



Original Article

Experimental study of surface quality and damage when drilling unidirectional CFRP composites



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ABSTRACT

In this study, an experimental investigation on the drilling of unidirectional carbon fiber reinforced plastic (UD-CFRP) composite was conducted using polycrystalline diamond (PCD) tipped eight facet drill. The quality of the drilled hole surface was examined through surface roughness measurements and surface damage by scanning electron microscopy (SEM). It was found that fiber pullout occurred in two specific sectors relative to the angle between the cutting direction and the fiber orientation. The thrust force was highly influenced by the feed rate than the cutting speed and it shows a significant variation throughout the rotation of the drill.

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1. Introduction

The application of fiber reinforced polymer composite materials is in increasing quantities in advanced structures because of its superior specific strength and stiffness relative to other material systems including metals. Major structural application areas include aircraft, space, automotive, sporting goods, marine, and other infrastructures. Other application areas include electronics with fiber reinforced polymer composites being used for circuit boards. In the medical industry, composites are being used for sockets, implants, and prosthetic limbs. Composite materials have also shown promises for product of miniaturization such as micromechanical flying insects, crawling robots and bio-mimetic fish-bots. Even though the

manufacturing process technology of composite materials has been advanced to the extent of producing the components to a near-net shape, still machining is necessary to meet the engineering specifications and producing holes for mechanical joining and assembly of composite parts with each other or with other materials.

In the aircraft manufacturing industry, many critical structural members are assembled by means of fasteners inserted into drilled holes. These drilling and fastening operations are being carried out at increasingly higher repetition rates. Because of the anisotropic and inhomogeneous nature of fiber-reinforced composites and the abrasive nature of the fibers, along with the drill conditions introduces process-induced surface damages. To assure the integrity of these fasteners,

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without defeating the advantages of composite strength characteristics, the need exists for improved methods of quality hole production [1]. Drilling induced damages such as spalling, delamination [2,3], edge chipping, fiber pullout, crack formation [1,4], and excessive tool wear [1] are undesirable and may compromise the structural integrity. The inhomogeneity of FRPs caused by the difference in properties of the fiber and the matrix materials will result in a machined surface that is less regular and is usually rougher in comparison with machined metal surfaces [5]. The surface condition of a drilled hole is affected by several process parameters that include the cutting speed and feed rate of the drill, drill geometry, the material(s) drilled and the rigidity of the fixture [5–8].

Therefore, the evaluation of the quality of drilled fastener holes must include both the general geometry of the hole and the condition of the hole surface. The purpose of this study is to investigate experimentally the quality of the hole surface and the damage in the UD-CFRP composite laminate. Effect of drilling parameters on cutting forces, rotational variation of thrust force, fiber pullout and its dependency on the interaction angle between the cutting direction, and the fiber orientation were investigated and presented.

2. Experimental methodology

2.1. Materials

In this investigation, a 6.35 mm unidirectional CFRP laminate was used. This CFRP laminates, which are products of Toray composites, are made of T800H high strength, intermediate modulus yarn, and toughened epoxy resin 3900-2. Each composite laminates are composed of 33 plies with an average ply thickness of 192 μm and 60% fiber volume fraction. The drilling coupons were prepared by cutting the panel to the size of 125 mm \times 175 mm using an abrasive water jet.

2.2. Experimental setup and procedure

Drilling experiments were conducted using a Haas TM1P milling machine equipped with Kistler Type 9123C rotating dynamometer along with Kistler Type 5223 signal conditioning box and with Kistler DynoWare DAQ pc software – input via pci DAQ card. A custom modular adjustable fixture was fabricated from steel to hold and consistently locate the work piece. A 6.35 mm diameter polycrystalline diamond (PCD) tipped eight-facet drill provided by STF precision is used in the drilling process. Fig. 1 shows the schematic diagram of the experimental setup. All drilling was conducted in dry condition without the use of coolant. The experimental plan was designed using design expert by taking cutting speed and feed rate as experimental factors at different levels where the summary is tabulated in Table 1.

All drilled holes quality was characterized in terms of surface roughness, drilling induced defects/damage, and delamination. Delamination was normalized through

Table 1 – Summary of experimental conditions.

| | |
|--|--|
| Equipment | Haas TM1P milling machine equipped with Kistler Type 9123C rotating dynamometer along with Kistler Type 5223 signal conditioning box |
| Workpiece material | 6.35 mm unidirectional CFRP laminate, which are a product of Toray composites with 33 plies having an average thickness of 192 μm |
| Drill tool | 6.35 mm diameter polycrystalline diamond (PCD) tipped eight facet drill |
| Cutting speed (rpm) | 1500, 3000, 4500, and 6000 |
| Feed rate ($\mu\text{m}/\text{rev}$) | 64, 128, 192, 256, and 320 |

dividing the delamination size by the drill diameter and it is referred as delamination factor. The drilled holes in this series of experiments were sectioned into two halves as shown in Fig. 2A, using a diamond circular saw to utilize a sectional view of the hole surface in order to take the surface roughness measurement and to prepare samples for scanning electron microscopy (SEM) examination. Surface roughness profiles were recorded from hole wall surface at six different positions axially parallel to the drill direction using a MahrSurf XR20 surface profilometer with a probe stylus radius of 2 μm and a cut-off length of 0.8 mm as per ANSI standard (Fig. 2B).

In an attempt to quantify the surface quality, the average surface roughness, R_a ; maximum peak-to-valley height, R_t ; root mean square roughness, R_q ; and ten point average surface roughness, R_z ; were evaluated from the surface roughness profiles. Defects were examined using both optical and scanning electron microscopy. SEM was extensively used in quantifying both delamination and fiber-pullout in order to observe the damage sectors around the hole. Delamination was quantified by defining using the delamination Factor as a ratio of maximum delamination to tool diameter.

Using the analysis of variance, the significant factors and their interactions effects were identified in terms of cutting speed and feed rate. Based on the measured data (drill forces, surface roughness and delamination) and the ANOVA, a

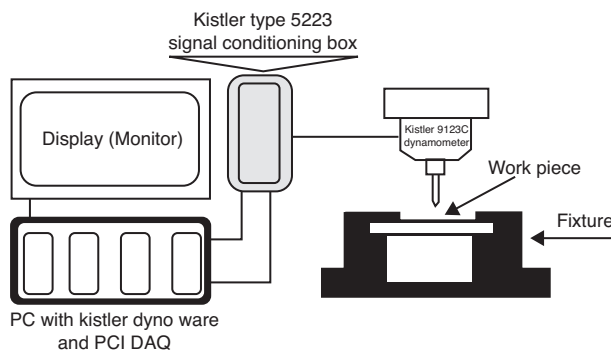


Fig. 1 – Schematic diagram of the experimental setup.

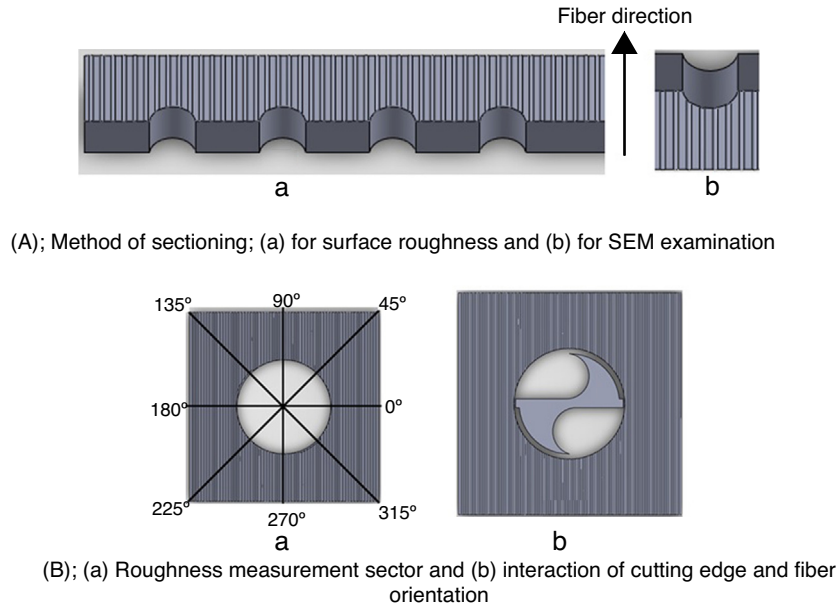


Fig. 2 – Schematic diagram of the drilled hole geometry and surface roughness measurement.

multiple linear regression model for the hole production process was developed using the form:

$$y(x) = C_0 + \sum_t C_i x_i + \sum_i C_{ii} x_i^2 + \sum_{j>1} \sum C_{ij} x_i x_j + \dots$$

in which the following are the coefficients:

- C_0 , constant;
- C_i , first order or linear effect;
- C_{ii} , second order or quadratic effect;
- C_{ij} , interaction effects

The variables are the parameters and denoted as follows:

- x_1 , speed (rpm)
- x_2 , feed rate (mm/rev)

Based on a design of experiments approach, the software then performs an analysis of variance (ANOVA) in order to determine the effects of each of the variables on each of the responses analyzed. The equations for thrust force, torque, surface roughness, and delamination factor follow in the next section. Depending on the model used to fit the data, individual effects and interaction effects can be determined as

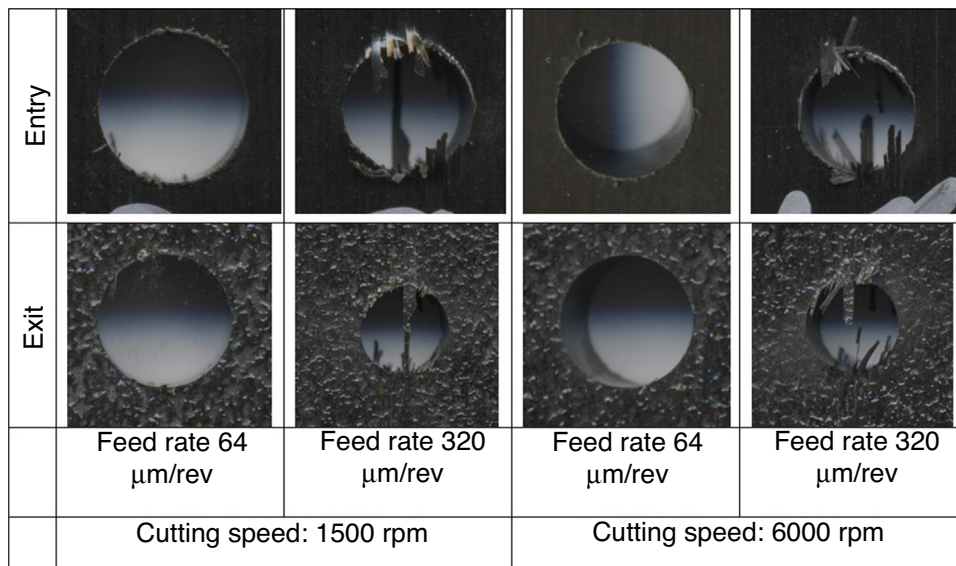


Fig. 3 – Typical holes produced by drilling process.

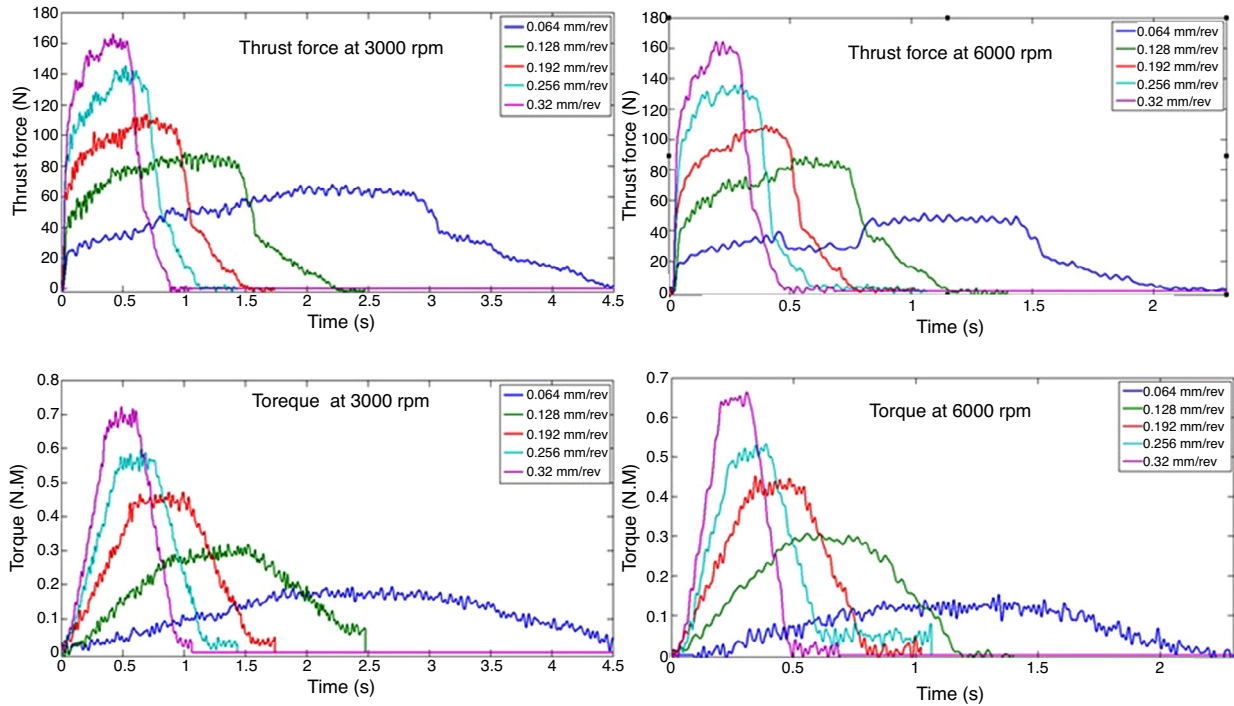


Fig. 4 – Typical representation of thrust and torque response.

significant with respect to each response. Once these are determined, an equation is generated using the various effects to fit the specified model.

3. Results and discussion

Fig. 3 shows the typical optical macrographs of holes produced at two different cutting speeds, using minimum and maximum feed rate. Note that the damage and delamination at drill exit is more than the drill entry as expected. The fiber breakout due to peel up at the drill entry is much smaller in comparison to the damage induced by delamination at the drill exit.

3.1. Thrust force and torque

Typical representations of the thrust force and torque profiles for two different cutting speeds with varying feed rate are shown in Fig. 4. The thrust force increases with a steep slope until the cutting edge of the drill fully engages into the workpiece, and then the thrust force continues to increase moderately while the cutting edge and the drill body engaged in the cutting process. Then, the thrust force starts decreasing slightly when the tip of the drill approaches the last few plies, where the number of uncut plies under the ply being cut is getting smaller and so do the resistance to the force exerted by the drill tip. When the tip of the drill penetrates the last ply and the cutting edge leaves the workpiece, the thrust force decreases rapidly and then goes to zero. The torque shows

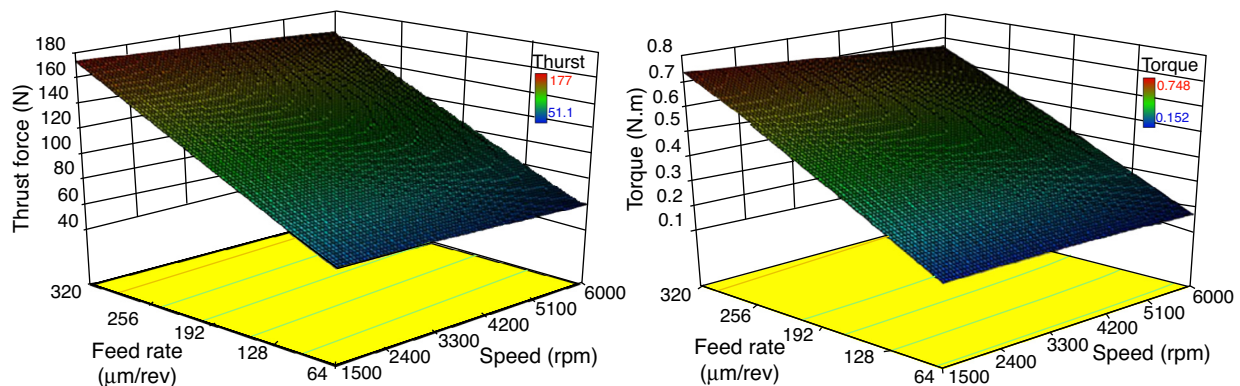


Fig. 5 – Effect of cutting conditions on thrust and torque.

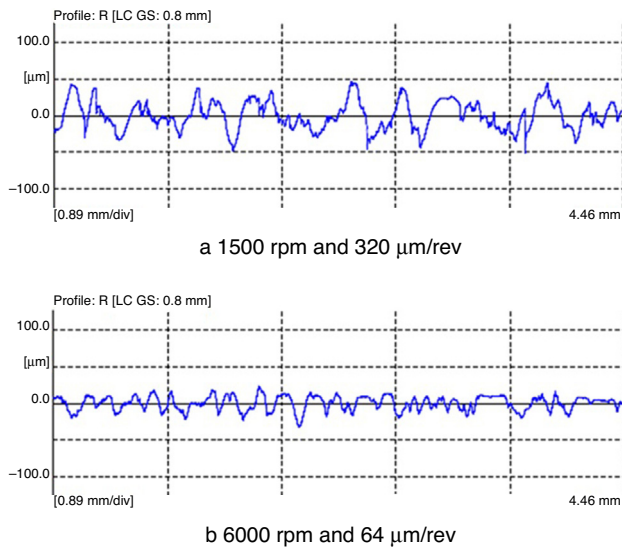


Fig. 6 – Typical surface profiles.

more or less the same behavior as of the thrust force. The thrust force and the torque both show an increasing trend with the increase of the feed rate for all cutting speeds and decreases with the increase of the cutting speed. The effect of drilling condition on the thrust force and torque is modeled by using ANOVA analysis and the surface response models. Fig. 5 shows the effect of cutting parameters on cutting forces. An average decrease of 9% was seen on the thrust force when the cutting speed increases from 1500 rpm to 6000 rpm regardless of the feed rate, whereas thrust force shows an average increase by 63% when the feed rate increases from 64 to 320 $\mu\text{m}/\text{rev}$. Thrust force is more influenced by the feed rate than the cutting speed. Higher thrust forces at high feed rate clearly induced the delamination as seen in Fig. 3.

3.2. Hole surface quality assessment

3.2.1. Surface roughness

Typical surface profiles recorded for two different cutting conditions are shown in Fig. 6. Surface roughness height variation is dominated by the feed rate regardless of the speed used. The surface describing parameters, namely, the average surface roughness, R_a ; maximum peak-to-valley height, R_t ; root mean square roughness, R_q ; and ten point average surface roughness, R_z ; were evaluated from the surface roughness profiles and presented as radar plots in Fig. 7.

Note that the average surface roughness, R_a (Fig. 7a) and R_q (Fig. 7c) as expected are smaller than other surface roughness parameters R_z (Fig. 7d) and R_t (Fig. 7b) [1,5,9]. The measured values of both surface roughness parameters (R_z and R_t) were found to be higher in two regions where the angle between the cutting direction and the fiber orientation is 135° and 315° . In addition, it can be seen from Fig. 7 that both R_a and R_t show the same trend regardless of the cutting speed or feed rate. It is clear from this that R_t is the best describing parameter to

describe not only the average surface roughness but also the fiber pull out as well.

Therefore, from the ANOVA analysis, a model for maximum peak-to-valley surface roughness was developed to study the influence of cutting parameters on surface roughness and it is presented in Fig. 8. A lower value of both parameters has been measured at 6000 rpm than the 1500 rpm for the same feed rate of 64 $\mu\text{m}/\text{rev}$, whereas for the feed rate of 320 $\mu\text{m}/\text{rev}$, lower value has been measured at the cutting speed of 1500 rpm than that of 6000 rpm. From this, it is clear that, it is possible to produce a better surface quality with a combination of high cutting speed and low feed rate. At the higher cutting speed, a better surface is produced at a feed rate of 64 $\mu\text{m}/\text{rev}$, which is one third of the ply thickness.

3.2.2. Machined surface morphology

In order to evaluate the surface morphology of the drilled hole surfaces, extensive SEM analysis was made to document the defects generated on drilling UD-CFRPs. Fig. 9 shows the typical defects observed in this series of experiments. Measurements of damage showed that the fiber breakout is no more than one ply deep (Fig. 9a), fiber pull out (Fig. 9c) was little over half the ply thickness and the delamination (Fig. 9d) was two ply thicknesses deep. Since the maximum surface roughness was measured on two points (135° and 315°), it is necessary to verify the region of the damage sector. Fig. 10 shows that the fiber pull-out has occurred in a sector rather than just at a point, and this sector approximately covers an average angle of $30\text{--}35^\circ$.

As seen in the SEM micrograph, the surface roughness/fiber pullout in these two regions/sectors was uniform from the top to the bottom of the hole. Within these experimental conditions, the two sectors are found from 135° to 175° and 315° to 355° (Fig. 10a). The SEM image indeed shows the two sectors where the surface roughness/fiber pullout is higher confirming the result shown in Fig. 7 that the highest values of surface roughness parameters were measured in these two sectors, namely at 135° and 315° . In order to examine further, we plotted the thrust force for one complete revolution of the drill as shown in Fig. 10b. As it can be inferred from the plot, the thrust force varies significantly throughout the rotation of the drill, which is an indication that the resistance of the material to the cutting force varies with the relative angle between the cutting direction and the fiber orientation. This variation of the thrust force can also represent the cutting action that takes place around the circumference of the hole. Forces are clearly different from position to position or sector to sector. The rotational profile of the thrust force reveals that there are two unloading sectors in each rotation approximately around 135° and 315° , where the fibers pullout was dominant in these sectors. This result indeed clearly relates to the proposed cutting mechanism [1], fiber pullout and surface roughness.

Delamination was quantified by delamination factor. A multi regression model was developed. Fig. 11 shows the variation of delamination factor for both peel-up (drill entry) and push-down (drill exit) for different cutting conditions. The

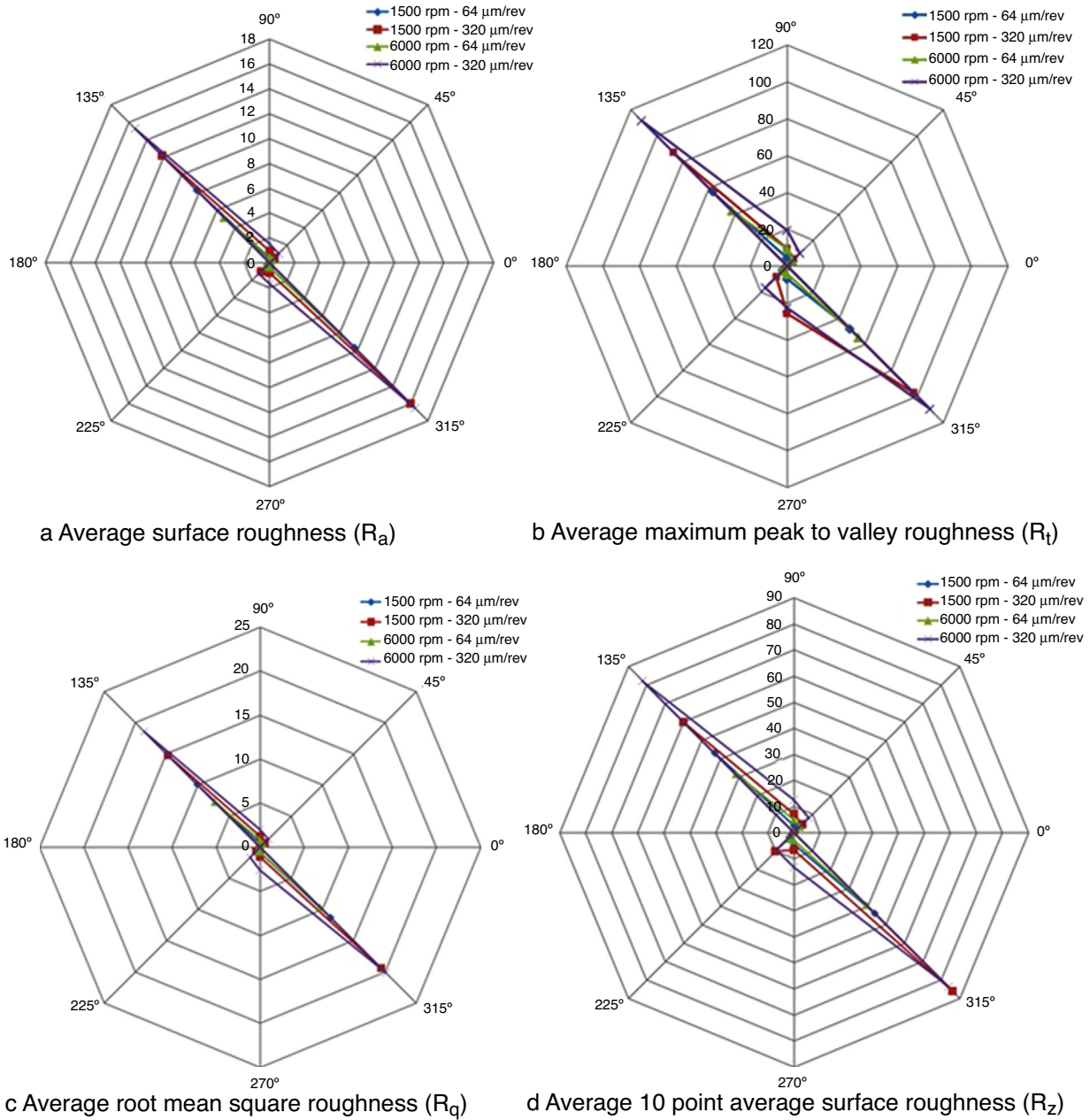


Fig. 7 – Surface roughness values at different cutting conditions.

delamination factor at the exit was always higher than the drill entry regardless of the cutting speed and feed. The delamination factor was found to have a linear and non-linear relationship with both speed and feed rate at the drill entry and exit respectively. Aerospace standard acceptable delamination factor of less than 1.4 for a 6.35 mm diameter drill was achieved at optimal drill condition of 64 μm/rev of feed rate with the cutting speeds of 4500–6000 rpm.

Arithmetic average surface roughness, R_a , being an average of averages, does not give a good indication of surface quality aspects in CFRP such as fiber pullout. Either R_z or R_t is an appropriate parameter to describe CFRP machined

surface. The surface defects observed are consistent with our prior investigations on CFRPs [1,7–10]. The data generated in this investigation (experimental data) correlates well between thrust force, delamination, and fiber breakout [2,3,10]. Thus, this correlation can be used as a monitoring parameter in an automated drilling operation. Thrust force can be monitored to determine when to change the drill and based on a pre-determined amount of thrust that can be correlated with the exit quality level; it can be used to determine the end of drill life. On-line detection of defects in CFRPs while drilling by the method of signal processing is currently in progress and will be reported in the future.

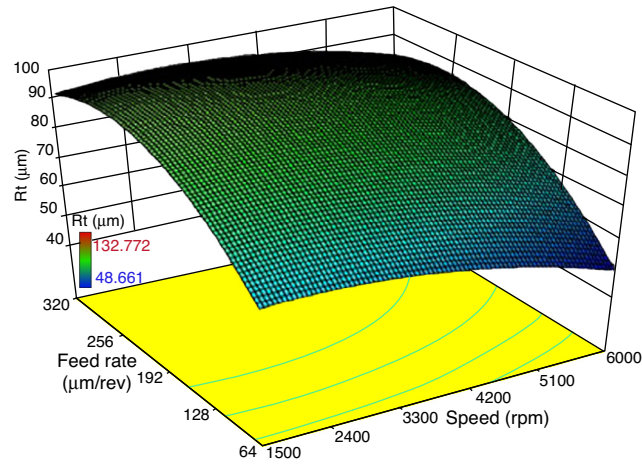


Fig. 8 – Effect of cutting condition on surface roughness (R_t).

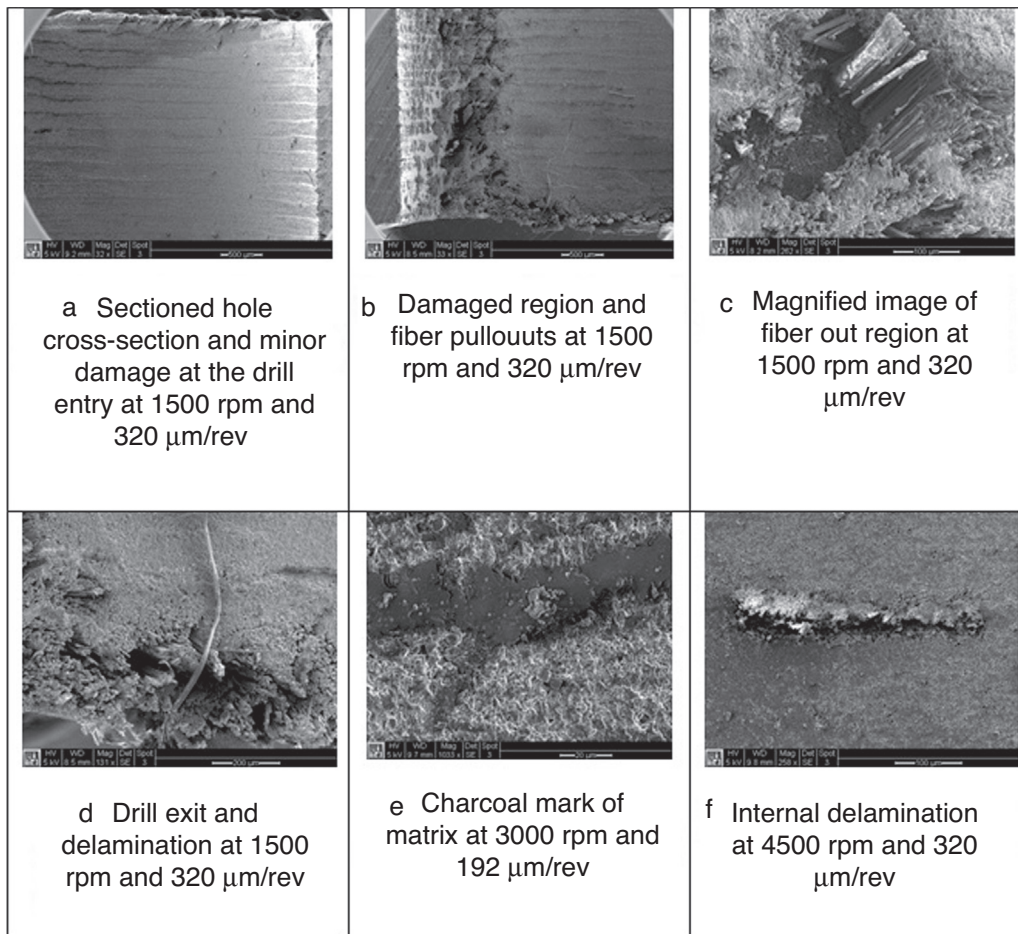
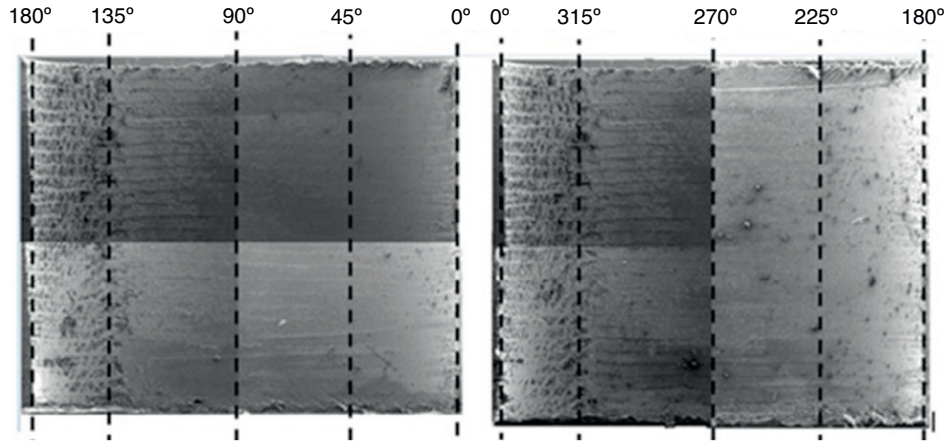
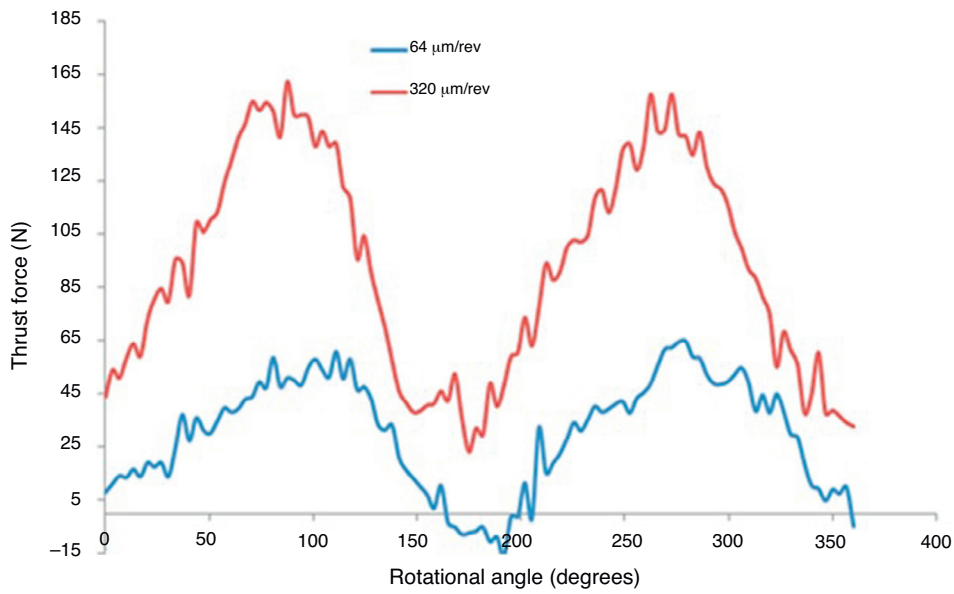


Fig. 9 – SEM micrographs of typical damage on the drilled hole surface.

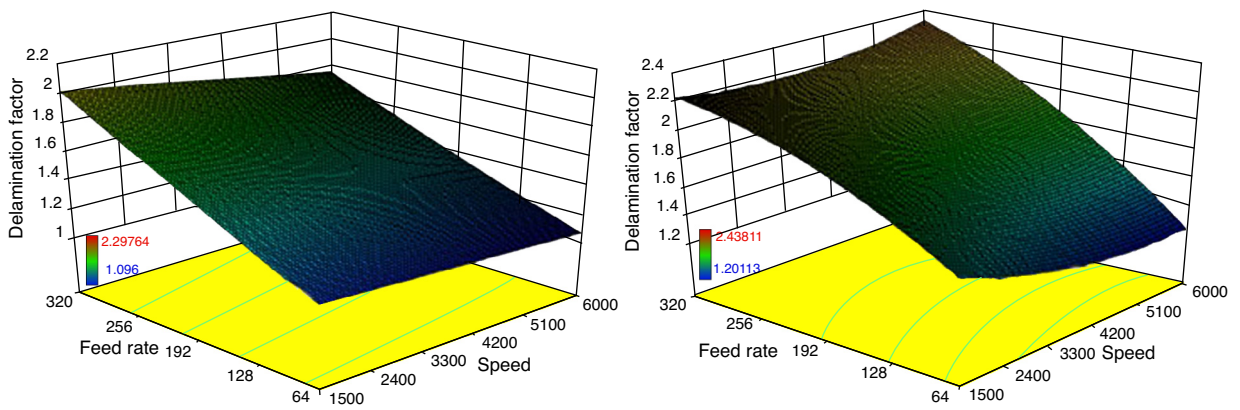


a SEM image of damage sectors of sectioned hole



b Variation of thrust force for one rotation of the drill

Fig. 10 – SEM micrographs of damages and rotational thrust force.



a Entrane (peel-up) delamination

b Exit delamination

Fig. 11 – Effect of cutting conditions on delamination factor.

4. Summary and conclusions

In an effort to characterize the quality of the hole surface and the influence of cutting parameters on the hole surface quality and resulting forces, experimental investigation on the drilling of unidirectional carbon fiber reinforced plastic (UD-CFRP) composite was conducted using polycrystalline diamond (PCD) tipped eight-facet drill. Cutting forces, surface roughness of the hole, delamination, and regions of fiber pull-out were studied. Based on this experimental investigation the following conclusions can be drawn:

- The thrust force increases with the increase of feed rate and decreases slightly with the increase of cutting speed. Overall, the thrust force is more influenced by the feed rate than the cutting speed. A prediction model for the thrust force was formulated and the model prediction agrees with the measured value of the thrust force with an average error of 3%. The thrust force varies significantly over the rotational position of the drill and a lower value of the thrust force was observed around the rotational angles of 135° and 315°.
- Rougher surface regions/sectors were observed along the circumference of the hole, throughout the hole depth. The maximum average surface roughness values (R_a , R_q , R_z and R_t) were associated with angles of 135° and 315° along the circumference of the hole. Fiber pullout is observed in two regions where the angle of interaction between the cutting direction and the fiber orientation is from 135° to 175° and 315° to 355°. Maximum peak-to-valley height, R_t was found to be a sensitive parameter to characterize the fiber pullout.
- Better hole surface quality was obtained with a combination of higher cutting speed and lower feed rate. Within the experimental conditions used, the minimum thrust force, delamination factor, and lower values of surface roughness (R_t) were associated with a cutting speed of 4500–6000 rpm and feed rate of 64 $\mu\text{m}/\text{rev}$.

Conflicts of interest

The authors declare no conflicts of interest.

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