Finite element analysis of the slot milling of carbon fiber reinforced polymer composites

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Abstract. Carbon Fiber Reinforced Polymer (CFRP) composites are widely used for making the components and primary structures in the field of aircraft, aerospace, automobile, medical, construction and many essential items which we use every day. These composite laminates are light in weight without compromising its strength. Hence, CFRP composites attract the researchers and the modern industries to investigate more on it. Industries rely on conventional machining process to achieve required shape and size, but CFRP composites show intrinsic behaviour while machining because of its non homogeneous properties. Selecting the appropriate tool and the cutting conditions for machining the CFRP composite, influences more in achieving the desired shape, size with close tolerance. In this paper, a 3D Finite Element Model is developed to simulate the slot milling process and to predict the cutting forces for the different cutting conditions. The reliability and accuracy of 3D FE analysis depend on the friction coefficient and failure model used in the FE model. These FE input parameters were applied in a wider range and analysis was carried out. The cutting forces obtained from the FE results are correlated with the experimental results to validate and to evaluate the influence of the FEM parameters. The outcome of this investigation is to suggest a suitable Failure model and the Friction coefficient, which ensures the reliability of the FE Model.

Keywords: CFRP Laminate, Slot milling Process, Cutting forces, 3D FEM, Failure Criteria, Abaqus.

1. Introduction

The applications of Carbon Fiber Reinforced polymers (CFRP) are very extensive in the field of Automobile, Aerospace and Aircraft since it is superior in strength to weight ratio, non corrosive and thermal resistance properties\cite{1}. More than 60 % of the materials used in the construction of aircraft are CFRP composites. Moreover, the CFRP material is used in making tennis rackets, automobile components, domestic items such as chairs and tables, sports equipments, bridges, pressure vessels, pumps, electrical panels, wheel chairs, automobile bumpers, suspension springs and much more. Mostly these items are made in near net shape; however milling operation is required to achieve the required shape and size. The different types of failure occur during the milling process, which must be investigated to get defect free products \cite{2}. Conducting experimental investigation require more resources and it is consumes more time; moreover it is not advisable for a wider machinability matrix \cite{3, 4}. This requirements leads to the development of 3D FE Models to analyze the milling operation,
which is very much suitable for studying the process at wider machinability matrix and effective even for elevated cutting parameter settings [5]. The 3D FE simulation result reveals the milling process very effectively and predicts the cutting forces during machining, chip formation process, chip characteristics and stress. However, the accurateness and consistency of the FE results rely on the FE model input parameter settings [6]. Hence, it is very much essential to investigate the influence of these FE model input model parameters to improve the quality of the 3D FE model and to get enhanced agreement with the experimental values [7]. The FE input parameters such as Friction coefficient, Element size, Failure model are vital parameters which influence more on FE output results. This paper aims in investigating the influence of Friction coefficient and the Failure model in the 3D slot milling simulation results and cutting force data. The validated FE model is used in this investigation and compared with the experimental result data from the literature [8]. The outcome of this investigation suggests a suitable failure model and friction coefficient for the researchers and industries to ensure good and consistent 3D FE model to simulate the slot milling process of CFRP laminate.

2. Milling experiment and results

The milling experimental studies are carried out in a NAMMIL vertical milling machine with the machining parameters given in the Table 1. The cutting parameters were selected based on the literature review and moreover, it helps to visualize and understand the chip formation, machining process effectively. The authors already have published a paper on the above mentioned experimental studies in detail [8]. The UD-CFRP composite laminates used in this experimental investigation measures 100 x 50 x 10 mm. The specifications and mechanical properties of the UD-CFRP composite laminate is given in the Table 2. A 10 mm diameter solid carbide end mill cutter coated with TiAlN is used for the slot milling operation [9]. The IEICOS mill tool dynamometer is used to obtain the cutting force data and the data is processed by an analogue to digital converter to plot the cutting force graph. The cutting force results obtained from experimental trials [8] are given in Table 3. The cutting force obtained from the experimental studies shows a fluctuating pattern which is due to the varying fiber orientation angle with the cutting edge of the tool (shown in Figure 3). The chips are mostly tiny, fragile and in the form of slightly curved flakes. The chips obtained from the experimental studies exposes the various composite failure modes such as fiber and matrix failure in tension, fiber and matrix failure in compression. The debonding of matrix and fibre, matrix cracking, interlaminar fibre failure is also observed in the milled chips.

Table 1. Machining parameters used in slot milling of UD-CFRP composite [8]

| Machining parameters         | Magnitude                  |
|-----------------------------|----------------------------|
| Spindle speeds, N (rpm)     | 350, 660, 900, 1700        |
| Cutting Speed, Vc (m/min)   | 10.99, 18.84, 28.26, 53.38 |
| Feed rate, f (mm/min)       | 50, 150, 350               |
| Depth of Cut (mm)           | 1                         |
| Fiber orientation           | 0° - Unidirectional        |

Figure 1. 3D FEA Model of slot milling CFRP laminate.
Table 2. Mechanical Properties and Specifications of UD - CFRP laminate [8]

| Specifications                                      | Value(s) |
|-----------------------------------------------------|----------|
| Modulus in Longitudinal Direction, $E_x$ (GPa)       | 135      |
| Modulus in Transverse Direction, $E_y$ (GPa)         | 10       |
| Modulus in Transverse Direction, $E_z$ (GPa)         | 10       |
| Shear Modulus along plane XY, $G_{xy}$ (GPa)         | 5        |
| Shear Modulus along plane YZ, $G_{yz}$ (GPa)         | 3.7      |
| Shear Modulus along plane XZ, $G_{xz}$ (GPa)         | 5        |
| Poisson's ratio, $\nu$                              | 0.27     |
| Density (Kg/m$^3$)                                  | 1590     |
| Resin / Fiber Ratio                                 | 35:65    |
| Polymer                                             | Epoxy Resin |
| Matrix                                              | Carbon Fiber |
| Allowable Tensile Strength in fiber direction, $X_t$ (MPa) | 1500     |
| Allowable Compressive Strength in fiber direction, $X_c$ (MPa) | 1200     |
| Allowable Tensile Strength along Transverse direction (Y axis), $Y_t$ (MPa) | 50       |
| Allowable Compressive Strength along Transverse direction (Y axis), $Y_c$ (MPa) | 250      |
| Allowable Shear Strength in XY plane, $S_{xy}$ (MPa) | 70       |
| Allowable Shear Strength in YZ plane, $S_{yz}$ (MPa) | 70       |
| Allowable Shear Strength in XZ plane, $S_{xz}$ (MPa) | 70       |
| Fiber Orientation (Degree)                          | 0        |

Figure 2. Changes in cutting force with cutting edge position during slot milling of CFRP Laminate [8, 13]. Cutting forces Vs Tool rotation angle in degrees.
3. FEA in slot milling of CFRP laminate
A 3D FE Model is developed (shown in Figure 1) in ABAQUS/Explicit to simulate the slot milling process and to understand the machining operation very effectively [10]. The End mill cutter is modeled in CATIA V5R14 [11] and workpiece (CFRP Laminate) is modeled in ABAQUS. The tool and the workpiece models are meshed with 3D elements and their material properties are incorporated with Autodesk Helius PFA plug-in [12]. The key FE input parameters are Failure model, friction coefficient, damage initiation and evolution criteria, output requirements, solvers, solving time, interaction properties between the tool and workpiece and the boundary conditions. A range of friction coefficients (0 to 1.0) and the Failure criteria such as Hashin, Christensen, LaRc02 and Puck were incorporated into the 3D FE model. The investigation was performed to report the influence of friction coefficients and to suggest a good failure model in order to enhance the accuracy of the 3D FE results and thereby ensuring the reliability of the FEM. The cutting force data obtained from 3D FE simulation results were compared with the experimental outcomes to evaluate the influence of the above mentioned FE model parameters.

4. FEA results and discussion
The Cutting force prediction is mandatory and essential to study the machinability of the CFRP laminate. Moreover, the larger fluctuation in the cutting force leads to poor quality of the milled surface and vibration of the machine. The composites are heterogeneous in nature and the cutting force varies with respect to fiber orientation and also with the cutting edge of the tool (shown in Figure 2) [13].

4.1. Comparison of cutting force data for various coefficient of Friction.
The interaction between the tool and the laminate is incorporated to the 3D FE model in order to define the surface erosion process of slot milling [14, 15]. The Coulomb friction theory with tangential behaviour is incorporated in the FE model to have a realistic machining approach. The friction coefficient used by the researchers for TiAIN coated tool and CFRP laminate is 0.7.
approximately [2]. The maximum cutting force is predicted using 3D FE simulation results for different friction coefficients and it is compared with the Experimental data (given in Table 3). The results reveal that, Friction coefficient approximately around 0.7 provides comparable results with the experimental data and the literature [8, 9]. Hence, friction coefficient of 0.7 is recommended for further FE slot milling simulation studies which possess similar input and output parameters.

Table 3. Predicted Cutting Force Data from 3D FE simulation for various Coefficient of Friction with HASHIN Failure Criteria.

| Machining Parameter settings | Force Component (N) | Expt. data | Coefficient of Friction (μ) | Maximum Cutting Force from FE results |
|-----------------------------|---------------------|------------|-----------------------------|--------------------------------------|
|                             |                     |            | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| F = 50 mm/min, Vc = 10.99 m/min | F_x | 35 | 24 | 24 | 23 | 24 | 23 | 25 | 38 | 24 | 25 | 24 |
|                             | F_y | 30 | 21 | 23 | 24 | 23 | 22 | 24 | 33 | 24 | 23 | 22 |
|                             | F_z | 11 | 1  | 2  | 1  | 2  | 1  | 3  | 7  | 1  | 2  | 1  |
| F = 150 mm/min, Vc = 10.99 m/min | F_x | 36 | 23 | 24 | 26 | 20 | 22 | 28 | 35 | 34 | 28 | 28 |
|                             | F_y | 28 | 24 | 23 | 22 | 21 | 20 | 24 | 26 | 24 | 22 | 24 |
|                             | F_z | 15 | -4 | -4 | -4 | -4 | 4  | 3  | 8  | 10 | 5  | 3  |
| F = 350 mm/min, Vc = 10.99 m/min | F_x | 32 | 32 | 14 | 18 | 20 | 23 | 15 | 30 | 27 | 26 | 23 |
|                             | F_y | 19 | -35| 13 | 16 | 20 | 20 | 12 | 17 | 20 | 22 | 18 |
|                             | F_z | 12 | 30 | 10 | 9  | 5  | 7  | 3  | 10 | 8  | -4 | -5 |

4.2. Analysis of cutting force profile for various failure models

The selection of suitable failure criteria plays a vital responsibility in the accuracy and reliability of the machining simulation results. Moreover, the selection of failure criteria also depends upon the capability of the criteria in predicting the requisites (failure modes of the laminate, interlaminar failure). The cutting force profile and the data predicted from FE simulations must be in good agreement with the experimental results. Among the four failure models used in this investigation, Hashin failure criterion recognizes all four modes of failure such as, fiber and matrix failure in tension, fiber and matrix failure in compression and moreover the results are in better agreement with the experimental results [16]. Whereas, Christensen criterion make sure the fiber and matrix failure only.
Predicted Cutting force Profile from 3D FE Model in Slot milling CFRP Laminate at $V_c = 10.99$ m/min, $N = 350$ rpm, Feed = 350 mm/min, Depth of cut = 1 mm.

The Puck criterion predicts the fiber failure and inter fiber failure, LaRC02 criterion discloses the fiber failure and matrix cracking only in unidirectional composites. The FE analysis is carried out with all these damage models at $V_c = 10.99$ mm/min. Spindle speed, $N = 350$ rpm, Feed rate = 350 mm/min, Depth of cut = 1 mm. The cutting force profiles obtained were compared (shown in Figures 4, 5, 6, 7). Hashin failure model provides a unique cutting force profile, and whereas Puck, Christensen, LaRe02 failure models shows an entirely different kind of cutting force profile. Moreover, cutting forces $F_x$ and $F_y$ simulated by the Hashin failure model overlaps each other which is in good accordance with the experimental cutting force profile shown in figure 3 and the literature [2, 9, 13]. Hence, from this investigation it is confirmed that Hashin failure model is good enough in satisfying our requirements and it is suggested for further 3D FE slot milling machining simulation studies.

4.3. **3D Finite Element simulation of chip formation process.**

The Chip formation can be visualized from Figure 8 which shows that, chip is formed due to plastic deformation and development of stress at the cutting zone. The Simulation results obtained from the developed 3D FE model shows the chip formation process.

a) Chip tend to curl  b) Chip breaking  c) Chip fragmented and released and Chip flows in air

**Figure 8.** Chip Formation Process in FEA Simulation at Cutting speed, $V_c = 28.26$ m/min and feed rate, $f = 50$ mm/min.
The chip have a propensity to curl slightly since the rake face of the tool slides over the composite laminate, however the inherent properties of the CFRP laminate does not allow the material to curl further, rather it breaks and forms a flake like chip. The chip obtained from FE simulation (shown in Figure 8) resembles the experimental chip, in size and shape. Since, the carbon fiber is brittle in nature the milled chip does not deform much, rather it is broken into tiny flakes which is understood from Figure 8.

5. Conclusion
The validated 3Dimensional FE model used in this investigation for slot milling simulating of UD-CFRP composite is trustworthy and good in predicting the cutting force profile and magnitude.

- The friction coefficient ranging from 0 to 1 is selected and 3D FE machining simulations studies are performed. The cutting force results predicted by the 3D FE simulation studies with the friction coefficient of 0.7 is in good agreement with the experimental results and the literature.

- Among the various composite failure models used in this research work, Hashin Failure model is suggested for further 3D FE investigations. Since, the cutting force profile and the data predicted by the Hashin damage criteria is in accordance with the literature and experimental results. Moreover, when compared to other failure models Hashin Failure model alone is capable of recognising all the mode of composite failures which is very much needed to predict at the earliest for avoiding premature component failures.

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