Parametric Study and Process Monitoring on Drilling of CFRP Composites

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Abstract

Carbon fiber reinforced plastic (CFRP) composite materials are finding huge applications in many industries due to their excellent properties i.e., high strength to weight ratio and corrosion resistance. Drilling of CFRP composites is required for assembly of these composites structures in aerospace industry. The present work focuses on investigation of the feasibility of drilling CFRP composite using drill bit made of tungsten carbide (WC) of diameter 10 mm and varying point angle under dry cutting conditions. The CFRP composite was fabricated using woven carbon fiber by hand lay-up technique having quasi-isotropic configuration i.e. fiber orientation of [0/90/45/-45]. This study involves online monitoring of thrust force and torque using dynamometer and providing a deep understanding of the relationship between hole quality and process parameters. The damage caused at the entrance of the drilled hole is characterized by delamination factor, circularity and surface roughness, which is evaluated by considering cutting speed (600, 800, 1000 and 1200 rpm), feed rate (0.05, 0.1, 0.2 and 0.25 mm/rev) and point angle (110°,118° and 125°) as affecting process parameters. In this work experiments are conducted to analyze the delamination using image processing technique, circularity using CMM and surface roughness using surface roughness tester.

Experimental results showed that the thrust force and torque, hole roundness decreases with increase in cutting speed and increases with increase in feed rate. The delamination factor decreases with increase in both spindle speed and feed rate. It has been observed that the WC tool with point angle 110° showed the best result compared to all other tools for drilling CFRP composite. It can be concluded that at high cutting speed, low feed rate and small drill point angle is best for drilling of CFRP composites.

Keywords: Drilling, Surface roughness, circularity, delamination, thrust force, torque.

1. INRODUCTION

Polymeric composite materials have found greater applications over the last decade; especially the use of CFRP in the aerospace industries has increased considerably. Being one of the sophisticated materials, the specific modulus and specific strength of CFRP composite are superior in compare to conventional materials. Machining of CFRP composite materials is an important and current topic in modern researches on manufacturing processes. Drilling is the most frequently employed machining operation for fibre reinforced materials owing to the need for joining structures. Drilling of CFRP is difficult to carry out due to the anisotropic, non-homogeneous and high abrasiveness of their reinforcing carbon fibres. In aircraft industry poor hole quality accounts for an estimated 60% of all part rejection. Factors like cutting parameters, tool geometries, tool materials, thrust force and torque greatly influence the drilling of CFRP laminates and quality of the drilled hole. The parameters such as cutting velocity and feed rate have greater effect on the drilling of CFRP laminates. The cutting velocity has a larger influence on the thrust force, torque, delamination, power, and specific cutting pressure, while drilling the CFRP composite laminates. By employing high spindle speeds, preferential removal of work piece takes place, which in turn produces smooth surface. On the other hand, at low spindle speeds due to slow penetration of the tool in the work piece produces more delamination [4]. The effect of cutting speed on cutting forces differ with various tool materials, but there is no significant change is noticed when the same drill material was taken [5]. A combination of low feed rate and point angle is advantageous in high-speed drilling of CFRP composite which in turn reduce damages at the entrance of holes. As the cutting speed is increased; which lead to reduction of the cutting edge action at number of passes across the same region. Therefore the friction between cutting edges and board increases the temperature elevation and the softening of the matrix phase, thus reducing damage in hole [6].

In drilling of the CFRP composite laminates, the feed rate had found to be major influence on the thrust force, torque, delamination, power and specific cutting pressure. With increase in feed rate, the delamination factor increases[3]. Lower the feed rate; lower both the thrust force and the torque generated in drilling. In order to improve the hole quality at the exit, the feed rate at the exit needs to be decreased during the drilling process. The low feed rates give better surface than high feed rates and can be preferred for drilling of CFRP composites [4].It can be noted that the area of cut increases with feed rate; demanding bigger thrust force with increasing damage[6].

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Many types of drills in terms of tool geometry made by different materials had been used in drilling of CFRP composites. This can be listed as twist drill, saw drill, step drill, step core drills, candle stick drill, PCD drill, brad and spur drill and dagger drill etc. Taking tool material into consideration, Carbide drill presents a better performance than the HSS drill, i.e. under the same cutting conditions (cutting speed and feed rate); the HSS drill always influenced a higher delamination factor. Carbide drills shows an almost no wear land in the flank surface as compared to the HSS drill which presents a wear value of 1/4th of the drill radius, apart from the corner [3].

The tool geometries also play an important role in drilling of CFRP laminates. Tangential force (i.e. torque) decreases with increase in point angle because the tool orthogonal rake angle at each point on the primary cutting edge increases with increasing point angle. On the contrary, the thrust force increases with increasing point angle. Therefore, in order to decrease the thrust force, the smaller point angle is a good choice for the drilling of CFRP composite materials [5]. When the point angle is reduced, the cutting edge angle also reduced, as well as the thrust force [6]. It is also observed that the delamination factor is also small at lower point angles. The possible reason might be at low point angle the thrust force reduces, which in turn minimizes the delamination damage[7].

Though various works were on composites drilling and process monitoring to reduce delamination, there were very few works on the study of drilled hole surface integrity in detail. Therefore, the present work mainly addresses the process parametric effect on drilled hole surface quality i.e. surface integrity characterized by circularity error, delamination and surface roughness on newly developed quasi-isotropic CFRP with different fiber orientation have been studied in detail. The full-factorial drilling design of experiments have been carried out considering different point angles along with above stated parameters which had not been focused in the previous works.

2. EXPERIMENTAL SETUP AND DETAILS

2.1 Machine, workpiece and cutting tool details

The experiments were conducted on Radial Drilling Machine MAS VR 6A as shown in Figure 1 with cutting conditions of 4 spindle rotational speeds (600,800,1000 and 2000 RPM) and 4 longitudinal feeds (0.05,0.1,0.2 and 0.25mm/rev). The workpiece specimen used for investigation is CFRP with 10 mm thickness and having fiber orientation of 0°/90° and 45°/-45° (quasi-isotropic). The resin used for fabrication of the composite is epoxy. The specimen was manufactured using hand lay-up technique with 50% fiber volume fraction.

The specimen is machined under dry machining conditions using solid carbide twist drill having drill diameter 10mm and point angle of 110°, 118° and 125°. The experiments were conducted as per full factorial method of design of experiments, which is used to study the factors and their interactions in three-factor four-level experiments i.e. a total of 48 drilling experiments.

Figure 1 CNC Drilling Machine set up (with dynamometer)

2.2 Performance evaluation parameters

2.2.1 Measurement of thrust force and torque

Thrust force and Torque have been acquired by digital drilling tool dynamometer for the different operation performed.

2.2.2 Measurement of circularity

Circularity error was measured using SPECTRA ACCURA CMM machine. The workpiece is placed on the machine table, and a ruby probe (2 mm diameter) continuously circulates around the internal wall of the hole. The measurements were carried out at twelve locations along the hole depth stated as 'top', 'Centre' and 'bottom' as shown in Figure 1**Error! Reference source not found.**. The scanning speed for the measuring probe was set at 1 mm per second which allows capturing points while rotating around the inner circumference of a hole. The value of circularity is obtained directly from CMM.

2.2.3 Measurement of surface roughness

Surface Roughness measurement been done using a portable stylus-type profile meter, Surftest SJ-210- Series 178-Portable Surface Roughness Tester at three different locations of the machined component and their average value is plotted for Ra value.

2.2.4 Measurement of delamination

An image analysis procedure was developed in figure 3 to extract the diameter from the images of the drilled holes. The developed procedure consists of the following steps. The first step is the conversion of the RGB image (Figure 2) to HSV format. The latter format consists of three levels, namely hue, saturation and value. Only the second level, i.e. the saturation level, is useful for the hole diameter measurement procedure [14].

A mask is applied to the second level (saturation.0.3), with the aim to convert it to binary black and white (BW) picture. This procedure is applied with the aim to identify the borders of the hole, as this task can be carried out more easily on BW pictures. On this image, smoothing is performed to exclude the uncut fibers the diameter measurement. The hole borders are then identified as the boundary pixels between the BW areas of the picture; the circumference that best fits the identified boundary pixels are then calculated using the mean squared algorithm, obtaining the hole diameter value.

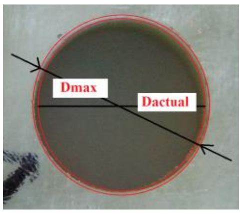

Figure 2 Original RGB image.

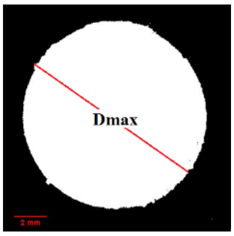

Figure 3 Black and white image after smoothing

3. RESULTS AND DISCUSSION

The interaction effects of drill spindle speed and feed rate at different point angle on thrust force and torque have been acquired using digital force dynamometer integrated with the drilling machine. And basing on that a graph was plotted. The sensor based observations at different machining condition has been explained with probable reasons in *section 3.1* and *3.2* and corresponding drilled hole quality in *sec 3.3 and 3.4* as follows.

3.1. THRUST FORCE

3.1.1. Effect of spindle speed

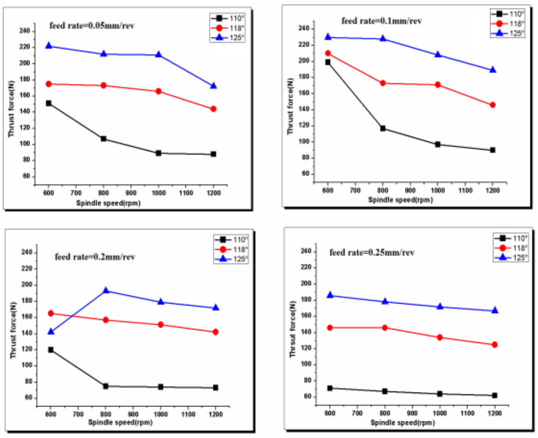

Figure 4 Variation of thrust force with spindle speed at different drill point angles

From Figure Figure 4, it may be summarized that with increasing spindle speed, the thrust force decreases which have found to be more predominant at lower feed rate. This was possibly due to increase in temperature at higher spindle speeds [6].

3.1.2. Effect of feed rate

In Figure 4, it has been observed that with increase in feed rate, the thrust force has been increased. It was observed that among the three drill bits, the drill bit with point angle 110° produced the least thrust force. The thrust force was found to be increased at higher tool point angle which resulted more damage on the internal surface of drilled hole. Therefore, it may be concluded that highly desirable low thrust force can be obtained at higher spindle speed, lower feed rate and small tool point angle.

3.2. TORQUE

3.2.1. Effect of spindle speed

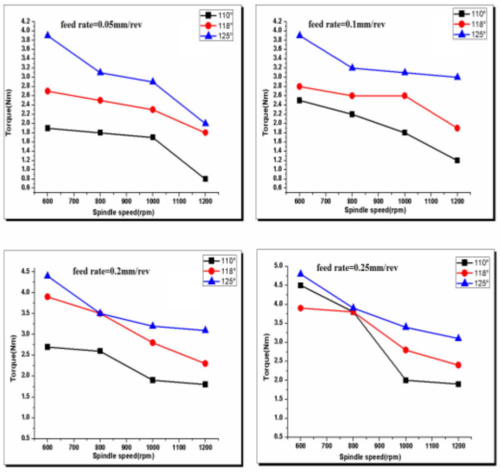

Figure 5 Variation of torque with spindle speed at different drill point angles

From Figure Figure 55, it has been found that at higher spindle speed, the tangential cutting force as well as torque decreased. This is due to the composite matrix softening at the high-speed condition. The higher spindle speed raised the cutting temperature and softens the CFRP, which eventually resulted in lower torque [6].

3.2.2. Effect of feed rate

It was observed that with increase in feed rate, the torque increased as shown in Figure 5. This is because as the large volume of material undergoing deformation during thrust, therefore highest cutting speed, lowest feed rate and hardest tool material employed for the investigation.

It had been noticed that among the three drill bit the least torque was found in the drill bit with point angle 110°.The torque value increases with increase in point angle. So, greater torque was resulted, which in turn larger damage to hole. Therefore, it can be concluded that best result i.e. less torque can be obtained at higher spindle speed, lower feed rate and small point angle.

3.3. CIRCULARITY

3.3.1. Effect of spindle speed

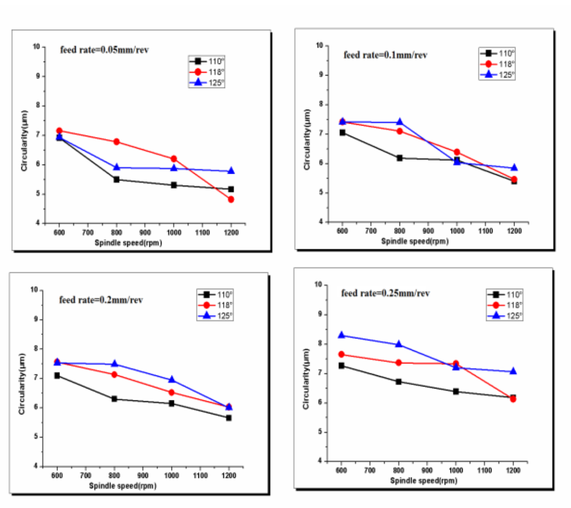

Figure 6 Variation of circularity with spindle speed at different drill point angles

It was observed that with increase in spindle speed, the circularity error decreases as indicated in Figure 6. The rotational stability of the drill is generally good at higher speeds, which was found to be better because of ploughing and frictional heating effect on CFRP [6].

3.3.2. Effect of feed rate

It was observed that with increase in feed rate, the circularity error was increased as per Figure 6. The reason resides in the fact that increase in feed elevates the axial force, which consequently results in higher radial forces that are mainly responsible for drill deformation and poor roundness.

It had been observed that among the three drill bit the least circularity error was found in the drill bit with point angle 110°.The reason is thrust force increases with increase in point angle. So, greater thrust force results in larger circularity error. Therefore, it can be concluded that best result i.e. less circularity error can be obtained at higher spindle speed, lower feed rate and small point angle.

3.4. SURFACE ROUGHNESS

The improvement in the drilled-hole surface roughness was found to be not uniform. The non-homogeneous structure of the composites makes it difficult to get a uniform surface throughout the hole from entrance to exit [7]. In the present work materials different behaviors of fibers differently oriented resulted inconclusive or insignificant for surface roughness. From the experiments, it was observed that the value of surface roughness varies in the range of 0.007-0.014µm.

3.5. DELAMINATION

3.5.1. Effect of spindle speed

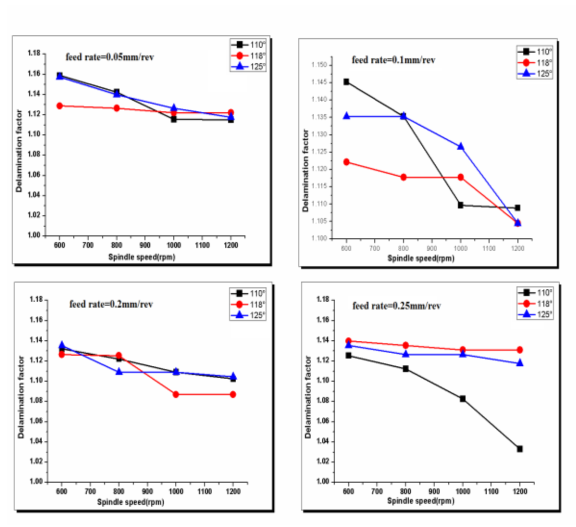

Figure 7 Variation of delamination with spindle speed at different drill point angles

In Figure 7, it was observed that at constant feed rate with increase in spindle speed, delamination in hole decreases, especially in case of feed rate at 0.1mm/rev. The reason was preferential removal of work piece material takes place, which in turn produces smooth surface at high spindle speeds; whereas, at low spindle speeds due to slow penetration of the tool in the work piece produce more delamination.

3.5.2. Effect of feed rate

From Figure 7, it may be concluded that with increase in feed rate, delamination in hole decreases. This is due to the reason that with increasing feed rate thrust force increases which results in softening of matrix. As a result, delamination decreases.

It can also be concluded that less delamination is obtained at high spindle speed, high feed rate and small point angle.

4. CONCLUSION

In this work, drilling of CFRP composites has been done using above mentioned process parameters. The process has been monitored using drill dynamometer. Based on this assessment, some of the observations concerning the work are summarized below:

- It was found that as point angle of the drill increases, the thrust force and torque also increases.
- The axial thrust force induced while drilling CFRP composites have good correlation with delamination. When the thrust force exceeds its threshold value,

delamination occurs and low thrust force reduces the extent of delamination.

- Other defects include edge chipping, pitting and poor surface quality in the walls of the drilled hole which can be avoided by employing suitable tool type and material with optimum tool geometry and process parameters.

- As per the data obtained, there was a reduction of 6.2% and 8.7% while performing the experiments at lower drill point angle of 110° in compared to 118° and 125°, respectively.

Considering all the parameters i.e. cutting speed, feed, thrust force and torque, it may be concluded that the best results were obtained at higher spindle speed, lower feed rate and small point angle.

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