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Finite element analysis of CFRP composite material machining: A Review

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Abstract - *Rapid increase in utilization carbon fiber composite material (widely used in aviation, aerospace, defense and automotive, electronic information and high-speed machinery and other civilian areas) in these years led to numerical modelling of material behavior & defect formation while machining. But anisotropic & inhomogeneous nature of material causes challenges while modelling & result interpretation. Based on the comprehensive literature survey from the past few years, it is noticed that limited research has been made and published concerning machining modelling of CFRP (Carbon Fiber Reinforced Polymer) composite material. This paper gives precise review of current trends in modelling of machining CFRP composites in different solvers in different countries. Some key contributions such as experimental and numerical studies are urgently demanded to address accurately various factors affecting machining of CFRP composite laminates.*

Key Words: **Finite element analysis; Drilling force; Drilling experiment; Carbon fibre composite material; Numerical Modelling; Delamination, Cutting forces**

1.INTRODUCTION

With the continuous improvement of composite materials properties, material machining technologies are increasingly high requirements. Carbon fiber composite material as an advanced composite material is widely used in aviation, aerospace, defense and automotive, electronic information and high-speed machinery and other civilian areas. Since the carbon fiber composite material having a large strength, corrosion resistance, damage tolerance, resistance to fatigue, thermal & acoustic insulation power, anisotropy, and poor thermal conductivity and other characteristics when compared to conventional material & alloys. Even though they have ability of near net fabrication, machining is required for drilling, to remove excess material. Due to the special mechanical properties of the composite materials, resulting in poor cutting performance. It can easily cause large plastic deformation and processing defects during the processing, such as micro-cracking, matrix burning, fiber-deboning, fiber pullout, fiber buckling, matrix cracking delamination, burrs etc. Lead to serious tool wear affecting machining precision and efficiency.

Using finite element simulation method, we can observe the physical phenomena in the process to simulate actual system by physical or mathematical models. Realized the visualization of parameters value, it can also be used to predict the surface defects in materials processing, guide the tool design and parameters optimization and optimize the cutting process parameters and so on. Therefore the application of finite element techniques to study the cutting process has a very important significance.

1.1 Metal Cutting versus Composite cutting

Shuji Usui et.al.[3] shows an essential difference exists between metal cutting and composite cutting physics. In metal cutting, the strain can become larger than 1.0, forming a continuous chip with little dust or internal damage. In composite cutting, strain is relatively small, while dust and internal damage are created. Cutting energy is combination of surface energy & friction. Additionally, according to Irwin's fracture theory, the plastic work associated with the crack propagation can be counted as surface energy as well.

Metal Cutting
Cutting Energy = Plastic Work + Friction

Composite Cutting
Cutting Energy = Surface Energy + Friction

1.2 Need for FE Analysis of machining of composite material

To eliminate work piece damage during machining, research has been carried out consisting of experimental investigation, empirical & analytical modelling, and numerical modelling consisting of finite element analysis. Drawback with experimental investigation is that it is expensive, time consuming & health, safety issues can be possible because of inhalation of fiber debris.

Drawback with empirical analysis is that they are only valid in operational window of experimental setup & do not account for effect in process mechanism. Drawback with analytical analysis is that they are made to satisfy assumptions that do not cater complete problem definition. In contrast, numerical methods can simulate the machining process with more complexity & give opportunity to evaluate results that are difficult to evaluate experimentally (stress at primary or secondary shear zone). However scale and accuracy of numerical simulation is limited to computational cost.

2. Finite Element modelling Technique

Alessandro Abena et.al. [1] shows that wide range of parameters must be considered when developing FE simulation of machining composites. Model scale has influence on material modelling and failure mechanism. For last 15 years material properties of composites is represented in FEA as equivalent homogeneous material (EHM). This technique is applied at macroscopic level where material is anisotropic and homogeneous. This provide useful information regarding bulk chip formation but lack in interaction between fiber-matrix, which is important to understand defect formation and propagation. But is relatively straight forward to implement at reasonable computational cost. New modelling technique was presented in paper is microscopic simulation methodology (fiber, matrix, and interface). These models have more computational cost, but they provide a comprehensive understanding of cutting mechanics.

To take advantage of both modelling techniques, anyone modelling method can be used at given location depending upon level of accuracy to be achieved. Workpiece material near tool can be modelled by micromechanical model and EHM further away from cutting zone to improve computational cost. Instead of quasi-static analysis, dynamic analysis give better results.

While micromechanical modelling interface of fiber and matrix is considered as separate entity, so that debonding is evaluated. Cohesive elements based on traction-separation law are implemented with thickness value to be zero. Their paper represents a cohesive zone model based on traction-separation law applied to small thickness (0.25μm) implemented via bespoke use subroutine.

Analysis is done on ABAQUS/Explicit. EHM section of workpiece is not in contact with tool, so material considered in that region is anisotropic and homogeneous with pure elastic behavior (4 node plane stress element with reduced integration). While at interface, modelling is done as individual phases with different failure models (element size 1μm). Behavior of matrix epoxy is complex because it is highly dependent on strain rate, temperature, loading. Cutting speed taken as 0.5m/min to have linear stress-strain curve. It was described as elastic-plastic curve, where plastic is defined by mean Von Mises yield criteria & isotropic hardening.

Carbon fiber experiences brittle mode damage. Failure is by maximum principal stress criteria. Carbon fiber is modelled as strain rate independent. Cutting tool is simulated as rigid body, due to elastic modulus is comparatively high than fiber, matrix.

New model (combined EHM & micromechanical model) developed shows close agreement with published experimental & numerical data. Result indicates compressive forces must be considered in numerical model in order to achieve accurate subsurface damage prediction.

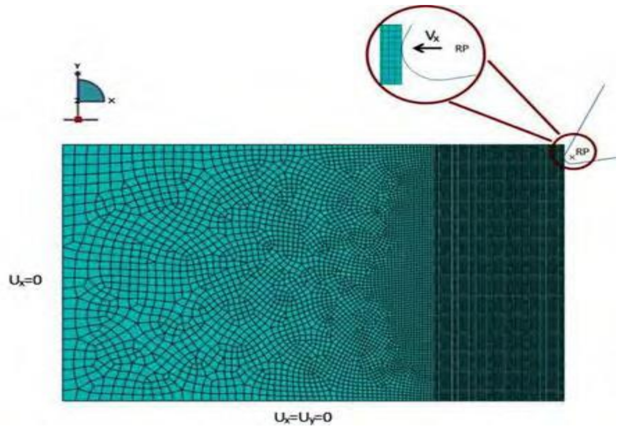

Fig.1: Initial undeformed FE model with boundry condition

Mingyang Wu et.al.[2] shows on the main cutting edge of drilling bit with different points, the rake angle is constant changing, which is from positive to negative gradually, from the most outside point of main chip edge to chisel edge, and on the chisel edge negative rake angle has reached the maximum.

Machining process is a process of elastic-plastic deformation coupling, and with large deformation and large strain, the linear relationship of elastic-plastic cannot explain composite material cutting process, because the composite material is composed of reinforced phase and matrix, at this point the relevant content of nonlinear finite element should be considered it is different from the way of the linear finite element stress and strain. Aim is cutting process simulation of composite materials, also included the shock, collision, forming etc. the analysis of dynamic problems, elastic-plastic stress-strain relationship model is the most classic material nonlinear mechanical problems, it has become the indispensable model in finite element analysis material nonlinear problems .

Deform-3D is a simulation system based on industry relevant for the analysis of metal forming and heat treatment processes, including imported models, meshing, adding constraints, post-processing step. Finite Element Simulation of machining is an extremely complex process, it need to have knowledge of the theory of finite element basis, while closely related to the mechanics, in the application of simulation software, to combine elastic mechanics, knowledge of fracture mechanics and plastic mechanics. Carbon fiber composite material cutting simulation process is based on the theory of elastic-plastic deformation of materials, this paper finite element simulation software

Deform-3D conduct drilling process simulation, analysis of variation in the drilling process drilling force and torque.

Due to the finite element simulation software Deform-3D provided in the material library does not include the carbon fiber composite material models, it is necessary to establish a new material model, then the need for mechanical and physical properties of the material-related parameters. The constitutive model of metallic materials include: Young's modulus, Poisson's ratio, thermal expansion coefficient, thermal conductivity, heat capacity, radiation. For special structure of carbon fiber composites, and traditional metal materials different, it is difficult to determine the constitutive relation. According to a feature flow stress-strain curve, choose empirical formula as an effective means of building a carbon fiber composite material constitutive model, the application Deform-3D software provides curve fitting techniques.

N.Duboust et.al.[4] shows a study on the milling of carbon fiber reinforced laminated composites. Models were validated by edge trimming experiments on a uni-directional laminate at different fibre orientations using a three flute PCD milling tool. MSC Marc was used to develop the model and in conjunction with a Hashin damage material model.

Machining trials were performed on a carbon fibre material made of fibre type T700GC and an epoxy resin matrix of Hexply M21.

Uni-directional samples were manufactured by pre-preg lay-up and autoclave cured. The finite element models were created using an implicit approach in the advanced nonlinear MSC Marc software. The cutter body was modelled as a rigid body and given rotational and feed direction velocity boundary conditions. The composite workpiece was modelled as an orthotropic EHM material. A Hashin damage model was used to reduce the stiffness of composite elements to a small residual value based upon the fibre and matrix tensile, compressive strengths and interlinear shear strength. Fully damaged elements were removed from post-processing visualization. Prior to damage the composite will have a geometrically nonlinear, elastic response depending upon its orthotropic elastic modulus.

The cutter was modelled as a rigid body with meshed solid elements to describe the tool surfaces. However a portion of the tip which is in contact with the workpiece was given elastic properties of PCD in order to simulate deformable contact.

Full integration, plane strain quadrilateral elements were used in the 2D model. A Lagrangian spatial framework was used; in which the material is fixed to the mesh. The use of reduced integration elements was advantageous in reducing the time for both the stiffness matrix assembly and stress recovery at each iteration for each of the element integration points. A reduction of the number of integration points from 8 to 1 was achieved in the 3D hex elements.

2.1 The finite element mesh

Mingyang Wu et.al.[2] define the workpiece material, due to the drilling is a very complex process, finite element technique to simulate drilling process is accompanied by huge amount of calculation, in order to make the calculation simple and convenient process, the difficulty of the problem is reduced, on the premise of meet the requirements of cutting simulation, the size of the established workpiece model should be reduced as much as possible.

Meshing is a very important step in the process of establishing the finite element model, the mesh in the form of a direct impact on the amount of calculation and calculation accuracy, with the increase of the mesh number, the higher the calculation precision and the longer the calculation time, therefore, the number of the grid can be defined by a measure of these two requirements.

The drilling process simulation is a highly nonlinear numerical calculation problem ,which defined by the element in the simulation has the strict request. Use of limited computing environment and larger feed rate, and meet the requirements of the mesh density, this will cause the cutting force and drastic fluctuations.

Shuji Usui et.al.[3] shows each ply is modelled separately as an independent UD-CFRP (Unidirectional CFRP) and has its own orthotropic elastic properties and material coordinate system. The UD-CFRP are stacked up according to stacking sequence of composite. Then each ply is discretized equal spacing orthogonal structured mesh. The structured mesh is aligned with fiber orientation. CFRP exhibits strong heterogeneity and anisotropy in its failure mode, which depends on the fiber and the ply orientation. Superimposing the mesh structure upon the UD-CFRP structure aids in capturing the fractures which occur in CFRP machining.

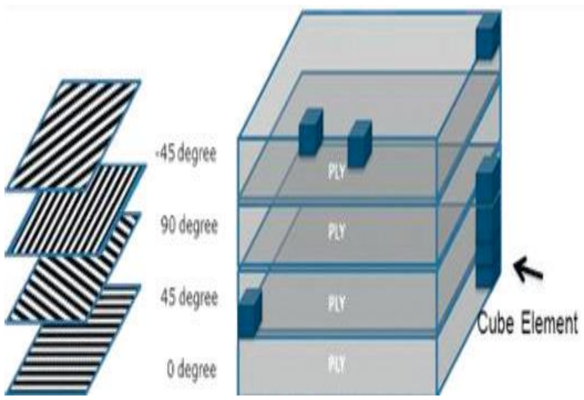

Fig.2: 0º/45º/-45º/90º cross ply layout and elements

2.2 Analysis steps & Boundary condition

Mingyang Wu et.al.[2] shows that the analysis of the drilling cutting force distribution, determine the finite element model and the constitutive model of the carbon fiber composite material, the definition of the analysis steps and boundary conditions, to simulate the dynamic drilling process. In the spindle speed is 3000 rpm and feed speed is 210 mm/min conditions, get the PCD drill bit simulation of cutting force and torque values, analysis of the changes to the Z drilling force of law. Make the drilling experiments, to obtain comparative experimental and simulation error value is 7.4%, which can verify the correctness of the carbon fiber composite material cutting finite element model, to improve the carbon fiber composite machining technology, drilling force prediction effectiveness, optimized tool parameters plays an important role. The simulation and experimental values of the drilling force found that the carbon fiber composite material during drilling X, Y direction cutting force can be approximated as zero.

3. Results & Discussion

Alessandro Abena et.al. [1] shows that predicted cuttting force from current FE simulation incarporating novel cohesive zone relationship compared against corresponding experimental & numerical FE results. Experimental data revealed a reduction in cutting force with increasing fiber orientation from 45° to 135°. Predicted cutting force obtained from both present simulation & numerical FE result in literature showed equivalent trend & exibited close agreement to experimental values for fiber angles of 90°& 135°, but were underestimated for those around 45°.

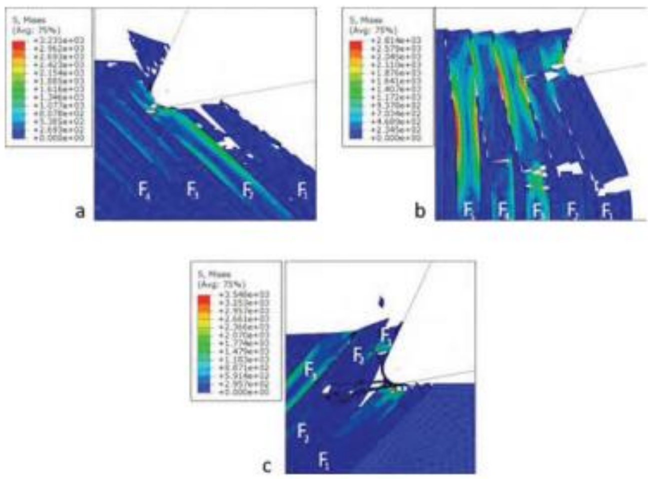

Fig.3.: Failure mode for 45°,90°,135°

3.1 Effect of orientation of fiber on machining process

Shuji Usui et.al.[3] shows the simulation result for a fiber orientation of 45° . The fiber is compressed and crashed in the transverse direction at the tip of the tool and then the chips were separated in Mode II fracture at the fiber/matrix interface. The chips formed in this orientation are smaller than those formed in the 0° orientation. Fig. shows the results for a 90° fiber orientation. The small chips were fractured and flew away periodically and macroscopic cracking on the machined surface along the fiber orientation were observed ahead of the tool. Fig. shows the results for the -45° fiber orientation case. The crack emanated ahead of the tool and proceeded deep down into the workpiece. The workpiece was split in half for this case in the orthogonal cutting experiment.

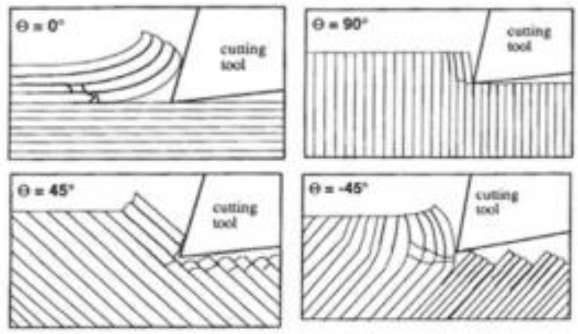

Fig.4: Orthogonal cutting mechanism of CFRP

4. Experimental Validation

4.1 Drilling force experiment

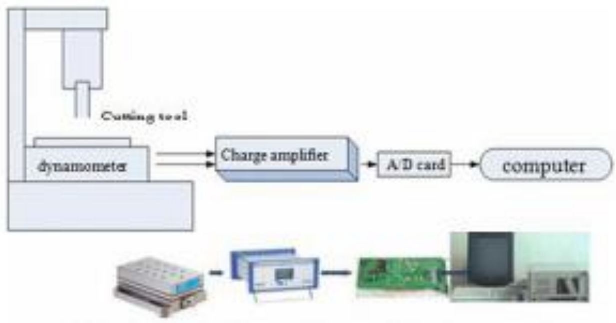

Fig.5: Drilling force measuring experiment system

Mingyang Wu et.al.[2] shows for the design of high speed drilling experiment system, which consists of two parts: machine tool parts and axial force measuring system, under the system of drilling carbon fiber composite materials. Machine tool selection triaxial linkage CNC milling machine VDL - 1000 E; Axial force measuring system is mainly composed of four parts: the dynamometer, PC, A/D signal acquisition card and charge amplifier, Kistler dynamometer using the Swedish company's 9275B.

With the dynamometer is fixed in CNC machine table, carbon fiber composite material plate by plate fixed on the load meter, dynamometer at work, will be produced in the process of drilling axial force is converted into electrical signal values of the same size, it again into numerical signals to a computer, by the corresponding computer software to record and analyze process data. The experimental parameters of the spindle speed of 3000 r/min, the feed rate of 210 mm/min.

4.2 Orthogonal machining validation

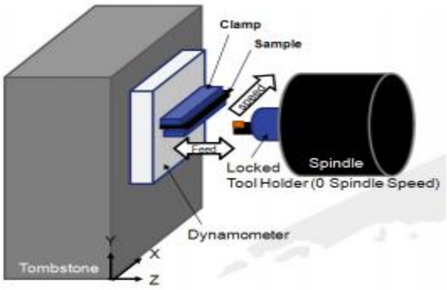

Fig.6: Machine test setup schematic for UD-CFRP orthogonal machining

N.Duboust et.al.[4] shows UD-CFRP orthogonal machining test was conducted at Third Wave Systems. The experiment was performed on a Mori-Seiki NH6300 horizontal machine. Fig. shows the machine setup. Unlike drilling, milling, or trimming, the experimental test used a cutting tool fixed in rotation by the locked spindle.

The cutting tool holder was designed to allow for the cutting insert to be positioned in direct alignment with the spindle center axis. The alignment of the insert in this way reduces the cutting moment on the spindle. The Kistler 9255B dynamometer collects forces via piezoelectric sensors in the X, Y and Z-directions. The fixture was designed to align the UD-CFRP specimen along the X-axis of the dynamometer. Fig. 6 shows the simulation model of the orthogonal machining in comparison to the experimental setting.

4.3 Experimental method

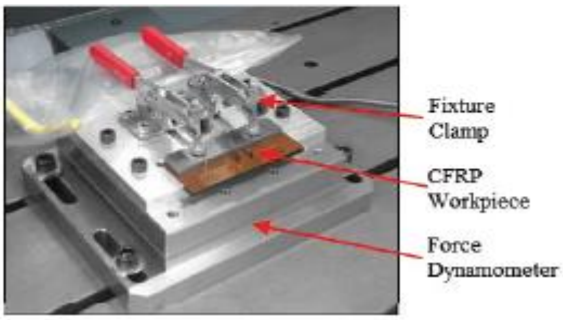

Fig.7: Workpiece, dynamometer, fixture

N.Duboust et.al.[4] shows machining trials were performed on a carbon fiber material made of fibre type T700GC and an epoxy resin matrix of Hexply M21. The sample has dimensions- 160mm length, by 65.5mm wide and 6mm thickness. The cutting tests were performed on samples with 45 and 90 degree fibre orientations. A 3 flute Poly crystalline Diamond (PCD) tool was used. A laser cut PCD tool was chosen due to its sharp cutting edge, high hardness, and resistance to wear; and is suitable for machining abrasive carbon fibers in CFRP. The PCD tool was also chosen because it has a zero helix angle; and the relatively simple geometry could be compared with FEM.

Machining was performed on 5-axis Cincinatti FTV machine tool and a Kistler dynamometer was used to record machining forces. A sampling frequency of 20,000 Hz was used in order to record machining forces in x,y and z direction. Where the Fx force is parallel to the tool feed and the Fy force is normal to the workpiece machined surface. Two levels of feed rate and cutting speed were used; a feed of 800 and 1200 mm/min and a cutting speed of 6000 and 8000 RPM. The axial depth of cut (ap) was kept constant at 6mm and the radial depth of cut (ae) at 2mm. The tests were performed using a worn and unworn tool with average an average edge radius of 10μm and 3μm respectively. These measurements were taken using an Alicona optical focus variation system. Each test was repeated once and the mean Fx and Fy cutting force were recorded.

5. Advanced Adaptive convergence control

N.Duboust et.al.[4] shows an advanced, adaptive convergence control was used with MSC Marc to ensure that the load step can reduce or increase within specified limits depending upon the degree of nonlinearity encountered within the iterative process. This means that more increments will be used when most required in the simulation, such as when there is contact or sudden material failure. This is useful in a milling simulation because at some points in time, as the tool rotates, there is no contact from the tool and the time step increments will be automatically increased, thus reducing the computational time significantly. For this reason the number of cutters was increased to six in the simulation, compared to the three on actual tool in the experiment. This was so that during the simulation there would be less time spent where there was no contact or cutting taking place. The feed rate and speed was decreased accordingly so that the size of chip removed will remain the same as in the experiment. It was also ensured that only one cutter is in contact with the workpiece at any one time. The convergence criterion was selected to converge on both nodal residuals and displacements. Strain objectivity was invoked through the use of large rotation option, to ensure zero non-physical strain development during the large rotations experienced by the cutting tool mesh.

An automatic, local adaptive meshing technique was used on the workpiece to decrease the element size in areas of high stress gradient and localized contact. A refinement level of two was used, which decreased the element size to 1/16th of the original size. This was applied to the elements in the top half of the workpiece and which were nearest to the tool contact.

A new FE method has been developed for modelling of the edge trimming process of fiber composites. 2D and 3D CFRP milling simulations were applied and validated against experimental data including the effects of tool wear and fiber orientation. The results showed that tool wear has a significant effect on the measured cutting forces, and must be taken into account when comparing numerical simulations and experimental results. It was shown that the cutting forces and surface damage will be different depending upon the fiber orientation. Increasing the feed rate was generally found to increase the machining forces, while increased cutting speed had the opposite effect due to uncut chip thickness. Higher cutting forces were found on the 90 degree fiber orientation which is due to the predominantly fiber shearing cutting mechanism.

MSC Marc was found to be useful software for the analysis of composite machining. A successful correlation was found between experiment and FE model and the model was able to give information on the effects of different fiber orientation and cutting parameters. The effect of tool wear was found to have a significant impact on measured cutting forces and had a stronger effect than either cutting parameters or fiber orientation. Further development of these 3D models will allow the analysis of models for edge trimming on laminates with multiple stacking sequences or varying fiber orientations. It will also allow the study of the effects of new and different tool geometries.

6. Summary

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

FE Analysis provides information about subsurface machining indepth. Different parameters such as material properties of composites, element to be used for analysis (modelling technique), boundary condition should be closely monitored so that there will be correllation between experimental and analysis results.

With knowledge available from FEA, machinig parameters can be modified to minimize delamination, fiber cracking etc.

Therefore, in order to produce defect free holes and mechanical joining of composite structures, the process of machining on CFRP needs to be monitored.

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