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The Influences of Varying Feed Rate on Hole Quality and Force in Drilling CFRP Composite

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Abstract

The selection of drill geometry and drilling parameters has high importance due to thermo-mechanical formations in drilling of carbon fiber reinforced polymer (CFRP) which has anisotropic structure. This study focused on the effects of drilling parameters on thrust force and hole quality in drilling of CFRP composites by applying constant and varying feed rate with uncoated WC drills having different point angles. Surface roughness, delamination factor and diameter plays a crucial role in the production of close-tolerance holes in hole quality. The quality of the hole surface was examined via surface roughness measurements and surface damage by scanning electron microscopy (SEM). Machinability experiments were performed with three different levels of drilling parameters that are point angle, cutting speed and feed rate. It was determined that thrust force (Fz), delamination factor (Fd) and surface roughness (Ra) values obtained in drilling processes by varying feed rate in hole exit are lower than that of constant feed rate with average of 21%, 14% and 36%, respectively. On the other hand, hole diameter (d) values obtained with varying feed rate in hole exit were higher than that of constant feed rate. The effects of drilling parameters on Fz, Fd and Ra were determined by analysis of variance with 95% confidence level and feed rate was found as the most significant parameter on them.

1. INTRODUCTION

Beyond aerospace industry, the demand for composite materials in manufacturing of automotive, marine, sport, chemical and biological equipment is gradually increasing (İsbilir and Ghassemieh, 2013). Advanced composite materials like fiber reinforced polymers (FRP) are commonly used in structural parts due to their attractive properties like high specific hardness, high strength and high corrosion resistance. Carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymer (GFRP) laminates are the most frequently used components recently in hybrid composite constructions with regards to their excellent mechanical properties (Soutis, 2005). Mechanical properties of fiber reinforced polymer (FRP) laminates change according to fiber positions in epoxy matrix. Especially, fiber reinforced laminate composites strengthening of two-way slabs (lattice structure) have maximum hardness and strength along each two-ways (Liu et al., 2012). Fiber reinforced polymer (FRP) composite materials are usually manufactured in geometry of final form in order to provide excellent assembly performance. Therefore, metal removal processes like milling, drilling etc. are needed to meet the requirements of quality and dimension in assembly (Singh et al., 2008). For instance, structural weight of about 52% of Airbus350 airplane is of composite materials and about 55000 drilling processes are performed in manufacturing of structural components in airplane (Faraz et al., 2009; Fan and Zhang, 2009). Thus, drilling is a very common process applied to carbon fiber reinforced polymers (CFRP) (Ahmad, 2009).

Fiber reinforced polymer (FRP) laminates usually presenting heterogenic characteristic, anisotropic structure and brittle behavior have poor machinability due to these properties (Xu et al., 2016). It requires

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more attention for each operation when machinability of CFRP composite materials become current issue. Especially, the need for drilling in tolerance of low roughness and suitable roundness because of requirement to high strength in assembly parts is an important safety problem for aerospace industry (Abrao et al., 2007). On the other hand, high temperature and chip formation as powder during drilling cause to deterioration in surface integrity of isotropic and heterogenic CFRP layers (Pecat and Brinksmeier, 2014). This situation, resulting from the differentiation of mechanical and thermal properties of matrix and reinforcement materials forming composite materials (Rao et al., 2007), causes a more difficult drilling process than traditional metal cutting processes (Xu et al., 2016).

The most common problem in drilling of composites is delamination that is defined as layer segregation in entry and exit of hole (Rao et al., 2007). Mohan et al. stated that the most important parameters in drilling of GFRP composites are cutting speed and material thickness for entry delamination, feed rate and material thickness for exit delamination according to their experimental and numerical studies (Mohan et al., 2007). El-Sonbaty et al. (2004) determined that cutting speed has negligible effect on thrust force (Fz), but torque values increase with increasing cutting speed. Latha ve Senthilkumar (2009) indicated that thrust force generally decrease with low feed rate and this situation decrease delamination. Karnik et al. (2008), emphasizing that delamination factor (Fd) is proportional with cutting speed and feed rate, similarly remarked that delamination increases with carbide drills having high point of angles. On the other hand, it is reported that anisotropic CFRP composites exhibit different machinability characteristics according to different fiber directions during drilling. It is emphasized that various surface damages like resin loss, remove from fiber and matrix degradation may arise on hole surface, causing irregular surface forms (Wang et al., 2015).

Apparently, many studies have been conducted about effects of parameters like drill materials and composite production parameters for thrust force, hole quality and delamination factor in drilling of CFRP composite materials. However, there is no extensive study about combinational effects of drill point angle and varying feed rate on hole quality. In this study, the effects of 50% reduction of feed rate in hole exit under dry cutting conditions drilling of CFRP composites on machinability factors like thrust force (Fz), surface roughness (Ra), delamination factor (Fd) and hole diameter (d) have been investigated experimentally and statistically using three various levels of drill point angle, cutting speed and feed rate.

2. MATERIAL AND METHOD

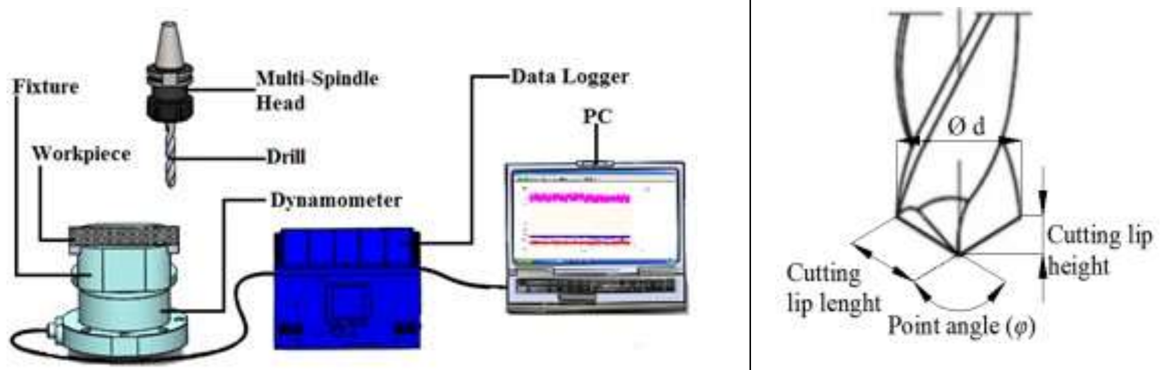
Carbon fiber reinforced polymer (CFRP) laminate were used as workpiece material in drilling experiments. The workpiece were produced from 40 layers of carbon fibre epoxy pre-preg woven lamina (245 g/m^2 - 2x2 twill HS-3K 0º/90º configuration) by vacuum bagging method. Finally, CFRPs produced at 10 mm thickness by compressing with vacuum were placed into furnace and a temperature of 120°C was applied to the system by four hours.

Drilling experiments were performed in CNC vertical machining center (Johnford VMC–550) with three different levels of point angle, cutting speed and feed rate in dry machining conditions. Karcan branded tungsten carbide (WC) drills were used as cutting tools. Drills have a diameter of 5 mm, helical angle of 30° and geometry of two cutting edges. Feed rate (f), cutting speed (V) and drill point angle (φ) were chosen as factors to apply full factorial experimental design in drilling of CFRP. The levels of these factors were determined by considering tool manufacturer's recommendations and studies on drilling of CFRP composites in literature. Drilling parameters with levels are given in Table 1. Drilling operations were repeated as three times and evaluations were done by taking arithmetic averages of machinability factors (Fz, Fd, Ra, d). In the light of experimental results, the effects of factors on Fz, Fd Ra and d were determined by analysis of variance (ANOVA) with 95% confidence level.

Table 1. *Drilling parameters and levels*

Factors	Levels
Point angle	120° - 130° - 140°
Cutting speed (m/min)	60 - 100 - 140
Feed rate (mm/rev)	0.05 – 0.1 – 0.15

Since the maximum spindle speed of the CNC milling machine used in the experiments is 6000 rev/min, suitable spindle speeds matching the appropriate cutting speeds were obtained using spindle speeder. Thrust force (Fz) values occurred in drilling process were measured with a system consisting of Kistler 9272 type dynamometer, Kistler Type 5070 amplifier and Dynoware software. The average surface roughness (Ra) on hole surfaces were measured as parallel to the drill direction with Mahr Perthometer M300 device. Five surface roughness measurements were performed for each hole surfaces occurred 5 mm distance from hole entry and 1 mm to hole exit. Hole diameter measurements from hole exit were performed by coordinate measuring machine (CMM) of hexagon metrology global performance. The surface damages were displayed via scanning electron microscope (SEM) in order to investigate the effects of drilling parameters and tool geometry on hole surface. The drilled holes were sectioned into two halves using a diamond saw to utilize a sectional view of the hole surface to prepare samples for SEM examination. Afterward, the samples were coated with 2-4 nm of Au/Pd in an ion beam sputtering system via Quroum Q150R machine. The experimental setup for drilling experiments (a) and drill geometry (b) are given in Figure 1.



(a) (b)

Figure 1. *The experimental setup for drilling tests and drill geometry*

The delamination (Fd) occurred by dissociating of laminate interfaces is generally calculated with the ratio of maximum diameter on delamination zone (Dmax) to drill diameter (D0) in plastic based fiber reinforcement composite materials (Eqn. 1) (Tsao et al., 2012). To determine the delamination factor values that result according to the drilling parameters, the images of all holes were taken by Dino-Lite with 37.3 magnification and diameter measurements were performed as shown in Fig.2a.

$$Fd = \frac{D_{\max}}{Do} \tag{1}$$

It is very important to minimize delamination tendency in hole entry and exit causing significant loss in loading capacity of assembly structure due to requirement of high safety in especially aviation industry. It is known that delamination is more severe generally in exit sides. Thus, drilling experiments were performed by 50% reduction of feed rate in 1 mm distance to hole exit in order to decrease push-up delamination consisting in hole exit (Fig. 2b). Accordingly, measurements of machinability criteria (Fz, Ra and Fd) were performed as two different ways that are till the distance of 1 mm from hole entry to exit and residual distance.

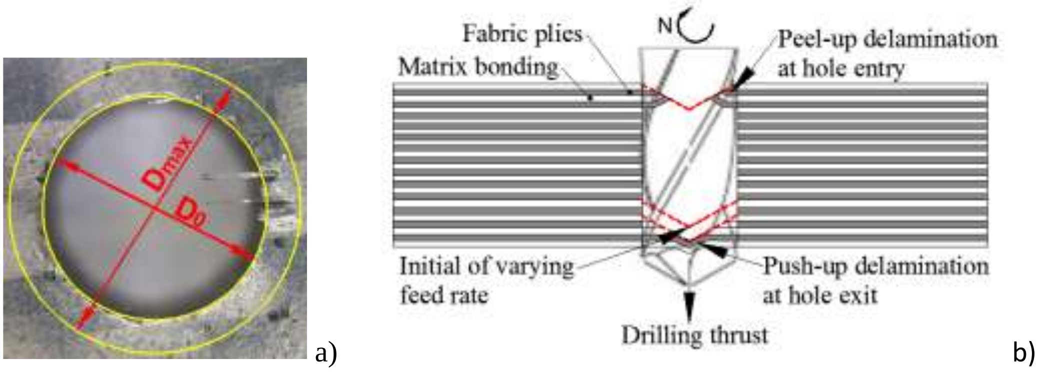


Figure 2. *a) Measurement of delamination factor, b) Schematic illustration of the delamination*

3. RESULTS and DISCUSSION

3.1. Analysis of Thrust Force

Thrust force (Fz) values measured in drilling of CFRP according to drilling parameters and drill point angles are given in Fig. 3. The Fz values under constant feed rate and its 50% reduced conditions at 1mm distance to hole exit are presented in the figure.

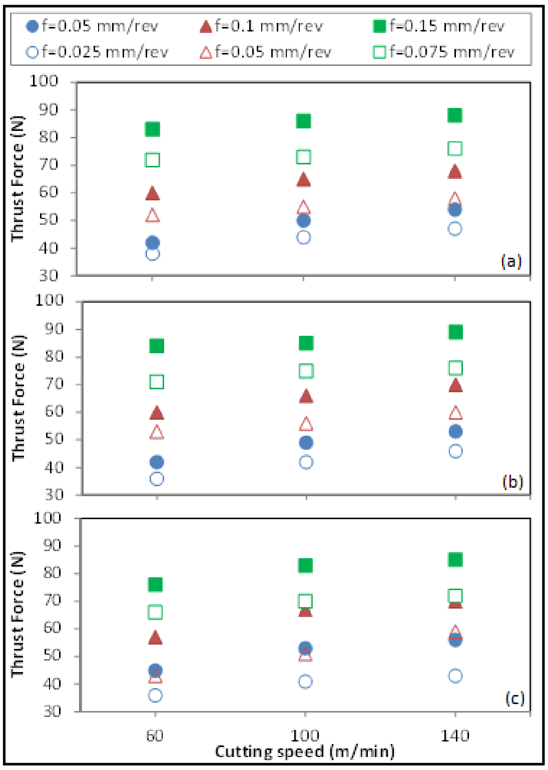


Figure 3. *Variation of thrust force; point angle of a) 120°, b) 130°, c) 140°*

When investigating Fig. 3, it is shown that thrust forces increase with increasing of feed rate and cutting speed. It is mentioned in literature that thrust force decreases depending on increasing temperature with increasing cutting speed (Abrao et al., 2007; Krishnaraj et al., 2012). However, an increment in thrust force with increasing cutting speed is observed in the Fz plots in Fig. 3. This result indications that the effect of cutting speed on Fz is less than effect of feed rate. The reason of increase in thrust force with increasing feed rate is mainly chip formation by high speed hitting of drill to fibers with increasing of uncut chip thickness. The lowest value for Fz with 120° point angle were measured as 38 N with lowest feed rate of 0.025 mm/rev and cutting speed of 60 m/min. On the other hand, it is also evident that the reduction of each different feed rate by 50% in hole exit reduces the Fz values. This decrease rates in Fz value were calculated as average of %10, %16 and %28 for 120°, 130° and 140° point angles for lowest cutting speed, respectively.

Examining Fig. 3b and 3c, it is obvious that the Fz values for drill point angles of 130° and 140° under both constant and 50% reduced feed rate conditions display similar trends with drills of 120° point angle. The lowest Fz value for 130° drill point angle were measured as 36 N in lowest feed rate and cutting speed. The result of all experiments, the lowest Fz value with constant feed rate was measured as 45 N in point angle of 140°, feed rate of 0.05 mm/rev and cutting speed of 60 m/min while it was measured as 34 N by 32% decrease in same drilling conditions with 50% reduction of feed rate. This reduction in Fz value contextually may be linked to the reduction of chip cross-sectional area that is caused by the reduced Fz values. Similar tendencies are shown for all drill point angles in experiments (Fig. 3). It has been determined that thrust forces decrease with increasing drill point angle from 120° to 140°. The main reason of this decrease can be thought as decrease in tool-chip contact area with increasing drill point angle. Tool-chip contact area decreases depending on decrease of cutting lip length and height with increasing drill point angle (Fig. 1b) and so thrust forces decrease with reducing friction forces.

On the other hand, analysis of variance (ANOVA) was performed to determine the effects of drilling parameters and drill point angle on Fz for drilling processes with 50% reduction of feed rate (Table 2). Here, the probability (P) value indicating importance levels of factors, degrees of freedom (DF), the sum of square (SS), mean square (MS), F values and the percent contribution ratio (PCR) is shown. P value should be lower than 0.05 in 95% confidence level in order to determine that any factor acting on the force is effective on it. ANOVA results also support the experimental results, while the most prominent parameter on thrust force is observed as feed rate with a PCR of 91.36%.

Table 2. *ANOVA result for thrust force*

Factor	DF	SS	MS	F	P	%PCR
φ	2	85.63	42.81	23.59	0.000	1.78
f	2	4391.4	2195.70	1209.88	0.000	91.36
V	2	274.07	137.04	75.51	0.000	5.70
φ*f	4	9.93	2.48	1.37	0.327	0.21
φ*V	4	9.26	2.31	1.28	0.356	0.19
f*V	4	22.2	5.54	3.05	0.084	0.46
Error	8	14.52	1.81			0.30
Total	26	4806.96				100

3.2. Analysis of Hole Quality

3.2.1. Delamination factor

Delamination is main problem in drilling of plastic based carbon fiber reinforcement composite materials. It is known that this formation cause to tolerance loss in assembly of CFRP, structural integrity of material and performance reduction in long life. Delamination is commonly occurred in hole exit and main reason of it is thrust forces changing according to drilling conditions (Xu et al., 2016). Relatively, the reduction of thrust force especially towards the hole exit appears as a requirement. In this study, variation of delamination factors (Fd) occurred in drilling of CFRP with constant feed rate and 50% reduction of feed rate according to drill point angle and drilling parameters is given in Fig. 4. It has been concluded that delamination factor increase with increasing feed rate and cutting speed when examining Fd values. At the same time, a significant decrease is seen on Fd values obtained with 50% reduction of feed rate in 1 mm distance to hole exit (seen Fig. 4).

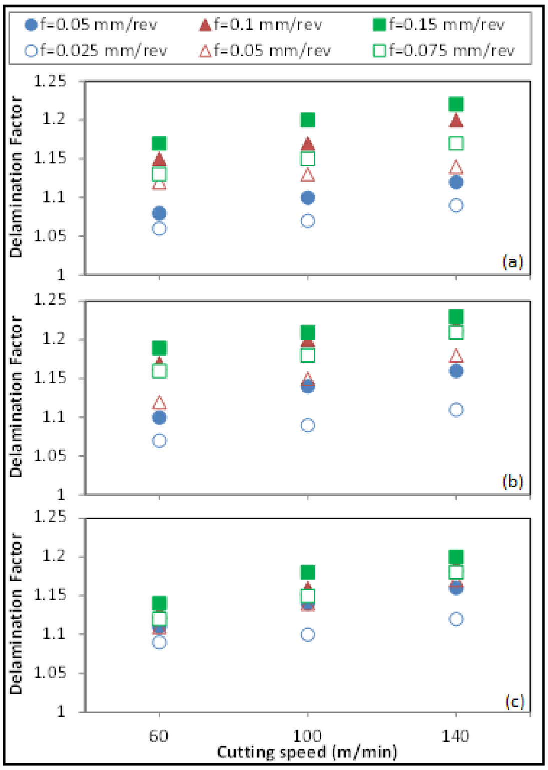


Figure 4. *Variation of delamination factor; point angle of a) 120°, b) 130°, c) 140°*

The lowest Fd value was obtained as 1.09 in drill point angle of 120°, feed rate of 0.05 mm/rev and cutting speed of 140 m/min, while it was obtained as 1.06 with 3% decline for 50% reduction of feed rate in same drilling conditions. This decrease ratio in Fd values was acquired 3% and 2% for 130° and 140° drill point angle, respectively by 50% reduction of feed rate in cutting speed of 60 m/min. The decrease ratio in Fd values for each drill point angle is 5%, 4% and 2% with increase of cutting speed from 60 m/min to 140 m/min. According to these results, it is possible to say that delamination factor increase with increasing drill point angle. Delamination images in drilling of CFRP with constant and varying feed rate for 120° point angle are given in Fig. 5. As can be seen the figure, the decrease of delamination factor to minimum is probable by 50% reduction of feed rate in hole exit. Hence, it can be concluded that this process provides considerable contribution to the demand of drilling with low roughness and suitable geometric tolerances in industries using CFRP materials (Xu et al., 2016; Abrao et al., 2007), and using varying feed rate by reducing it towards the hole exit is an effective method.

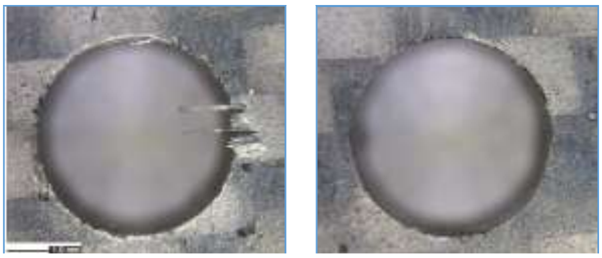


Figure 5. *Delamination images for feed rate; a) Constant, b) Varying*

Moreover, analysis of variance (ANOVA) was applied to determine the effects of drilling parameters and drill point angle on Fd (Table 3). As can be seen from the variance analysis in Table 3, the most important parameter affecting delamination factor is feed rate with 64.64% PCR. On the other hand, it is also shown that cutting speed (V), point angle (φ) and interaction between point angle-feed rate (φ*f) are important parameters with 22.05%, 6.42% and 4.46% PCR.

***Table 3**. ANOVA result for delamination factor*

Factor	DF	SS	MS	F	P	%PCR
φ	2	0.002467	0.001233	34.15	0.000	6.42
f	2	0.024822	0.012411	343.69	0.000	64.64
V	2	0.008467	0.004233	117.23	0.000	22.05
φ*f	4	0.001711	0.000428	11.85	0.002	4.46
φ*V	4	0.0004	0.0001	2.77	0.103	1.04
f*V	4	0.000244	0.000061	1.69	0.244	0.64
Error	8	0.000289	0.000036			0.75
Total	26	0.0384				100

3.2.2. Surface roughness

Surface roughness is one of the surface integrity criteria for all parts manufactured by machining and also is a parameter to be considered in the analysis of the hole quality in CFRP drilling. In this study, variation of average surface roughness (Ra) occurred in drilling of CFRP with constant feed rate and 50% reduction of feed rate according to drill point angle and drilling parameters is given in Fig. 6.

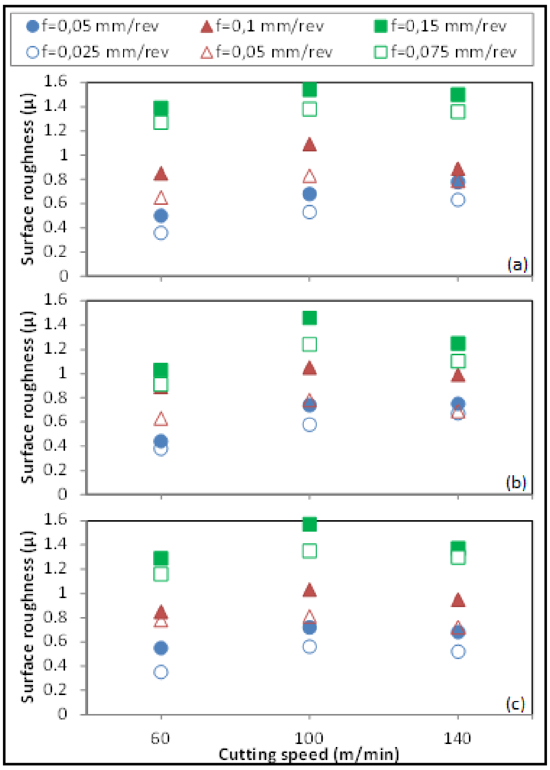


***Figure 6**. Variation of surface roughness; drill point angle of a)120°, b) 130°, c) 140°*

Examining Fig. 7, similar tendencies for average surface roughness (*Ra*) are observed for each drill point angle. Surface roughness values obtained in drilling process with constant and 50% reduction of feed rate increase with increasing feed rate. Meanwhile, the lowest *Ra* values were obtained in the lowest feed rate and cutting speed for each three drill point angles. It is possible to conclude that the surface damages minimizes with the adhesion of matrix material to the hole surfaces as a result of chip formation that occurs like ploughing in low deformation rates (seen Fig. 7a,b). Besides, it is understood from the figure that variation of surface roughness according to drilling parameters with increasing cutting speed are different tendency from *Fz* and *Fd*. Surface roughness increases with increasing cutting speed from 60 m/min to 100 m/min, subsequently, roughness tends to decrease. As mentioned in recent studies (Merino-Pérez et al., 2015), this is mostly originated from the incomplete cutting of fibers and their removal from the matrix with the increasing cutting speed and/or the surface defects on drilled hole that occur as a result of matrix-fiber debonding. Surface roughness decreased 6-13% in cutting speed of 140 m/min. This result can be referred to the probable remaining of the hole surface temperature below the glass transition temperature of matrix material as a result of decreasing cutting time with high cutting speed. The lowest *Ra* was measured as 0.50 µm with constant feed rate in drill point angle of 140°, feed rate of 0.05 mm/rev and cutting speed of 60 m/min while it was measured as 0,35 µm by 30% decrease in same cutting conditions with 50% reduction of feed rate in result of all drilling experiments. The highest *Ra* value was obtained as 1.38 µm in drill point angle of 120°, feed rate of 0.075 mm/rev and cutting speed of 100 m/min for drilling with varying feed rates. These results partly supports formation of fiber pull-out and fiber fragmentation (seen Fig. 7c), in drilling with high cutting speed and feed rate as can be mentioned in Merino-Pérez et al. (2015). Additionally, severe debonding at fiber matrix interface due to the increasing drilling temperature with higher cutting speed lead to matrix debris and cavities (seen Fig. 7d), thereby resulted in poorer surface roughness.

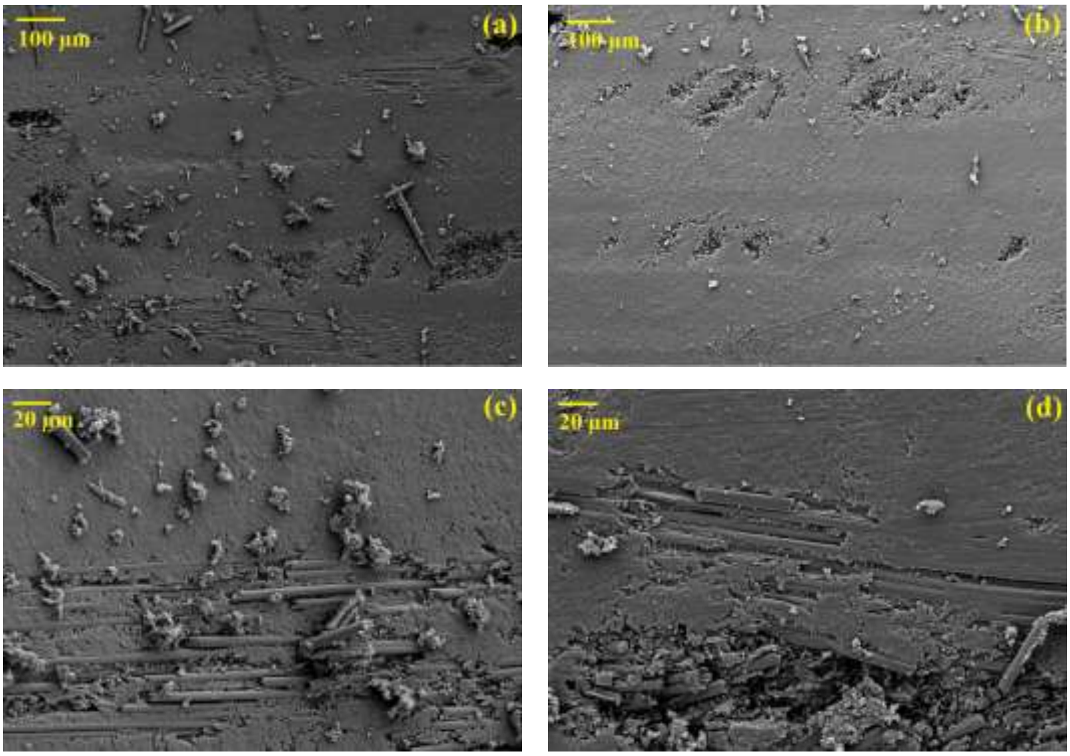


Figure 7. *SEM micrographs of the drilled hole surface; a) V= 60 m/min, f=0.05 mm/rev; b) V=60 m/min, f=0.025 mm/rev; c) V=100 m/min, f=0.15 mm/rev; d) V=140 m/min, f=0.15 mm/rev*

Analysis of variance (ANOVA) was performed to determine the effects of drilling parameters and drill point angle on Ra that is a significant factor for performance life of structural part manufactured from CFRP (Table 4). As seen in the ANOVA table, the most important drilling parameter that effects the surface roughness is feed rate with a PCR of 87.5%. The other statistically significant parameters over *Ra* are cutting speed (V) with PCR of 6.07%, 2.49% and 1.78%, interaction between point angle-feed rate (φ*f) and point angle (φ), respectively.

Table 4. *ANOVA result for Ra*

Factor	DF	SS	MS	F	P	%PCR
φ	2	0.04869	0.02434	8.83	0.009	1.78
f	2	2.40549	1.20274	436.04	0.000	87.5
V	2	0.16709	0.08354	30.29	0.000	6.07
φ*f	4	0.06842	0.01711	6.2	0.014	2.49
φ*V	4	0.01109	0.00277	1.01	0.459	0.40
f*V	4	0.02622	0.00656	2.38	0.138	0.96
Error	8	0.02207	0.00276			0.80
Total	26	2.74907				100

3.2.3. Hole size

Another significant factor taken into account in determining the hole quality is the hole size. Especially, the need to drilling in desired tolerance with low roughness and suitable roundness due to necessity of high strength in assembly parts is an important safety problem in aerospace industry (Abrao et al., 2007). In this study, variation of hole diameter values occurred in drilling of CFRP with constant and varying feed rate according to point angle and drilling parameters is given in Fig. 8.

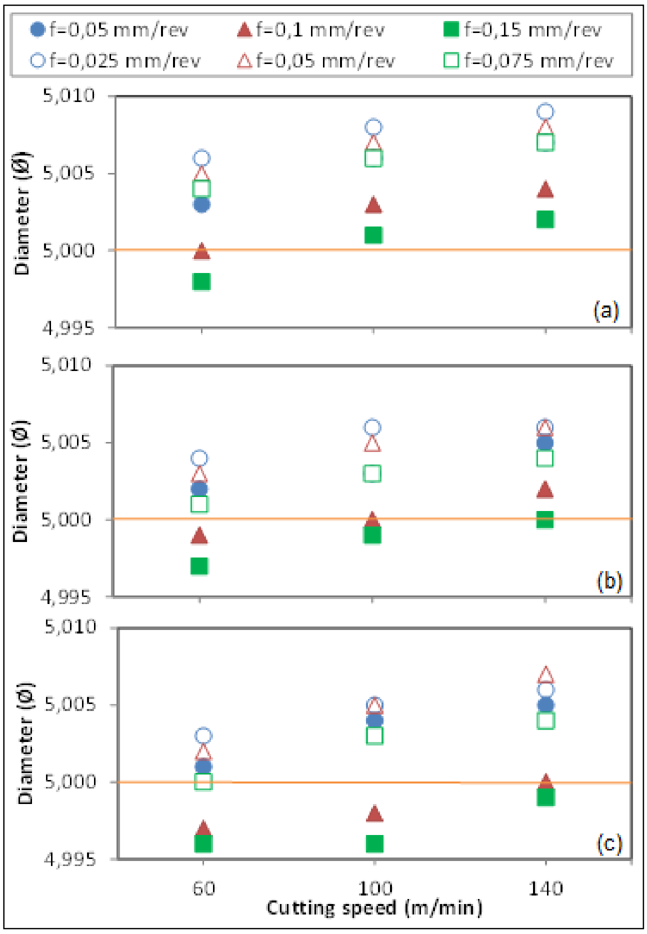


Figure 8. *Variation of hole diameter; drill point angle of a)120°, b) 130°, c) 140°*

As seen from Fig. 8, the hole diameters increased with 50% reduction of feed rate for all drill point angle. The main reason of higher hole size than nominal value can be explained with cutting temperature varying according to feed rate and cutting speed. It is generally known that the cutting temperature increases with lower feed conditions due to the low thermal conductivity of CFRP (Ashrafi et al., 2016). As the high cutting temperature with an increasing drill engagement time results in workpiece expansion once the feed rate is low. As can be seen from graph, hole sizes diverged to nominal value with increasing cutting speed. The reason of that is thermal softening of workpiece caused by increasing cutting temperature with increasing cutting speed. On the other hand, the highest hole size were measured as 5.09 mm in drill point angle of 120, cutting speed of 140 m/min and feed rate of 0.025 mm/rev. this result can be explained with decreasing in tool-chip contact area due to increasing drill point angle. Decreasing in cutting lip length and height with increasing drill point angle (see Fig. 1b) will lead to reduce of friction through tool-chip interface, which decreases generated heat, thereby result in CFRP hole sizes closer to the drill diameter.

The analysis of variance (ANOVA) was performed to determine the effects of drilling parameters and drill point angle on hole diameter (Table 5). As seen in the ANOVA table, the most important drilling parameter that effects the hole diameter is cutting speed with a PCR of 40.16%. The ANOVA results indicate that the feed rate and the drill point angle influence the hole diameter by 33.60 % and 22.14%, respectively.

Table 5. *ANOVA result for hole diameter*

Factor	DF	SS	MS	F	P	%PCR
φ	2	0.000041	0.000021	223.6	0.000	33.60
f	2	0.000027	0.000013	144.4	0.000	22.14
V	2	0.000049	0.000024	264.4	0.000	40.16
φ*f	4	0.000002	0.000000	4.60	0.032	1.64
φ*V	4	0.000001	0.000000	4.00	0.045	0.82
f*V	4	0.000001	0.000000	2.20	0.159	0.82
Error	8	0.000001	0.000000			0.82
Total	26	0.0000122				100

4. CONCLUSIONS

In this study, the effects of drill point angle, cutting speed and feed rate on machinability factors (Fz, Ra, Fd, d) when drilling of CFRP composites with uncoated WC drill bits by applying constant and varying feed rate were experimentally and statistically analyzed.

- The lowest values for Fz and Ra were measured as 34 N and 0.35 µm, respectively with drill point angle of 140°, feed rate of 0.025 mm/rev and cutting speed of 60 m/min while the lowest value of delamination factor was obtained as 1.06 with drill point angle of 120°. In the lights of these results, optimization of drilling parameters can be performed for machinability outputs by using full factorial design.
- It was determined that Fz, Fd and Ra values obtained with 50% reduction of feed rate in hole exit is lower than that of constant feed rate with 12-30%, 10-16% and 20-52%, respectively.
- The most important parameter for Fz, Fd and Ra was feed rate with a PCR of 91.36%, 64.64% and 87.5% according to ANOVA results, respectively. On the other hand, cutting speed was determined as secondary important parameter with a PCR of 22.05% on delamination factor which is the most important machinability factor.
- Hole diameter (d) values obtained by using CMM device with varying feed rate were closer to the nominal drill diameter than that of constant feed rate. This situation attributed to the instability and thermal expansion of the workpiece due to increasing cutting temperature at lower feeds and higher speeds.
- It is possible to decrease delamination factor to minimum with varying feed rate in hole exit when drilling of CFRP composites. This process may be evaluated as disadvantages with regards to drilling operation time. However, the usage of varying feed rate in drilling of CFRP is recommended as productive method for industrial applications by considering that there are very positive results with regards to hole quality depending on especially Fd, d and Ra.

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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