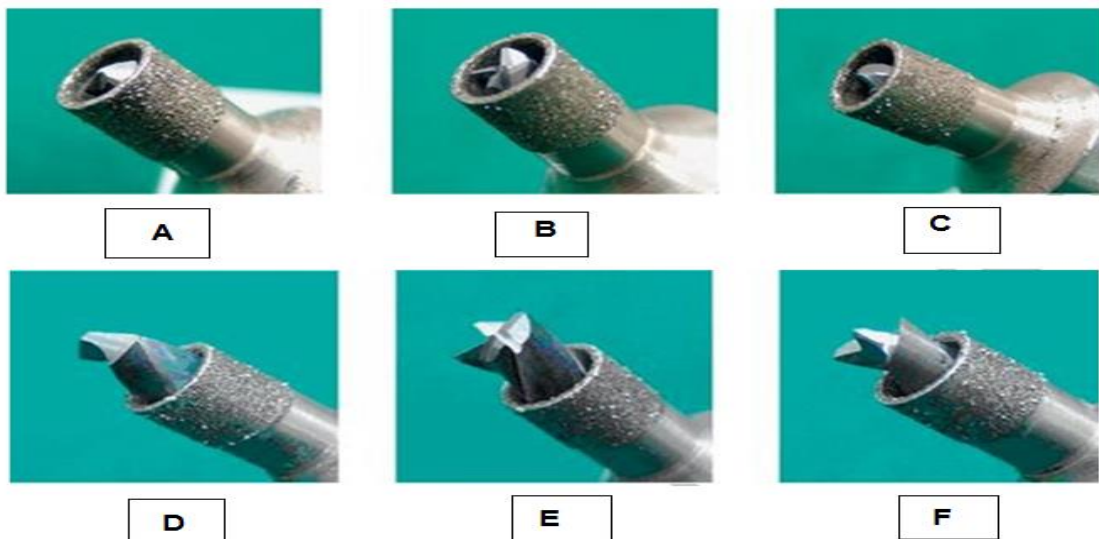


Fig. 4. Special type of core drills (a) Core-twist drill, (b) Core-saw drill, (c) Core-candlestick drill, (d) Step-core-twist drill, (e) Step-core-saw drill and (f) Step-core-candlestick drill (From, Tsao CC, Chiu YC. Evaluation of drilling parameters on thrust force in drilling carbon fiber reinforced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



which led to the slight improvement in surface roughness of the composite material. Enemouh et al. 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. investigated on how the machining parameters and tool geometry, effects the machinability of drilling in carbon fiber 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 work piece due to which fast tool wear and poor surface finish is obtained. 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) is the numerical simulation method. 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. In this section, work done by various researchers on orthogonal cutting and drilling induced delamination by using finite element method has been briefly introduced.

### Finite element method (FEM)

The different types of FEM modeling approaches include (a) macro-mechanical approach [12] (b) micro-mechanical approach and (c) macro-micro combined approach [12]. 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. 3D macro-mechanical approach was considered. Different range of fiber 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 fibers 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.

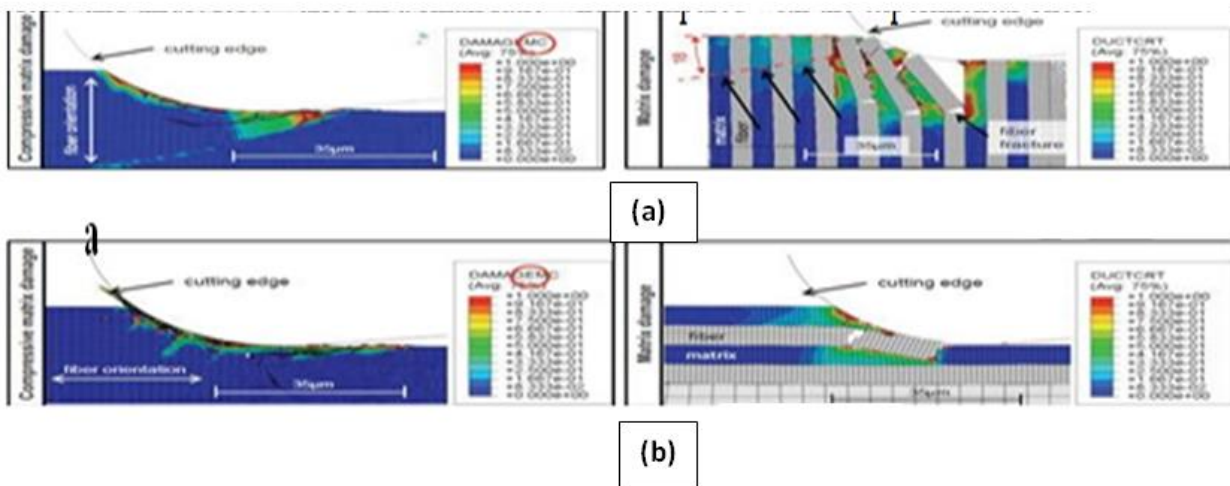


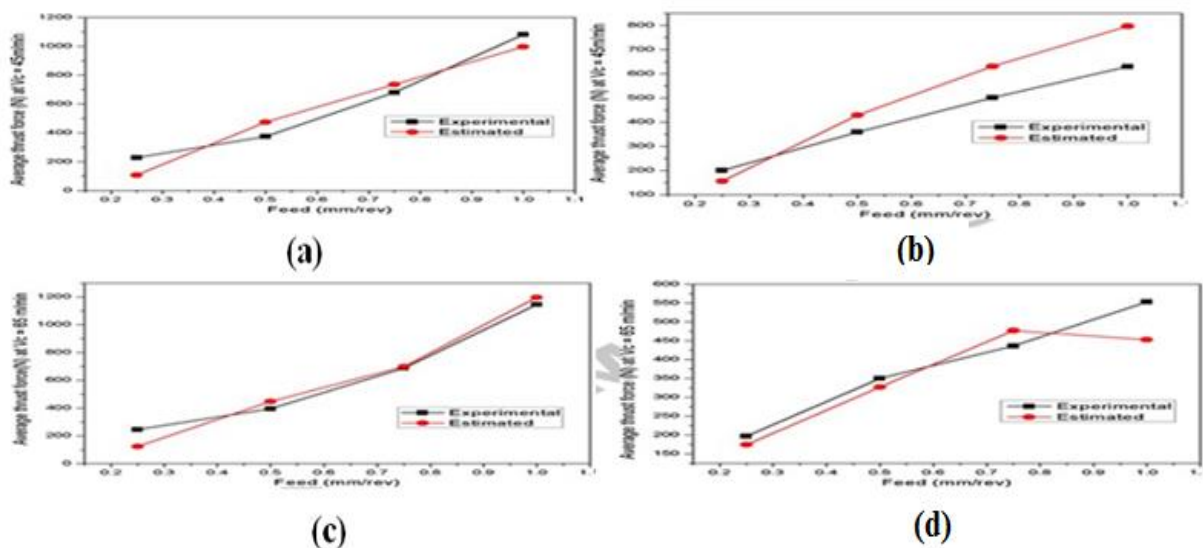
Fig. 5. (a) Macroscopic and Microscopic level damage distribution for 90° fiber orientation and (b) Macroscopic and Microscopic level damage distribution for 0° fiber orientation (From, Rentscha R, Pecata O, Brinksmeier E. Macro and micro process modeling of the cutting of carbon fiber reinforced plastics using FEM. Procedia Eng 2011; 10: 1823–8. Reproduced with permission of Elsevier)

Cutting of carbon fiber reinforced plastic by using FEM approach was studied by Rentscha et al. 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 fiber orientation and microscopic approach was developed for explicit matrix representation. 0° and 90° fiber orientations were used for the investigation. The obtained results as shown in Fig. 5, 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.

### Drilling operation by finite element method

Rakesh et al. investigated delamination on fiber reinforced plastics using FEM approach. The experiment was carried out using three different tools, twist drill, Jodrell and trepanning tool. 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. 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 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. 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. did an experimental and finite element study on woven glass fiber 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 work piece. 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 was 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. 6(a) for HSS tool, Fig. 6(b) for carbide tool, 6-27% deviation for higher cutting speed (Vc) 65 m/min for both the drill bits as shown in Fig. 6(c) for HSS tool, Fig. 6(d) for carbide tool. Ozden and Elaheh 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.



**Fig. 6.** 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 (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)

### 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. During machining, as the cutting speed, feed rate increases a better surface finish is achieved. Literature survey provides, that the tool materials used for cutting of these composite materials such as polycrystalline diamond (PCD) provides an 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 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. 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 unidirectional CFRP, that is 0°, 45°, -45° and 90°. For 0° orientation the peel fracture took place along the fiber interface as shown in Fig. 7(a). For 45° orientation as shown in Fig. 7(b), the simulation result showed that the chips were separated by mode II fracture at fiber/ matrix interface. For 90° orientation small chips were formed and macroscopic cracking was observed as shown in Fig. 7(c). For -45° orientation during orthogonal cutting the work piece was split into half as shown in Fig. 7(d). The simulation results showed that the 90° orientation caused more damaged to the work piece 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. 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.

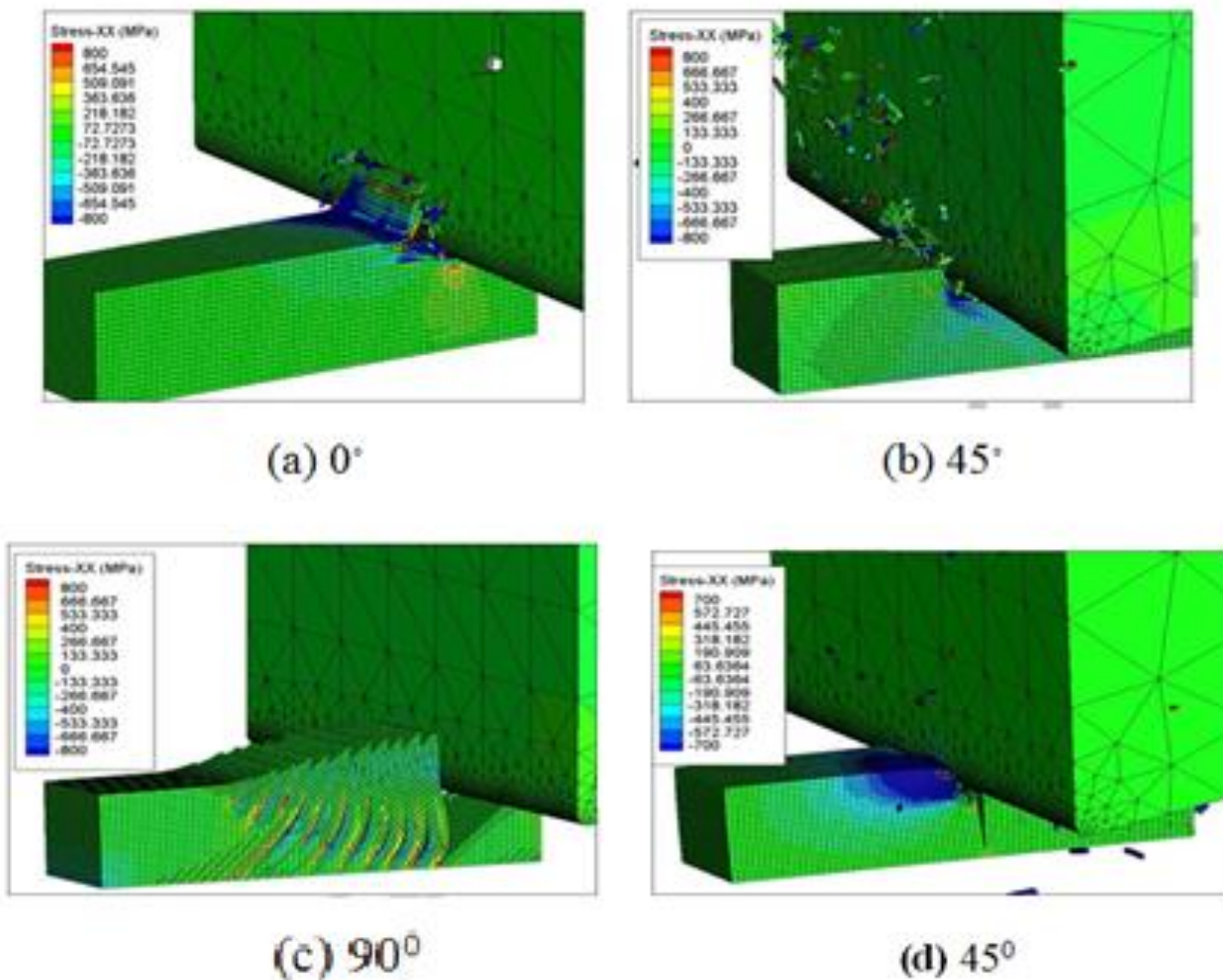


Fig. 7. Orthogonal cutting performed for four different orientations (From, Shuji U, Jon W, Troy M. Finite element modeling of carbon fiber composite orthogonal cutting and drilling. Procedia CIRP 2014; 14: 211–6. Reproduced with permission of Elsevier)

Progressive failure occurred during machining of GFRP whereas catastrophic damage was noted in CFRP as shown in Fig.8. Chip formation during machining of GFRP composite was studied by Takeyama and Iijima . They reported that metal like chip formation was noted during machining the composite and the formation of chip depended on the fiber orientation.

Stress strain relation, tool wear and particle debonding were studied by Pramanik et al. 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 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. 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. 9(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. 9(b). The results were compared with the experimental results

obtained by Kannan et al. who had also conducted the machining on MMC's. The experimental and simulated results showed a slight deviation of less than 20%.

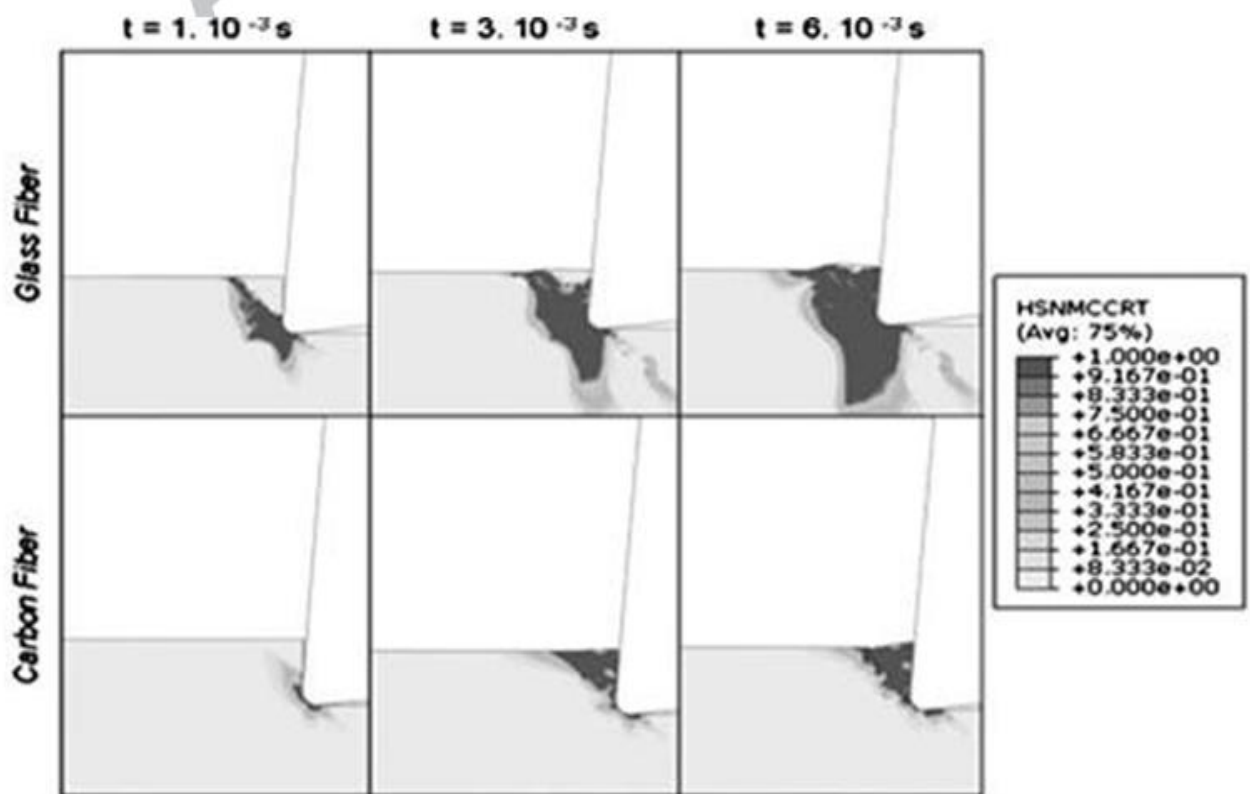


Fig. 8. Comparison of matrix damage occurring in CFRP and GFRP composite (From, Carlos Santiuste, Xavier S, Maria Henar M. Machining FEM model of long fiber composites for aeronautical components. Compos Struct 2010; 92: 691–98. Reproduced with permission of Elsevier)



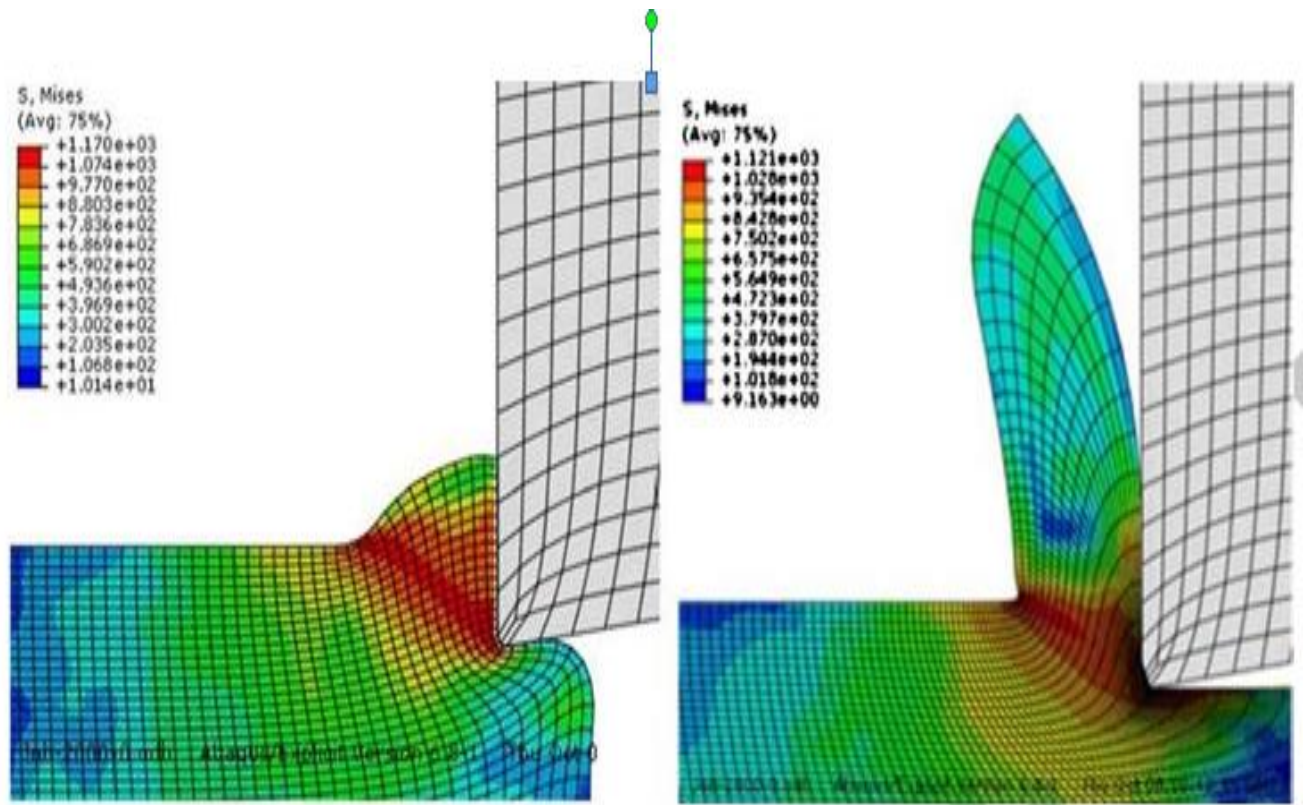


Fig.9. Formation of chip (a) initial stage (b) when depth of cut is increased (From, Li Zhou, Huang ST, Wang D, Yu XL. Finite element and experimental studies of the cutting process of Sic/Al composites with PCD tools. Into J Adv. Manu Techno 2011; 52: 619–6. Reproduced with permission of Springer)

### 3. 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) 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.

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