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Impact assessment of fillers on the machinability of carbon fibre reinforced polymer composites

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Abstract

Carbon fibre reinforced polymer (CFRP) composites are widely applied due to their exceptional specific mechanical properties. The mechanical machining of these composites is often required; however, the existing expertise on the machinability of CFRP composites with fillers is deficient. Therefore, the main aim of the present study is to experimentally investigate the machinability of CFRPs with and without milled carbon fillers. Drilling experiments were conducted in different CFRP structures, and the cutting force and microgeometry were analysed through the analysis of variance (ANOVA) technique. The experimental results show that the fillers have a significant influence on the microgeometry.

Keywords: CFRP; Filler; Drilling; Cutting force; SEM

1. Introduction

The application of carbon-fibre reinforced polymer (CFRP) composites is getting more popular in high-end industries like aerospace, marine, energy and automobile [1,2]. This is mainly due to their excellent strength-to-weight ratio and easy-to-shape processability [3,4]. Although these composites are often manufactured ready-to-shape, their post-manufacturing is often required to meet dimensional requirements for assembly [5]. Mechanical drilling is the most applied post-manufacturing technology of CFRP, as this can provide excellent hole quality and high material removal rate (MRR) [1]. Even though the mechanical drilling of CFRPs is appropriate and required, many typical composite machining challenges make it difficult to apply [6]. The inhomogeneity and anisotropy of the composite and the abrasive wear-effect of the carbon fibres often result in machining-induced delamination, burrs, fibre-matrix debonding, tearing, fibre pull-outs and rapid tool wear [6–8].

Fillers are often used in polymeric composites to improve mechanical properties (*i.e.* strength and stiffness) and fracture toughness, but their influence on machinability is not studied widely yet [9,10]. Ponnuvel and Moorthy [11] investigated whether the application of multi-walled carbon nanotubes in fibrous polymeric composites improves the hole quality. They found that the application of fillers reduced the probability of drilling-induced delamination formation on both the entry and exit sides. Carbon nanotube was added into CFRP composites by Li et al. [12] and analysed the drilling-induced delamination-formation ability. They proved by drilling experiments that the application of carbon nanotube fillers decreased the delamination factor by 16%. Heidary et al. [13] investigated the effect of carbon nanotube fillers on the delamination and flexural properties of the glass fibre-

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reinforced polymer (GFRP) composites. They found that the feed has the most significant influence on the thrust force and delamination, followed by the nano-content and spindle speed, respectively. Kumar and Singh [14] analysed drilling-induced delamination and surface quality of CFRP filled by carbon nanotubes. They could significantly improve the mechanical properties of the filled CFRP composite (24% in flexural strength and 28% in interlaminar shear) and decrease the delamination factors at the entry and exit sides by 21% and 29%, respectively. They also reported that the drilling process in the filled CFRP was carried out more smoothly. In another work of Singh and Kumar [15], the drilling responses of multi-walled carbon nanotube filled GFRP was investigated. Their experimental result showed that the larger the filler content in the composite, the better the hole quality (delamination and surface roughness) is. Kumar et al. [16] conducted drilling experiments in filled and unfilled GFRP composites and analysed the thrust force and surface roughness. They concluded that the thrust force was lower in the filled CFRP than in the unfilled one; however, the unfilled CFRP was more advantageous from the point of view of surface roughness.

Other researchers also studied the effect of fillers on specific indicators of machinability of polymeric fibrous composites like Rajmohan [17], Premnath [18], Kaybal et al. [19], Monoranu et al. [20], and Celik et al. [21]; and each concluded that the proper content of filler application in polymeric composites often results in better to machine composites. Despite the reviewed studies suggesting that the machinability of filled CFRPs may be advantageous from the point of view thrust force and delamination, no comprehensive study is available on the thrust force, burrs, delamination and surface microstructure. Therefore, the main objective of the present paper is to compare the machinability of three different composites with different milled carbon filler contents from the point of view cutting energetics and drilling-induced micro and macro-sized geometrical damages.

2. Experimental setup and methods

The mechanical drilling experiments were performed in three different types of carbon fibre reinforced composite sheets (T, M and MT). In the case of each workpiece, the matrix material consisted of IPOX MH3010 epoxy resin and IPOX MH3124 cycloaliphatic amine-based hardener, which were mixed in a ratio of 100:33. The composite sheets differed from each other in their carbon reinforcement structure: milled carbon fibre with an average length of 45±28 μm (M), nonwoven mat (T − also called felt) and their combination (MT) were used in the workpieces.

The M composite was processed via silicone form casting. The epoxy resin and the reinforcement were stirred for 15 minutes with an IKA RW16 mechanical stirrer (the fibre content of the composite was targeted to 20 wt%), then the hardener was added, and the mixture was homogenised by a 1.5-1.5-1.5 minutes stirring-resting-stirring cycle. The mixture was poured into the silicone form and the curing process was carried out at room temperature for 14 hours, which was followed by a post-curing process in Despatch LBB2-27-1CE drying oven (60 °C, 2 hours).

In the case of the T composite, a heated compression moulding technology was applied. The nonwoven mats were placed and impregnated manually into a pre-heated (for 60°C) mould, for this the same resin system (components and mixing ratio) with the same mixing-resting-mixing cycle was used as in the case of cast formed composite with milled fibre reinforcement. Then they were pressed with 100 bar pressure at 80 °C for 20 minutes in a Metal Fluid Engineering 30T hydraulic press to execute the crosslinking process.

The MT composite was produced by heated compression moulding technology. The nonwoven mat layers were placed into the pre-heated mould (at 60°C) and impregnated with the identical mixture that was used in the case of silicone form casting. It has to be highlighted that the mats were fully impregnated, however, the majority of milled fibres could not penetrate the inner part of the mat. After the hand lay-up process, the mould was closed and the curing process was executed with the hydraulic press at 80 °C and 100 bar pressure for 20 minutes.

Drilling experiments were performed using a three-axis Kondia B640 machining centre. All the machining operations were done in accordance with the dry machining method which is the most suitable way of machining composite materials, with the help of a Nilfisk GB733 industrial vacuum cleaner, as shown in Fig 1a. The thrust force was being measured throughout the machining process, for which a KISTLER 9257BA three-component dynamometer was applied, along with a KISTLER 5070 multi-channel charge amplifier and a National Instruments USB-4431 dynamic signal acquisition module. For the drilling a Tivoly Polaris 150 Sim Dim 6537K Ø10 mm diameter TiNAl coated solid carbide drill was selected (Fig 1b).

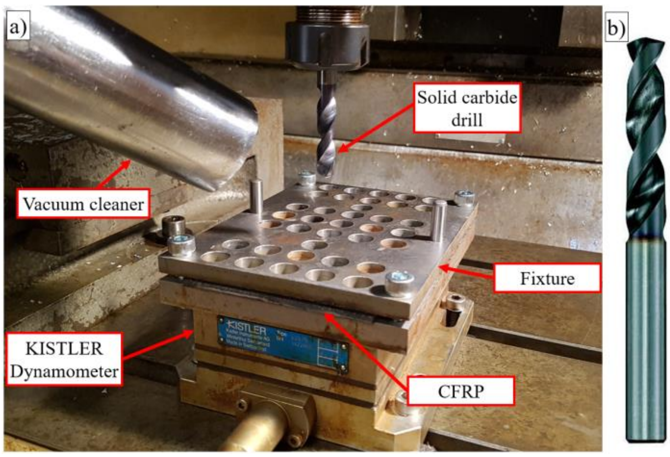

Fig. 1. (a) Experimental setup; and (b) applied twist drill.

In order to obtain a reasonably accurate understanding of the machinability of the investigated composites, a Central Composite Face-Centered (CCF) design was chosen due to the limited volume and the complicated production method of these materials. Table 1 shows the factors and their levels that were used in the experiments.

Table 1. Applied factors and their levels.

Factors	Levels		
	-1	0	1
Feed − f (mm/rev)	0.10	0.20	0.30
Cutting speed − v_c (mm/min)	50	100	150
Type of composite	T	M	MT

A Mitutoyo 361-804 optical microscope was used to inspect the surface of the drilled holes and to capture the necessary images for burr and delamination analysis. The burr factor (F_b) was calculated through digital image processing (DIP) of the images of the holes, as expressed by Eq. (1).

$$F_b = \frac{A_b}{A_{nom}} \quad (1)$$

Where A_b (mm) denotes the burr area and A_{nom} (mm) is the nominal hole area. The delamination factor was manually measured using a circle fitted to the delaminated area and to the nominal hole contour. In the case of drilling the delamination factor (F_d) is defined as the ratio of the circular diameter that is fitted to the damaged area (D_{max}) and the nominal diameter of the hole (D_{nom}), as it is expressed by Eq. (2).

$$F_d = \frac{D_{max}}{D_{nom}} \quad (2)$$

A custom-built Python program was used to collect, filter, slice and compute the characteristic properties of the force datasets. A Butterworth lowpass filter with a cut-off frequency of f_c=300 Hz was used to filter the signals. The raw and processed thrust force (F_t) datasets are plotted in Fig. 2.

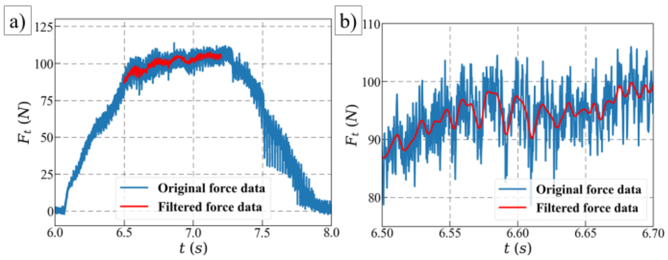

Fig. 2. Force data filtering and processing: (a) raw dataset (blue) and the filtered and trimmed dataset (red); (b) enlarged part of the raw dataset (blue) and the filtered and trimmed dataset (red).

The analysis of variance (ANOVA) technique was implemented to determine the impact of each factor on the thrust force. A factor was considered to have a significant effect on the thrust force at a significance level of at least α=0.05.

3. Results and discussion

3.1. Drilling-induced burrs and delamination

The drilling of the three composites showed that each material produced high-quality holes in all test conditions, considering the resulting burr, as shown in Fig 3. As it was not possible to determine the burr metrics for any of the composites, no further investigations were carried out in this direction.

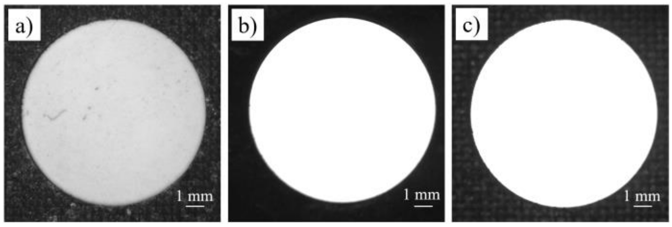

Fig. 3. High-quality drilled CFRP holes in the case of (a) nonwoven mat (T), (b) milled (M), and (c) mixed (MT) reinforcing structures (f = 0.2 mm/rev, v_c = 100 mm/min).

Despite the fact that almost no burr was formed, small drilling-induced geometric errors appeared in the form of delamination in the case of the nonwoven mat (type T composite) reinforcement structure, but these faults were also only observed on the exit side of only three holes (at hole no. 2, 8 and 10). Since there was no correspondence between cutting speed and feed of these holes, it cannot be concluded that the technological parameters have a significant influence on the formation of this minimal delamination, these geometric errors occurred quasi-randomly. Furthermore, the amount of these errors are small (F_{d2} = 1.11; F_{d8} = 1.09; F_{d10} = 1.07), therefore, they do not have a significant influence on the applicability of the composite. Taking all this into account, it was observed that the holes produced in case of all three composite types have high quality.

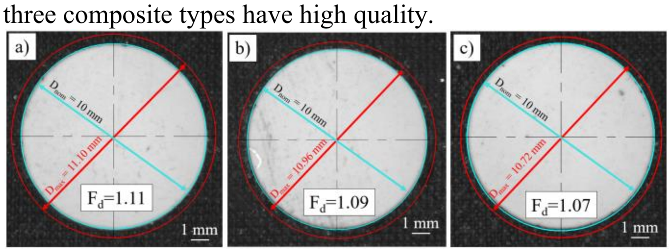

Fig. 4 Drilled holes in the nonwoven reinforced CFRP composite with delamination: (a) hole number 2 (b) hole number 8 and (c) hole number 10

3.2. Thrust force

The effect of the fillers is mostly manifested in the thrust force that occurs in the drilling process. The thrust results for each experimental hole can be seen in Table 2.

The result of ANOVA analysis (Table 3) showed that all factors *i.e.* the feed (F-value = 367.62 ; P-value = 0.000), cutting speed (F-value = 25.22 ; P-value = 0.000) and type of composite (F-value = 100.00 ; P-value = 0.000) have a significant effect on the thrust force. The main effect plots in Fig 5 illustrate that as the feed and cutting speed increase, the resulting thrust also increases. Among the three types of composites, the nonwoven mat reinforcement structure showed the smallest thrust force, while the mixed reinforcement structure produced the highest.

Table 2. Result of thrust force evaluation along with the technological parameters (f and v_c).

Number of test	Parameters		F_t (N)		
	f (mm/rev)	v_c (m/min)	*T*	*M*	*MT*
1	0.10	50	108.45	127.64	134.07
2	0.30	100	164.69	205.30	208.02
3	0.30	50	156.52	200.29	207.41
4	0.20	100	142.30	173.08	187.83
5	0.20	100	147.45	177.39	195.05
6	0.20	100	144.44	174.16	171.38
7	0.20	150	147.75	178.30	190.98
8	0.30	150	166.92	211.05	224.77
9	0.20	50	136.05	163.73	157.79
10	0.10	100	120.36	134.97	144.84
11	0.10	150	133.34	140.17	144.46
12	0.20	100	143.68	170.21	159.88
13	0.20	100	141.02	172.07	191.58

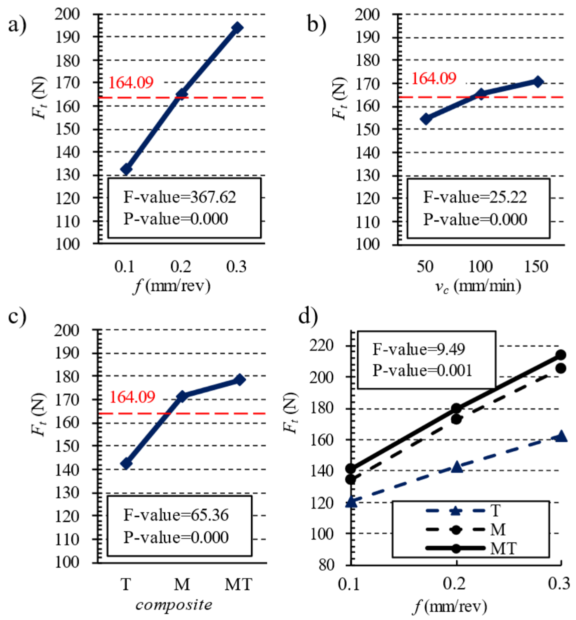

Fig. 5. Main effect and interaction plots for F_t: main effect for (a) f, (b) v_c and (c) type of composite; (d) interaction for f and type of composite.

Table 3. ANOVA table for thrust force: f versus v_c versus type of composite.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	11	28777.0	2616.1	55.86	0.000
Linear	4	27762.3	6940.6	148.21	0.000
f	1	17215.4	17215.4	367.62	0.000
v_c	1	1180.8	1180.8	25.22	0.000
composite	2	9366.1	4683.0	100.00	0.000
Square	2	74.0	37.0	0.79	0.464
$f{\cdot}f$	1	15.2	15.2	0.32	0.574
$v_c{\cdot}v_c$	1	31.5	31.5	0.67	0.420
2-way interaction	5	940.7	188.1	4.02	0.007
$f{\cdot}v_c$	1	7.2	7.2	0.15	0.698
$f{\cdot}$*composite*	2	888.4	444.2	9.49	0.001
$v_c{\cdot}$*composite*	2	45.1	22.5	0.48	0.623
Error	27	1264.4	46.8		
Lack-of-fit	15	317.9	21.2	0.27	0.991
Pure Error	12	946.5	78.9		
Total	38	30041.4			

The effect of fillers on thrust force is not completely in accordance with the properties that have characterised fillers so far. The use of carbon filler is expected to improve mechanical properties, thus making it even more difficult the machinability, but unlike carbon nanotube fillers, milled carbon fillers do not provide lubrication during drilling and therefore machining is not going to be facilitated. Furthermore, the increase in thrust is also caused by the fact that the fibres in the reinforcing structure containing the filler may also be oriented in the same direction as the drilling process, making it significantly more difficult, as it was observed by Geier et al [22]. The application of the filler cannot reduce the thrust force because, the filler was concentrated between the textile layers and not evenly distributed, making machining significantly more difficult. This is discussed in-depth in Section 3.3. The resultant fibre content of the composite also increased with the addition of the filler, which resulted possibly in an increase in thrust force. Our experience suggests that the high thermal conductivity of carbon fibres reduces the temperature of machining while drilling, therefore, a further aim of our research is to investigate this phenomenon.

3.3. SEM investigations

Scanning electron microscope (SEM) images were captured with a JEOL JSM 6380LA SEM to analyse the representative surface characteristics and machining-induced microsized damages of the examined CFRP composites. The sample surfaces were prepared with a JEOL JFC-1200 fine coater, the acceleration voltage was set to 10 kV, and the imaging was performed with a 40 spots size.

In Fig. 6a-6f, the effect of feed on the overall surface quality can be seen. It is visible that in the case of M composites (Fig. 6a-6b), the increase of the feed produces a much rougher surface structure. The larger feed generated more voids in the composite structure, which can be caused by fibre pull-outs and matrix fragmentation. This effect is more common in the case of T composites, as can be seen in Fig. 6c-6d. The sizes of the voids can reach the size range of 100 µm. As the MT composites are the hybrid composition of the M and T composites, the same tendency is observable in Fig. 6e-6f. The composed structure of MT composites can also be inspected in Fig. 6i, a smaller scaled image of the average machined surface of MT composites. In general, it can be stated that the overall surface quality of machined CFRP features deteriorates with the increase of the feed. This phenomenon can be correlated with the thrust force and the transferred energy increase.

In Fig. 6g-6h, the general fibre orientation of different reinforcement structures can be seen. The milled carbon fibres can be located and directed in 3D quasi-randomly due to the manufacturing process of the fibres, also the homogenising process and the average fibre length: when this type of reinforcement structure is manufactured, the fibres are not arranged (or partly arranged) in one direction as in the case of woven (*e.g.* UD-CFRP) and nonwoven fabrics. Furthermore, the length of fibres does not allow a high adhesion (mainly because of electrostatic reasons) of the individual fibres. In contrast, the nonwoven mat structure has quasi-infinite long (compared to the diameter of the fibre) filaments which are arranged planarly (it is quite rare to have fibre direction perpendicular to the plane of the mat). For these reasons, there is a higher probability of having fibres directed axially to the drill, which can increase the load-bearing capacity of the composite, which can explain the resulted thrust force tendency. Geier et al. [22] explained this outlined phenomenon in detail.

In Fig. 6j, fibre pull-outs (the place of fibre embedding) and fractured fibres can be seen. The SEM images also prove the critical role of the fibre cutting angle (θ): if the fibre direction is close to parallel to the cutting speed vector ($\theta \approx 0°/180°$), the fibres tend to be pulled out from the matrix instead of being cut. However, if $0°<\theta<180°$, the fibres will have a mainly shearing dominant fracture (instead of a tensile fracture with more energy need [23]). The fibre pulling-out could have higher energy demand than the fracture; therefore, the type of fibre damage can correlate to the overall quality of the machined composite feature. By investigating the number of fibre pull-outs, conclusions can be drawn about other structural damages (*e.g.* delamination, cracking, *etc.*), which also correlate with the energy input of machining. Nevertheless, this correlation requires further investigation.

4. Conclusions

In this study, CFRP composites with three different states of filler content were mechanically drilled and the cutting energetics, micro and macro geometrical damages were evaluated. Based on the present study, the following conclusions can be drawn:

- Digital image processing analysis of optical microscopic images of holes showed no significant drilling-induced damages (burrs and delamination), some small damages appeared quasi-randomly.
- The ANOVA results show that the feed had the most significant effect on the thrust force, followed by the type of reinforcement structure and the cutting speed, respectively. It was found that the feed has an increasing effect on thrust force, and the nonwoven carbon mat reinforced polymer composite with milled carbon fibre fillers (MT) had the largest thrust force values.
- SEM investigations also proved the surface quality deterioration effect of the increasing feed. The microscopic images showed the typical fibre orientation of the reinforcement structures, and the quasi-randomly located and directed fibres of the filler can explain the larger thrust force values. The correlation between machining energetics, micro and macro-structural damages should be investigated in the future,
- As carbon fibres have excellent thermal conductivity, the fibre content and orientation can affect the cutting temperature. Therefore, the authors want to investigate the possible positive effects of fillers on cutting temperature reduction and quality improvement.

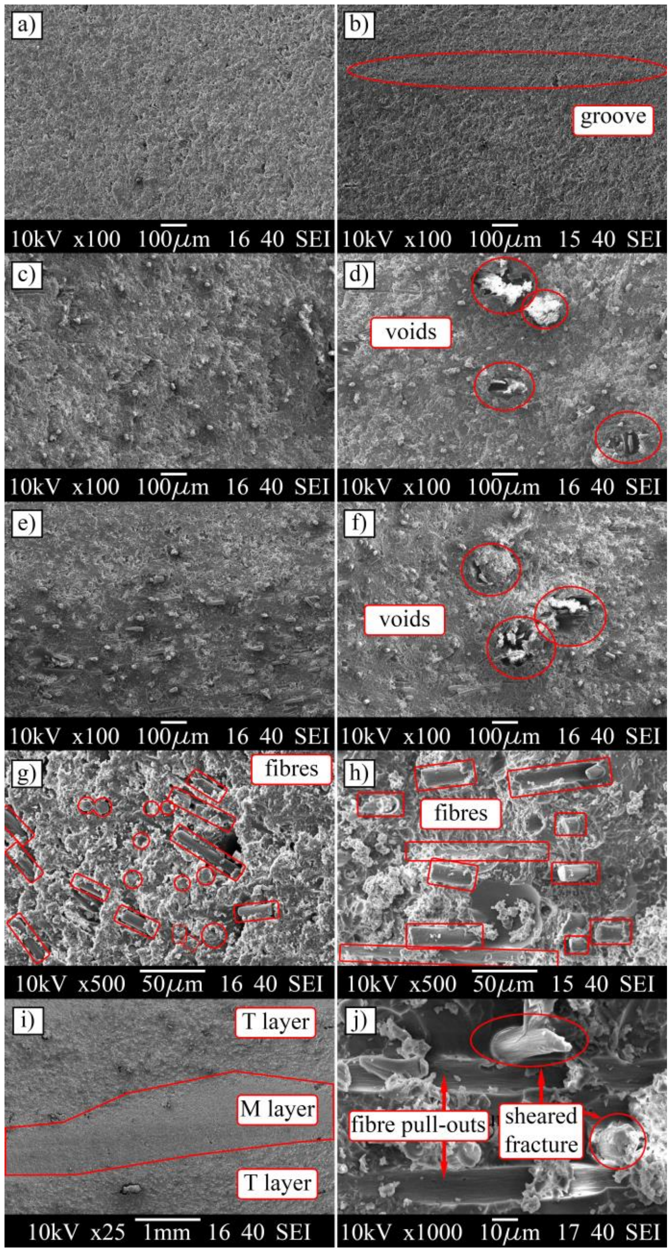

Fig. 6. SEM images of the representative surface characteristics and machining-induced microsized damages of the examined composites: (a)-(b) surface characteristics of M CFRP drilled with 0.1 mm/rev (Fig. 6a) and 0.3 mm/rev feed (Fig. 6b); (c)-(d) surface characteristics of T CFRP drilled with 0.1 mm/rev (Fig. 6c) and 0.3 mm/rev feed (Fig. 6d); (e)-(f) surface characteristics of MT CFRP drilled with 0.1 mm/rev (Fig. 6e) and 0.3 mm/rev feed (Fig. 6f); (g) representative quasi-random 3D fibre orientation of M CFRP; (h) representative quasi-random 2D fibre orientation of T CFRP; (i) layer-type separation of MT composite; (j) fibre cutting angle dependence of fibre damage.

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