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Drilling of Uni-directional Carbon Fibre Reinforced Plastics with PCD Tools: Experiment and Finite Element Study

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Abstract – *Carbon fibre reinforced plastics (CFRP) are increasingly being used in aerospace due to its high strength to weight ratios, high resistance to corrosion and low thermal expansion coefficient. One of the preferred methods used and necessary to assemble (CFRP) components is drilling operation, polycrystalline diamond (PCD) tools is one of the solutions for drilling (CFRP). Different challenges are faced when drilling (CFRP), ''Peel-up'' and ''Push-out'' are two distinguishable delamination mechanisms associated with drilling of composite laminates. In this research, 3D finite element model (FEM) is developed for predicting the thrust force and torque at planned feed rate and speed combinations. The (FEM) results are found to be a close agreement with the experiment results.*

Keywords: Drilling, Delamination, Finite Element Model, Polycrystalline Diamond

1.0 INTRODUCTION

Increasing demand in a variety of industries (such as aircraft, spacecraft, automobile, marine, chemical processing equipment, and sporting goods) for high-performance, lightweight structures have stimulated a strong expanding development of fibre reinforced polymer composite laminates [1]. As a result, advanced composite materials make about 50% of the structural weight of Boeing 787 and Airbus A350XWB. Generally, parts made of composites are produced to a near-net shape, but additional machining operations are often required to facilitate component assembly. For example, joining of composite components to a structure often requires manufacturing holes in them in order to place bolts or rivets. To manufacture these holes, drilling is a commonly used machining process [2]. However, the defects and damages, such as delamination, burr, microcracking, swelling, splintering and fiber pullout, are commonly visible after drilling. The delamination at the entrance and exit planes of workpiece appears to be the most critical defect, which results in lowering the bearing strength and requires additional manufacturing operation to repair for increasing its service life under fatigue loads. Many references have shown that the thrust force is a major factor responsible for drilling-induced delamination and it mainly depends on drill materials, drill geometry and feed rate [3].

The direct experimental approach to study machining processes is expensive and time consuming, especially when a wide range of parameters is included: tool geometry, materials, cutting conditions, etc. The alternative approaches are mathematical simulations where numerical methods are applied. Amongst the numerical procedures, the finite-element methods (FEMs) are the most frequently used [4].

Rakesh et al [5] developed a finite element model in order to investigate the drilling behavior of FRPs, hey have concluded the drill point geometry plays a significant role in defining the damage characteristics while drilling in FRP laminates. A judicious selection of the drill point geometry on the basis of work-piece material will lead to production of damage free holes. Strenkowski et al [6] described a three-dimensional drilling model to determine the thrust force and torque in drilling process. They predicted the forces can be readily coupled with solids models, so that complex drill geometries can be accurately represented. Barschke et al [7] presented simulations of the behavior of composite materials based on kinematic restrictions among the fibers themselves and among fibers and the surrounding resin, the approach was used to obtain the material properties for a two layered material which can be applied to a three dimensional structures.

There have been many different geometry drill bits such as twist drill, step drill, brad point drill, slot drill, straight-flute and core drill made of different tool materials such as high speed steel (HSS), uncoated cemented carbides, coated cemented carbides, and polycrystalline diamond (PCD), have been used to understand the drilling processes of composite laminates. PCD has been one of the preferred solutions for the drilling of CFRP. However, given the manufacturing demands, a single drilling solution would be required to drill all possible material stackcombinations which include CFRP stacked with aluminum (Al) and CFRP stacked with titanium (Ti), all of these possible combinations must be drilled with accuracy, excellent surface finish, minimal coolant usage and minimal exit burr, over the course of thousands of holes in the least amount of time possible [8]. Durao et al [9] studied the effect of two variables on the drilling process of composite materials: the tool material and the tool geometry. Two tool materials – tungsten carbide (WC) and polycrystalline diamond (PCD) – with the same twist drill geometry were evaluated; and three different tool geometries of the WC drills – twist, Brad, and step, were assessed, results show that feed rate is the most important factor for delamination reduction, followed by tool geometry. Zhou et al [10] carried out a two-dimensional orthogonal cutting experiments and simulation analysis on the machining of SiCp/Al composites with a polycrystalline diamond tool, the results indicate that the cutting speed and depth have significant effects on the cutting force, and the predicted cutting force is in agreement with that of the experiment. Persson et al [11, 12] investigated the effects of hole machining defects on static strength and fatigue life of carbon/epoxy composite laminates. Traditional drilling processes were implemented using polycrystalline diamond-tipped drill (PCD) and cemented carbide drill with a sharp tip angle (Dagger drill). They reported that hole machining defects significantly reduced the static strength of pin-loaded PCD specimens about 11% compared to defect-free holes specimens, while this reduction percent become 2–3% for Dagger specimens. The fatigue strength at 106 cycles was, respectively, reduced to about (19–27%) and (9–11%) for PCD and Dagger specimens compared to defect-free holes specimens.

In this study a 3D finite element model for simulating the drilling process is developed to investigate the relative significance of the drilling parameters on thrust force and torque.

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2. EXPERIMENT SETUP AND MATERIALS

The workpiece used in the drilling experiment was a 4mm thickness of uni-directional CFRPVTM264, prepared using the hand lay-up process, its features and mechanical property database is available from Advanced Composite Group (ACG) datasheets [13].

Drilling tests were carried out on 3 axis HAAS CNC machining centre with maximum 10000 rpm. A six component force-torque Kistler dynamometer type 9257B was used to obtain the thrust force and torque. An eight channel Kistler charge amplifier type 5070A was used to amplify the thrust force and torque signals which were transferred to the data acquisition card, Fig.1 shows schematic drawing of experimental setup [9].

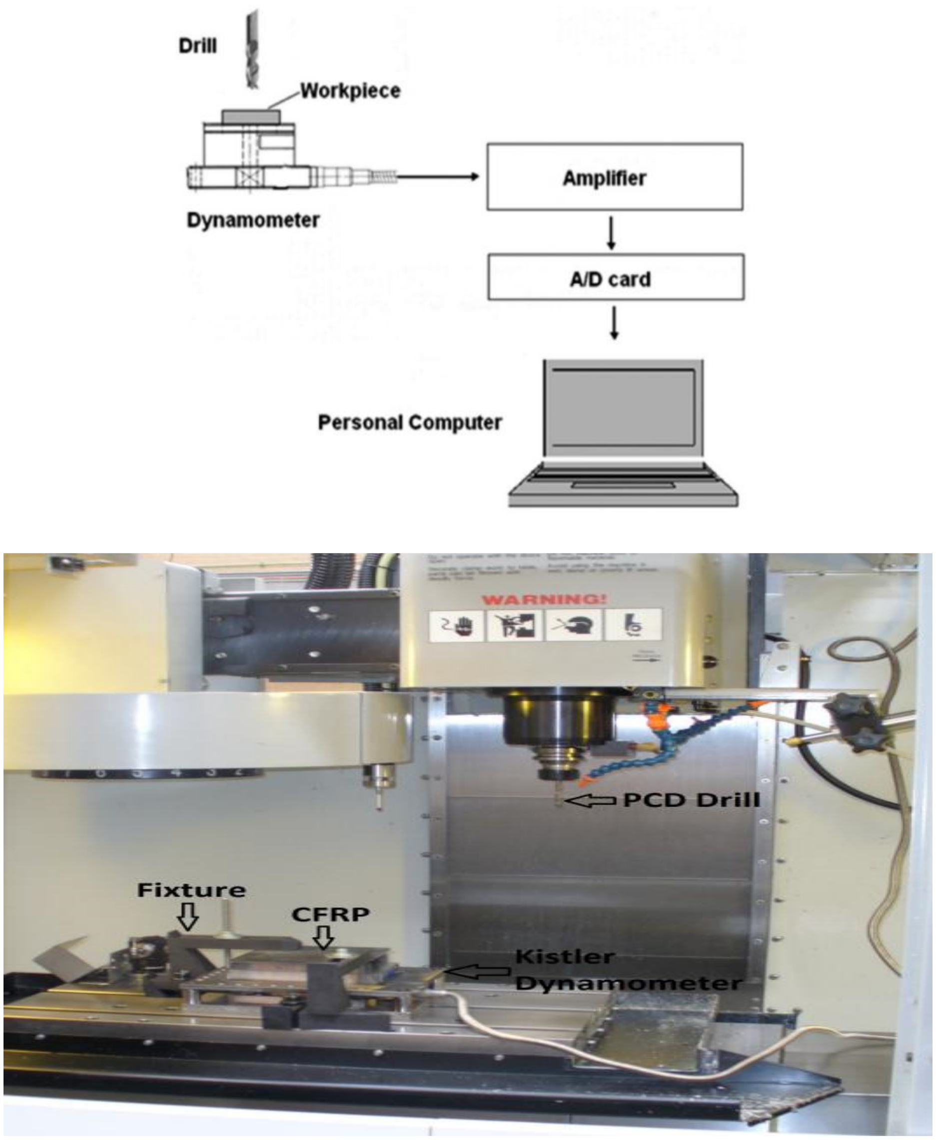

Figure 1: Experimental Setup

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3.0 FINITE ELEMENT SETUP

3D Lagrangian formulation finite element (FE) models of both twist drill and CFRP composite were developed using ANSYS-EXPLICIT &AUTODYN software. These models aimed to simulate the drilling process, predict induced cutting forces, torque, stress distribution in the work piece, and the delamination at the hole exit caused by the variant of different polycrystalline diamond (PCD) drill bit point angles. The heat generation was ignored since high amount of coolant was used in experiments to keep the temperature close to the room temperature. The FE model is shown in Fig.2.

3.1 Drill Bit Geometric Model

An 8mm diameter twist drill which has 120 degree point angle and 30 degree helix angle geometry was modeled in Autodesk Inventor and exported to Ansys Explicit. The twist drill was meshed with solid185 eight node linear tetrahedral elements. The mesh was refined at the drill tip with 300µm elements, total number of elements used to mesh the tool was 6,894. The drill was modeled as a flexible body to inflect the stresses on the drill but on the other hand which increased the computational time of the FE analysis, there were other assumptions which were considered to decrease the computational time of the FE analysis:

Due to being the chips mostly in form of powders, a 25mm drill length was modeled. The heat generated in the simulation process has been ignored, as high amount of coolant was used in the experiments.

3.2 Workpiece Geometric Model

A uni-directional CFRP composite laminate with stack sequence of [(0/90)2]s was used in the FE analysis having dimensions of 20mmx20mmx1.6mm consists of 8 plies. The thickness of each ply was 0.2mm. The workpiece was meshed with shell181 four node linear quadrilateral elements. The mesh was refinement in the drilling area with 200µm elements, total number of elements used was 4,205, while the contact interfaces between the plies were meshed with four node linear quadrilateral contact & target elements, total number elements used was 3,364.

3.3 Boundary Conditions and Loading

The boundary conditions were enforced on the twist drill and workpiece to enable simulation process, the twist drill was located at the top centre of the workpiece and was made to rotate (angular velocity) around the Z axis (urz) and moved in the cutting direction (uz). The workpiecewas fixed from the sides from moving (ux=uy=uz=0). Cutting parameters are listed in table.1.

Table 1: Cutting parameters used in drilling

Drilling parameter	Magnitude
Drill diameter (mm)	8
Spindle speed (rpm)	2500, 5000, 10000
Feed (mm/rev)	0.05, 0.10, 0.125
Feed rate (mm/min)	125, 500, 1250

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3.4 Material Modelling

A layered modeling approach was used for different components of composite laminate, the material model used for the workpiece was orthotropic homogeneous elastic assigned according to the fibre orientation through a defined local coordinate system, Table 2 shows the material properties of VTM264 obtained from the literature [14].

Table 2: Mechanical properties of unidirectional VTM264 laminate.

E11	E22	E33	v12	v13	v23	G12	G13	G23	CURED PLY THICKNESS
117GPa	7.47GPa	7.47GPa	0.33	0.02	0.33	4.07GPa	4.07GPa	2.31GPa	0.2mm

Hashin damage mechanism and failure criterion for the composite material was defined in the FE simulation process to simulate the damage process of matrix and fibre [15-16].

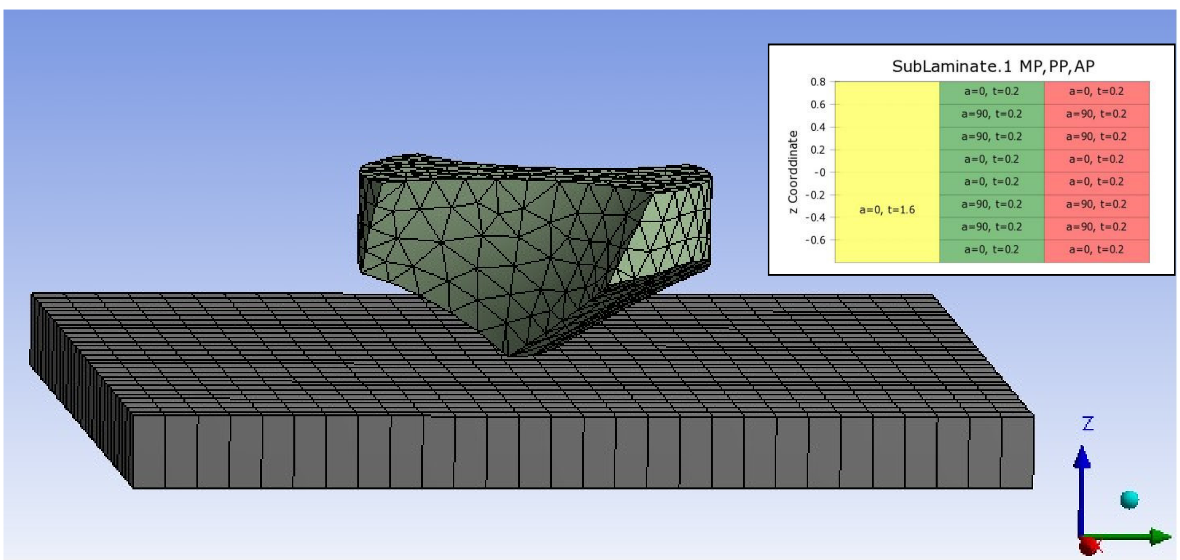

Figure 2: Finite element model of VTM264 CFRP Laminate &PCD twist drill

Tensile Fibre Mode

$$\left(\frac{\sigma_{11}}{\sigma_{11t}^{f}}\right)^2 + \left(\frac{\sigma_{12}}{\tau_{12}^{f}}\right)^2 = 1 \quad \sigma_{11} > 0 \qquad (1)$$

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Compressive Fibre Mode

$$\left(\frac{\sigma_{11}}{\sigma_{11c}^{f}}\right)^2 = 1 \quad \sigma_{11} \leq 0 \tag{2}$$

Tensile Matrix Mode

$$\left(\frac{\sigma_{22}}{\sigma_{22t}^{f}}\right)^2 + \left(\frac{\sigma_{12}}{\tau_{12}^{f}}\right)^2 = 1 \quad \sigma_{22} > 0 \tag{3}$$

Compressive Matrix Mode

$$\left(\frac{\sigma_{22}}{2\tau_{12}^{f}}\right)^2 + \left[\left(\frac{\sigma_{22c}^{f}}{2\tau_{12}^{f}}\right)^2 - 1\right]\left(\frac{\sigma_{22}}{\sigma_{22c}^{f}}\right)^2 + \left(\frac{\tau_{12}}{\tau_{12}^{f}}\right)^2 = 1 \quad \sigma_{22} \leq 0$$

When Hashin's criteria have been fulfilled in any mode damage will be initiated.

4. RESULTS AND DISCUSSION

4.1 FE Model Validation

There is a comparison of thrust force and torque between drilling experiment and FE simulation.Fig.3 and Fig.4 show the data of both thrust force and torque in a drilling process when the spindle speed of 5000 rpm and feed rate of 500 mm/min. Experiment results show the average thrust force is 123.3 N whereas the FE result shows 118 N, the experiment torque is 0.39 N.m and FE torque result is 0.36 N.m. The accuracy between the experiment and the FE simulation results are very close which indicates the FE model is accurate.

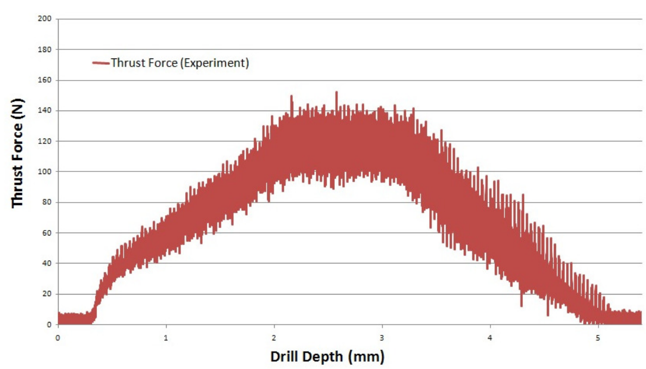

Figure 3(a): Experimental result of thrust force

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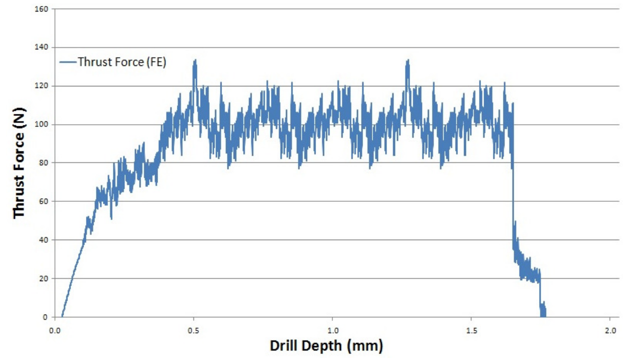

Figure 3(b): Simulation result of thrust force

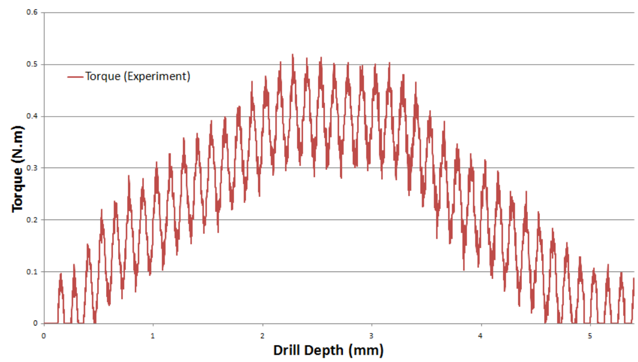

Figure 4(a): Experimental result of torque

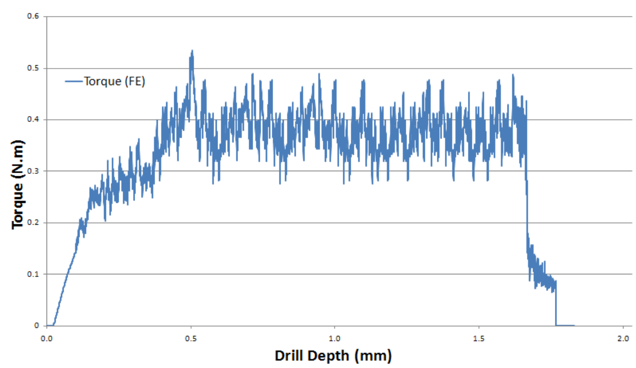

Figure 4(b): Simulation result of torque

4.2 Thrust Force & Torque Analysis

Feed rate is considered one of the major parameters that affect drilling of composite materials. As shown in Fig.5(a) and Fig.5(b), thrust force and torque go up with the increase of feed rate when spindle speed is constant (1000rpm). To be specific, thrust force in FE Simulation was estimated minimum of 52 N at 125 mm/min feed rate, and highest was 134 N at 1250 mm/min feed rate. Whilst the torque in FE was estimated 0.1 N.m at 125 mm/min feed rate, and the highest was 0.42 N.m at 1250 mm/min feed rate.

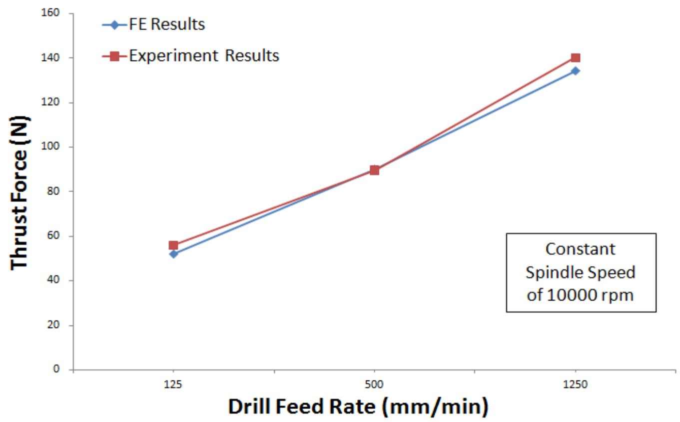

Figure 5(a): Thrust force analysis (Experiment and FE)

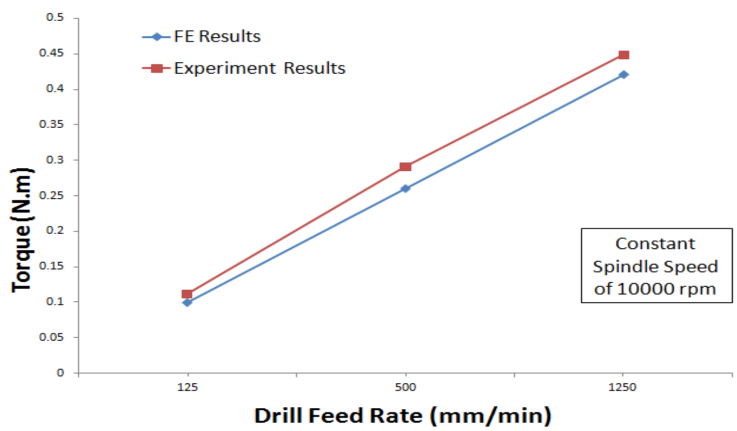

Figure 5(b): Torque analysis (Experiment and FE)

4.3 Optimization of Drilling Parameters

In order to predict how feed rate and cutting speed affect thrust force and torque in drilling process, a combination of drill feed rates and cutting speeds were chosen (Table 2) and by using the validated FE model for the study. The overall study shows from Fig. 6, that thrust force and torque increase with the increase in drill feed rate and decrease with the increase in spindle speed, it is found that thrust force increased by 158% when the drill feed rate increased from 125 mm/min to 1250 mm/min at cutting speed of 10000 rpm, torque increased by 320%. Also thrust force decreased by 35% when cutting speed increased from 2500 rpm to 10000 rpm at 125 mm/min, torque decreased by 61%.

Table 2: Cutting parameters used in optimization study

Spindle speed (rpm)	2500, 5000, 10000, 10000, 10000, 7500, 7500
Feed rate (mm/min)	125, 500, 1250, 125, 500, 125, 500

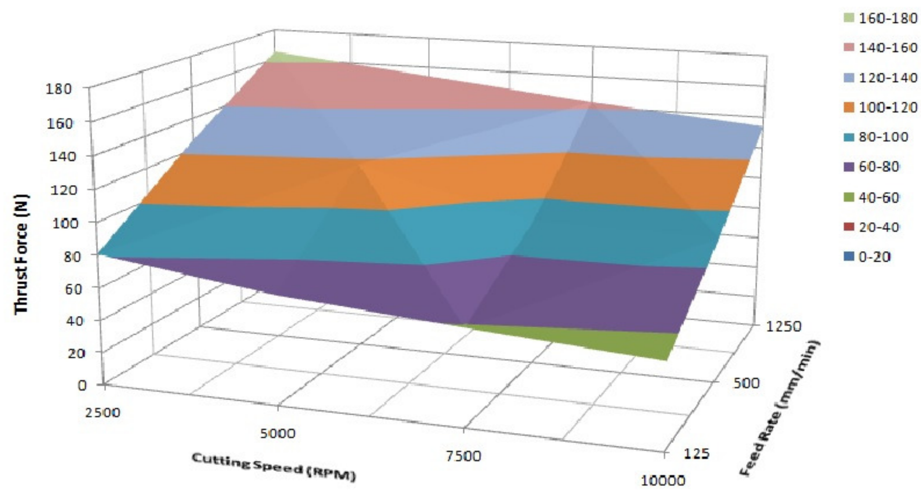

Figure 6(a): Effect of drill feed rate and cutting speed on thrust force.

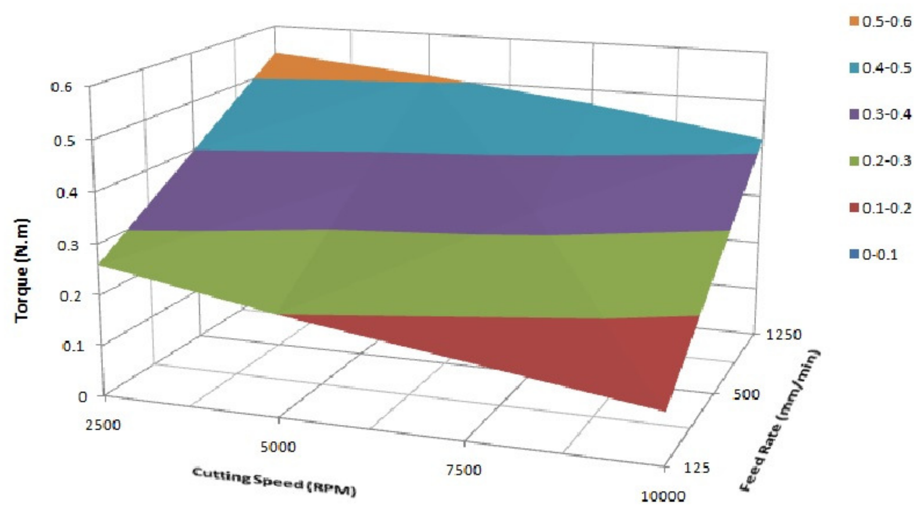

Figure 6(b): Effect of drill feed rate and cutting speed on torque.

5. CONCLUSION

Finite and experiment approach for drilling UDCFRP was developed to study the effects of cutting speed and feed rate on thrust force and torque. It was significantly shown that the thrust force and torque increase with the increase of feed rate, this indicates the importance of reducing feed rate to achieve better results with respect to drilling forces.

The study is based on a constant dill point angle of 120°, future studies will be conducted on different point angles and finding its effect on thrust force and torque.

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