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Influence of workpiece constituents and cutting speed on the cutting forces developed in the conventional drilling of CFRP composites

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ABSTRACT

This work investigates the influence of cutting speed and workpiece constituents on the thrust force and torque developed in the conventional dry drilling of woven carbon fibre reinforced polymer (CFRP) composites using uncoated WC-Co tools, by applying experimental techniques and statistical test methods. The type of thermosetting matrix showed significant impact on both the maximum thrust force and torque developed, whilst the type of carbon fibre fabric and cutting speed showed negligible effects on the maximum thrust force. Cutting speed exhibited a strong influence on the maximum torque developed; and high modulus CFRP composites showed increased sensitivity to cutting speed and strain rate compared with intermediate modulus composites. In the characteristic helical machining and feed directions in drilling, the strength and failure behaviour of the composite is dominated by the mechanical properties and failure mechanisms of the matrix, which explains the significant impact of resin on the cutting forces. On the other hand, the impact of cutting speed on torque is justified by the negative impact of strain rate on the ability of the matrix to transfer the load to the reinforcement, thus explaining the decreasing the maximum torque with the increasing cutting speed.

1. Introduction

Understanding the cutting forces developed in the drilling of fibre reinforced polymer (FRP) composites, especially those reinforced with carbon fibres (CFRP), is a fundamental task towards further exploring other phenomena related to the machining of composites, such as chip formation, machining dynamics, heat generation, machining-induced damage, or tool wear/tool life. This last factor, tool wear, is one of the major concerns in aerospace industry, provided that a better understanding will allow optimising tool life models and tool replacement management, thus reducing the manufacturing costs [1,2].

Investigations carried out by Davim et al. [3] studied the impact of drill geometry (118° point angle drill versus spur drill), cutting speed and feed speed (or penetration rate) on the thrust force (F_z), amongst other factors, in the drilling of glass fibre reinforced plastic (GFRP) composites using cemented carbide tools. The analysis of variance (ANOVA) data analysis showed that the specific cutting pressure decreased with increasing penetration speed and cutting speed, whereas thrust force increased with penetration feed speed. The spur geometry developed a lower thrust force than the 118° point angle drill when comparing the same cutting parameters and for the considered geometries, penetration speed was the factor having the highest impact on both the cutting pressure and the thrust force.

Following on from their previous work, Davim et al. [4] studied the impact of cutting speed, feed and of type of resin on the specific cutting force, delamination factor and surface roughness in the drilling of two different GFRP composites using a cemented carbide tool (spur geometry). The authors considered two composites having a 65% fibre volume (V_f) and different polymer matrices: unsaturated polyester (Viapal VUP 9731) and propoxylated bisphenol A-fumarate (AT-LAC 382-05). Based on the analysis average and ANOVA of the data collected, the authors reported that the

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unsaturated polyester-based composite showed a lower specific cutting pressure than the propoxylated bisphenol A-fumarate-based one, feed rate being the parameter having the most significant influence on it for both composite systems. The delamination factor increased with both cutting parameters; however the unsaturated polyester-based composite exhibited the lowest damage. On the other hand, the surface roughness increased with both the increasing feed rate and the cutting speed; however the cutting speed showed a higher impact on the surface roughness than on the feed rate.

Tsao [5] assessed and compared the influence of machining parameters (diameter ratio, feed rate and spindle speed) on the drilling-induced thrust force and delamination in CFRP drilling using compound core and core-saw drill bits. A compound core-special drill consists of an outer core drill (a hollow grinding drill with bonded diamond machining surface and decreased thickness) and a conventional drill bit of a varying geometry within the core drill. In these tools, the inner and the outer parts of core-special drills can rotate at different speeds and directions. Results obtained from applying the Taguchi method showed that core-saw drills yielded better results than core drills. Feed rate and spindle speed were the factors having the highest impact on thrust force and delamination, whereas the effect of diameter ratio was negligible.

Tsao and Chiu [6] expanded the previous work conducted by Tsao in this area and assessed the impact of drilling parameters on thrust force in the drilling of CFRP composites using compound core-special and step-core-special drills. In a compound step core-special drill, the height of the inner drill is higher than that of the outer drill. The ANOVA analysis conducted in this study revealed that cutting velocity ratio, feed rate and inner drill type (twist, saw and candlestick types) were the factors having higher impact on the developed thrust force. A high negative cutting velocity ratio (inner and outer parts spinning in opposite directions) showed a significant reduction of thrust force.

Recent work by Khashaba [7] reviewed the work carried out on the correlation between drilling parameters (feed, speed, drill wear and geometry) and machinability outputs such as thrust force, torque (M_z), residual strength, surface roughness and thermo-mechanical damage in machining polymer matrix composite (PMC) materials. According to this review, the contribution of the chisel edge to thrust force ranged between 40% and 60% of the total thrust. In order to reduce the thrust force and produce delamination-free holes, this work advised to consider tool geometries that are able to distribute the thrust towards the drill periphery instead of concentrating them at the hole centre, as well as applying pre-machining techniques, such as step drills, pilot holes or backing plates, when possible. Decreasing feed rate towards the hole exit was a strategy reported to yield delamination-free holes. Khashaba also reported that high drilling temperatures combined with the low thermal conductivity and glass transition temperature (T_g) of the composite lead to matrix pyrolysis, composite damage and enhanced tool wear; whilst the stress concentration due to the softening and subsequent solidification of the matrix yielded a reduction in the residual mechanical properties around the holes drilled.

Feito et al. [8] carried out an investigation on the influence of the drill geometry on the drilling of CFRPs, focusing on the drill point angle and tool wear since these factors greatly affect cutting forces and hole quality. Fresh tools showed negligible influence of point angle on thrust force, however significant influence was observed when combined with the effects of wear. Entry and exit delamination factors increased with the increasing point angle; however entry delamination diminished with wear progression, although exit delamination increased. ANOVA analysis showed that wear, point angle and feed rate are the parameters having most influence on thrust force, on the other hand the effect of cutting speed was found to be negligible.

A number of authors also applied analytical and numerical models to investigate the cutting parameters, machining forces and delamination in the drilling of carbon/epoxy composites. Phadnis et al. [9] investigated the effect of cutting parameters on thrust force and torque in drilling CFRP composites both experimentally and numerically using a 3D finite elements (FE) model accounting for complex kinematics at the drill-workpiece interface. Experimental assessment of the drilling-induced damaged was performed using X-ray tomography. Results showed good agreement between experimental and numerical data. Thrust force, torque and delamination damage increased with the increasing feed rate, however reduced gradually with increasing cutting speed. The FE model showed that low feed rates and high cutting speeds yielded the best results in CFRP drilling for the considered parameters.

Feito et al. [10] studied the delamination prediction in CFRP drilling by comparing two numerical models. The complex model included the rotatory movement of the drill, penetration in the composite plate and element erosion. The simple model considered the drill acting as a punch that pierced the workpiece and whilst overestimating the predicted delamination factor, had a much lower computational cost compared to the complex model. The influence of thrust force on the delamination factor was studied using the simplified model. Results showed that the maximum level of delamination reached a plateau at a certain thrust force level, which matched that induced by complete perforation of the composite with a punch featuring geometry similar to the drill; therefore it can be used as an upper limit for conventional drilling.

A recent review by Kumar and Singh [11] compared the work reported on conventional and unconventional machining of CFRP and GFRP composite. Regarding the cutting forces, conventional drilling (CD) yielded higher values of thrust force and torque compared to rotatory ultrasonic conventional machining (RUCM). Thrust force increased with the increasing feed rate, however tool geometry showed significant impact on thrust force and allowed it to reduce.

As shown above, an important part of the work carried out in the study of the cutting forces in the drilling of FRPs focused on optimising a number of factors, such as drill bit geometry and cutting settings, in order to minimise delamination and improve analytical models to predict it. However, there is a gap with respect to the specific influence of the workpiece constituents on the cutting forces (i.e. thrust force and torque) in the drilling of woven CFRP composites. The aim of this work focuses on investigating the impact of workpiece constituents (type of resin and CF reinforcement), number of consecutive holes and cutting speed on the cutting forces (thrust force and torque) developed in order to give further insight into the effect of resin on tool wear in the drilling of CFRP composites. This investigation captured the cutting forces and the damage around the boreholes developed in drilling three CFRP composites (combining different thermosetting resins and CF fabrics) in dry conditions using a spindle dynamometer, scanning electron microscopy (SEM) and X-ray microcomputed tomography (X-ray μCT); and discussed the impact of each factor on the forces developed based on the results obtained from graphical analyses and hypothesis tests.

2. Materials and experimental methods

2.1. Composite panels

The carbon fibre/epoxy composite plates considered in this study were manufactured at the Composites Centre of the Advanced Manufacturing Research Centre with Boeing, The University of Sheffield. These plates were made from prepregs plies having a 55% V_f supplied by Cytec Engineered Materials following

Table 1
Thermomechanical properties of the thermosetting resins considered [12,30,31].

	T_g (E′ onset, °C)	tanδ peak (°C)	CTE < T_g (10^{-6}/°C)	CTE > T_g (10^{-6}/°C)	Hardness < T_g (GPa)
MTM44-1	182.4	222.5	~60	~60	0.34
MTM28B	104.8	136.9	~50–80	~150	0.24

Table 2
Cutting conditions utilised in this investigation. The feed rate (f_n) was constant for all the conditions, 0.05 mm/rev.

Condition	Spindle speed (n, rpm)	Cutting speed (V_c, m/min)	Feed speed (V_f, mm/min)
1	2500	50	125
2	5000	100	250
3	7500	150	375
4	10,000	200	500

the vacuum bag moulding method. 40 plies were laid-up to an approximate thickness of 10 mm in $[(0,90)_3/(\pm45)]_{5s}$ stacking sequence. Curing of the plates then took place following cure cycles according to the specifications indicated by the supplier to develop full mechanical properties and maximum T_g. Finally, the cured panels were cut down to 150×150 mm using water-jet cutting technology.

This investigation considered three different composite systems combining two types of woven carbon fibre fabrics (CF0300 and CF2216) and two types of toughened thermosetting resins (MTM28B and MTM44-1):

- MTM28B CF0300,
- MTM44-1 CF0300 and
- MTM44-1 CF2216.

MTM28B is a toughened automotive grade DGEBA-based resin having a T_g of approximately 100 °C, whilst MTM44-1 is a toughened high-end aerospace grade resin having an approximate T_g of 180 °C. CF0300 is a high strength (HS) woven carbon fibre (CF) fabric featuring 3000 filaments/tow and an approximate tensile modulus of 230–240 GPa whilst CF2216 is a high modulus (HM) woven CF fabric having 6000 filaments/tow and an approximate tensile modulus of 340 GPa. Both carbon fibre fabrics feature 2/2 twill and a density if 199 g/m^2. Table 1 summarises the thermomechanical properties of the resins utilised. Additional information about the thermal behaviour and heat dissipation of the CFRP systems considered is can be found in previous work carried out by the authors [12,13].

2.2. Drilling tool, force and temperature acquisition equipment

The tool utilised in this investigation was an uncoated Ø6.35 mm WC-10%Co CoroDrill 856 drill bit, supplied by Sandvik Coromant, which features a 120° point angle, two-flute, double angle geometry. This geometry was utilised since it provided

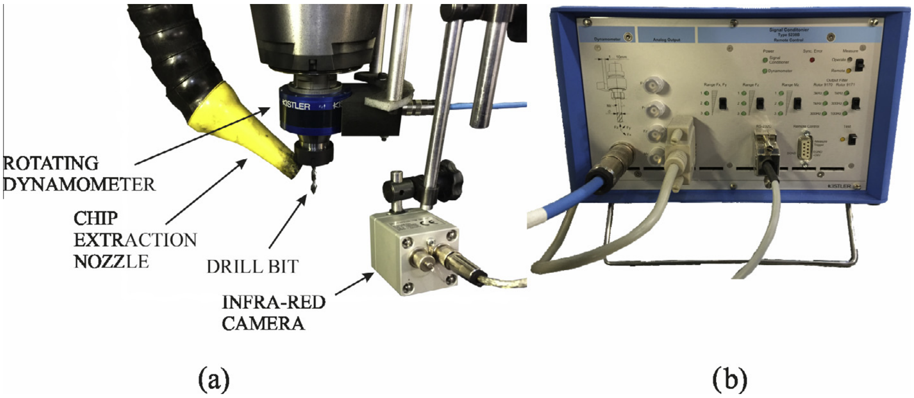

Fig. 1. Views of (a) Sandvik CD 856 drill bit fitted in Kistler 9123C1 spindle dynamometer and (b) Kistler 5221B1 DAQ unit.

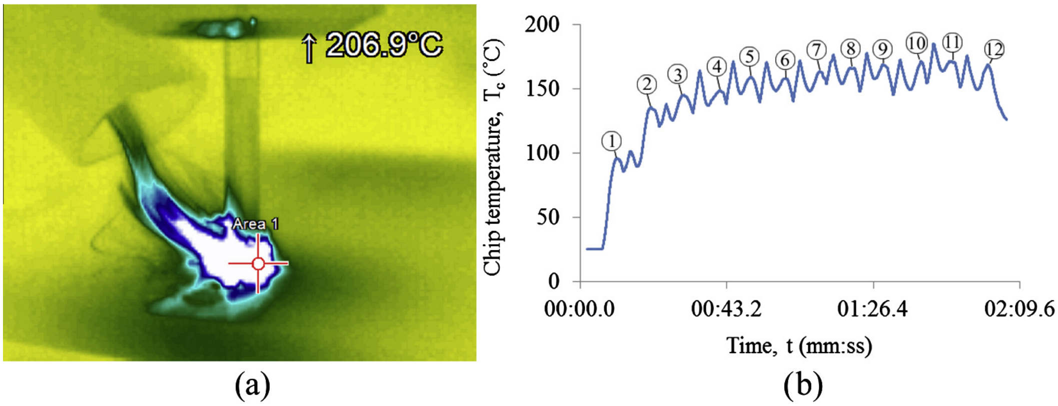

Fig. 2. (a) Snapshot obtained from a radiometric video recorded with the infra-red camera tracking the hotspot (Area 1, 1 × 1 pixel measurement area) and (b) example of drilling temperature data after being processed.

Table 3
X-ray CT scanning parameters.

Energy (kV)	49
Current (μA)	179
Reconstruction size (px)	2000 × 2000
Voxel size (μm)	8.18
Number of radiographs	516 (360°)
Exposure time (ms)	1180
Scan time (min)	32

Table 4
Flank wear (V_B) developed after drilling 12 consecutive holes in the considered composite systems at 50–200 m/min (2500–10,000 rpm) cutting (spindle) speed and 0.05 mm/rev feed rate. V_B expressed in microns (μm), measured using a tool maker's optical microscope and Clemex software.

	Flank wear (V_B, μm)			
	50 m/min (2500 rpm)	100 m/min (5000 rpm)	150 m/min (7500 rpm)	200 m/min (10,000 rpm)
MTM28B CF0300	38.0	27.5	29.5	26.0
MTM44-1 CF0300	37.0	36.0	43.0	34.5
MTM44-1 CF2216	46.5	47.0	43.5	45.5

intermediate values of tool life, tool wear and hole quality amongst other two other considered geometries (regular 120° point angle and spur drills) in previous investigations carried out by Sandvik Coromant [14,15]. Full details on the tool geometry are available in previous research carried out by the authors [16]. The CNC machine utilised was a three-axis DMG MORI DMU 60monoBLOCK fitted with a Kistler spindle dynamometer having an average measured static run-out of 12 μm. The experiments were performed in dry conditions, provided that this is the common practice in aerospace industry in machining large size parts, where the operation cannot be performed inside a CNC machine. Each cutting condition used a new tool in order to minimise any effect derived from the accumulated tool wear. The force measurement equipment consisted of a Kistler 9123C1 spindle dynamometer and a Kistler

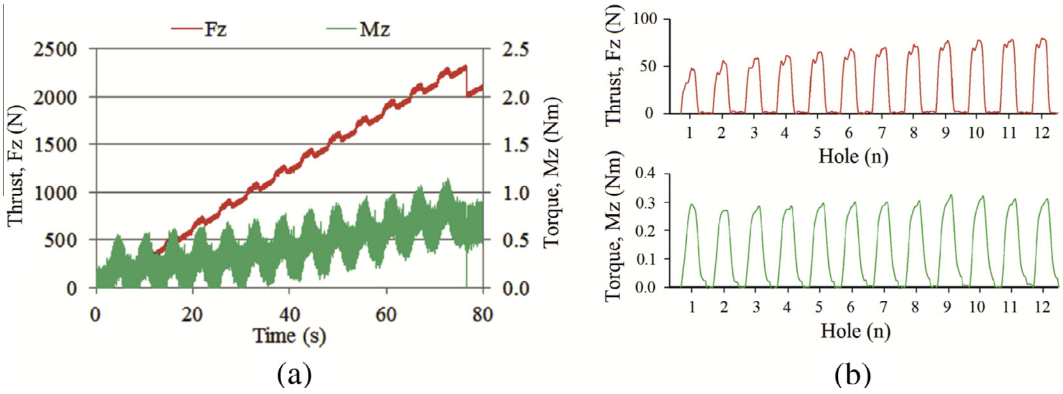

Fig. 3. Example of (a) raw and (b) filtered and drift corrected thrust force and torque data.

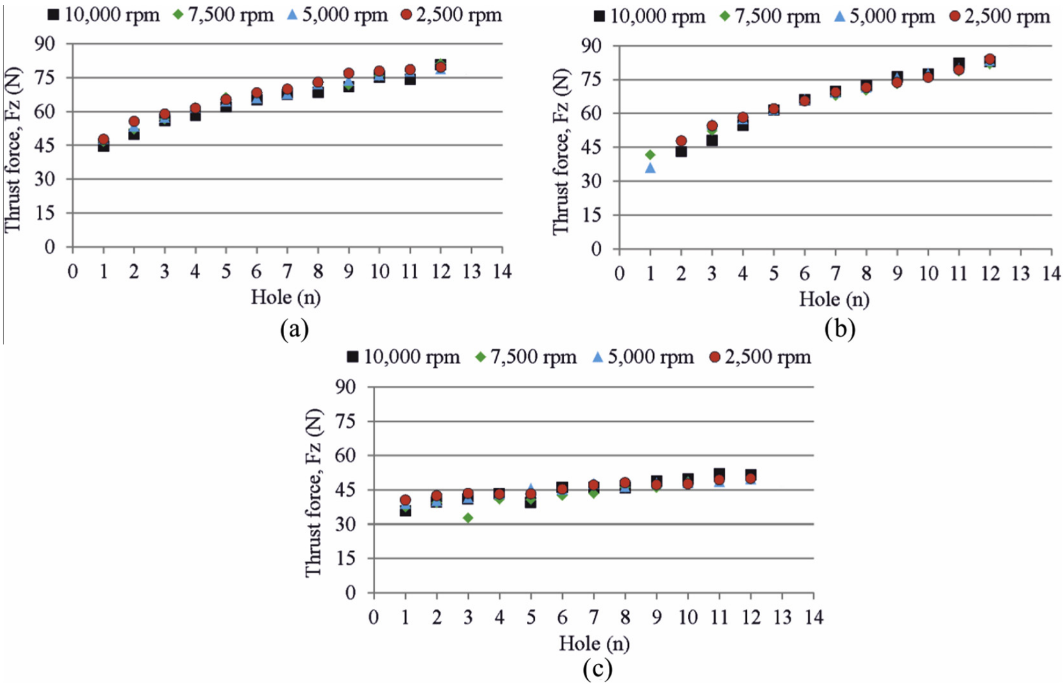

Fig. 4. Maximum thrust force developed in drilling each hole in (a) MTM44-1 CF0300, (b) MTM44-1 CF2216 and (c) MTM28B CF0300 composite systems, at the considered cutting speeds.

Table 5
Maximum temperatures developed in drilling the three selected CFRP systems at different cutting speeds (50–200 m/min, 2500–10,000 rpm). The temperatures tabulated correspond to the 12th hole drilled for each condition, once a steady state was reached (Fig. 2b). Temperatures were measured on the chips generated, as depicted in Fig. 2(a).

	Maximum temperatures, T_{Max} (°C)			
	50 m/min (2500 rpm)	100 m/min (5000 rpm)	150 m/min (7500 rpm)	200 m/min (10,000 rpm)
MTM28B CF0300	145.3	163.9	171.2	176.9
MTM44-1 CF0300	209.2	218.2	231.0	213.8
MTM44-1 CF2216	183.4	189.6	189.8	172.8

Table 6
Multi-factor ANOVA analysis for thrust force (F_z) and torque (M_z). Factors statistically significant are highlighted in green. Standard error (S) and coefficient of determination (R^2) for each model are provided.

	F_z	M_z
Type of resin	F_{stat} = 485.050 p_{value} < 0.001	139.570 <0.001
Type of CF fabric	2.440 0.121	62.420 <0.001
Cutting/spindle speed	1.560 0.203	71.190 <0.001
Number of holes	44.330 <0.001	4.600 <0.001
S/R^2	4.805/89.89%	0.028/82.22%

5221B1 DAQ data acquisition unit (Fig. 1), which captured the developed thrust force and torque at 10 kHz sampling rate.

This acquisition rate exceeds the minimum suggested by the Nyquist-Shannon theorem, which indicates that the minimum acquisition frequency must be higher than the revolution frequency of the tool (i.e. the spindle speed in revolutions per second) multiplied by the number of cutting edges (two in the case of the tool utilised) [17]. In this investigation, the minimum sampling rate for the maximum cutting speed considered is ~333 Hz.

At the same time, a Micro-Epsilon thermoIMAGER TIM 160 infra-red camera captured the temperatures developed in the drilling operation by measuring the temperature of the chips generated (Fig. 2(a)). The peaks marked with numbered balloons (Fig. 2(b)) correspond to the temperature of the chips generated during the drilling of each hole, whilst the sharp peaks corresponds to the subsequent tool retractions and were not computed. It can be observed that after approximately 5 holes, the maximum temperature reached a steady state. This infra-red camera features a 160 × 120 pixels optical resolution, spectral range 7.6–13 µm, thermal sensitivity of 0.08 K and an acquisition rate of 120 Hz. The temperature measurement window utilised was 0 °C/250 °C and the emissivity of the chip was set to $\varepsilon = 0.90$ [18].

2.3. Cutting forces developed in the drilling of CFRP composites

This work studied the impact of the workpiece constituents, cutting speed and number of consecutive holes drilled on the forces developed in CFRP drilling in a range of cutting speeds between 2500 and 10,000 rpm (Table 2). Despite cutting speeds above 6000 rpm usually being utilised in conventional drilling of CFRPs, these have been considered in this investigation in order to test the influence of cutting speed in a wider range and to provide a wider range to assess the statistical impact of cutting speed and its interaction with the other factors considered (i.e. workpiece constituents and number of holes). Twelve consecutive holes per condition were drilled in order to reach a steady state temperature, as shown in Fig. 2(b), plus an additional blind hole in order to inspect the drilled surface using scanning electron microscope (SEM) and X-ray microcomputed tomography (X-ray µCT) techniques. The SEM equipment utilised was a Carl Zeiss EVO LS25 microscope in variable pressure (VP) mode. This configuration allows scanning non-conductive materials, such as the epoxy resin, without coating the specimen. The X-ray µCT device utilised was a Bruker Skyscan scanner featuring a 20–100 kV X-ray source, an 11 MP X-ray detector and a maximum detail detectability of 0.5 µm. Table 3 summarises the scanning parameters utilised to perform the X-ray µCT scans. The data obtained was analysed and processed using Bruker's NRecon, CTAn, CTVox and DataViewer software.

A low pass filter (5 Hz, 2nd order filtering) and linear drift compensations were applied using Kistler DynoWare and Sandvik Coromant proprietary software, as illustrated in Fig. 3. The scatter in the original data, which was removed by the low pass filter applied, corresponds to the characteristic cutting of each fibre orientation, as studied by Wang et al. [19,20]. However, as shown in the study, by filtering the signal the maximum cutting forces can be investigated, making it a relevant signal processing approach for this investigation. After conditioning the signal, the software divided each hole into drilling steps corresponding to the hole entry, tool fully engaged and tool exit and extracted the maximum values of thrust force and torque for each hole.

The impact of each factor (type of resin, type of CF fabric, cutting speed and number of consecutive holes drilled) and their main effects on the cutting forces were assessed by means of hypothesis testing (ANOVA analysis) and graphical analysis using Minitab 17 software.

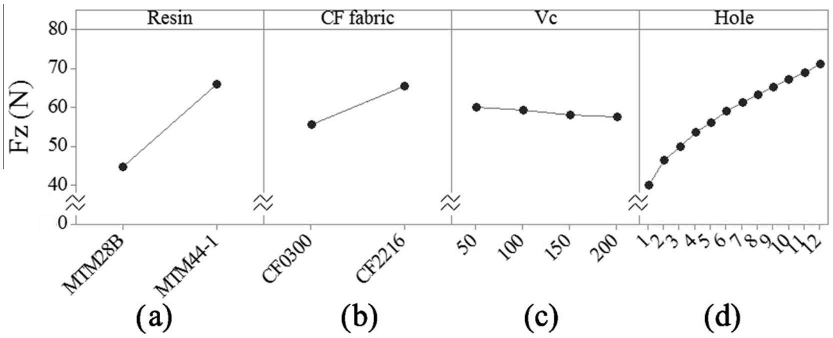

Fig. 5. Factors main effects on the maximum thrust force developed in CFRP drilling.

3. Results and discussion

3.1. Correlation between workpiece constituents, cutting speed, number of holes and cutting forces in the drilling of CFRP composites

Fig. 4 illustrates the maximum thrust force with an increasing number of holes for the three CFRP systems studied.

As shown in the figure, the maximum thrust force curves obtained in drilling the composites with the same resin (MTM44-1) and different CF fabrics (CF0300, Fig. 4(a) and CF2216, Fig. 4(b)) did not differ significantly, whilst those corresponding to the composites with the same CF fabric (CF0300) and different matrices (MTM44-1, Fig. 4(a) and MTM28B, Fig. 4(c)) presented noticeable differences in their respective slopes and the maximum values, thus indicating a strong effect of the resin on the maximum thrust force. This suggests that, in the drilling of CF composites, the mechanical strength of the composite in the feed direction (perpendicular to the CF fabric reinforcement plane) depends on the mechanical strength of the resin. Moreover, the curves corresponding to each cutting speed consistently overlapped for all the composites, suggesting a negligible influence of the cutting speed on the maximum thrust force, which will be further assessed in the statistical analysis.

The observed effect of the resin on the maximum thrust force in the drilling of composites is in good agreement with the reported literature [4,21]. As reported in the available literature, the thermomechanical properties of the resin, such as T_g and elastic modulus, are closely related to its degree of cross-linking and molecular structure [22–24]. Hence higher cross-linked resins, such as MTM44-1, feature improved mechanical strength and stiffness compared to lower cross-linked systems like MTM28B, therefore explaining the behaviour described.

The effect of the other factor having significant impact on the maximum thrust force, the consecutive number of holes drilled, can be explained by two contrasting subfactors: tool wear and machining temperature. Table 4 shows the tool wear developed after drilling 12 consecutive holes for each CFRP system and cutting speed.

As shown in the table, it can be observed that despite tool wear was low (V_B values were well below the flank wear failure criterion for his tool, 222 μm, 3.5% of the tool diameter), it accounted for the increase of the maximum thrust force. Furthermore, MTM44-1 CF0300 composite yielded flank wear values ~25% higher than MTM28B CF0300, which suggests that the resin, despite not being an abrasive element itself, plays an important role in the abrasive properties of the CFRP system.

As highlighted, temperature is also a factor with respect to the maximum thrust force results observed. Table 5 presents the maximum temperatures developed in drilling the three considered CFRP composite systems, which are often above the glass transition temperature of the composite (except for MTM44-1 CF2216 system drilled at 200 m/min).

Above T_g the storage modulus (E′) decreases to a great extent, which should have a positive impact on the maximum thrust force (i.e. to reduce it). However, as seen above, the maximum thrust force increased with the increasing number of holes drilled. Therefore, temperature worked other ways and tool wear is the key factor: the increase of flank wear implies the growth of the contact surface between the tool and the workpiece and, therefore, the increase of the maximum thrust force.

The impact of the factors considered (types of resin and CF fabric, cutting speed and number of holes) on the thrust force was studied in an ANOVA and factors main effects analyses, as shown in Table 6 and Fig. 5, respectively. The hypothesis test indicated that the type of resin and the number of holes have a significant impact on the maximum thrust force developed (explained by the fitted model to a good extent, since $R^2 = 89.89\%$), whilst the effects of the type of CF fabric and cutting speed were found negligible (p-values 0.121 and 0.203, respectively).

Regarding the behaviour of the maximum torque, Fig. 6 presents the results obtained at cutting speeds between 50 and 200 m/min for the three CFRP systems studied.

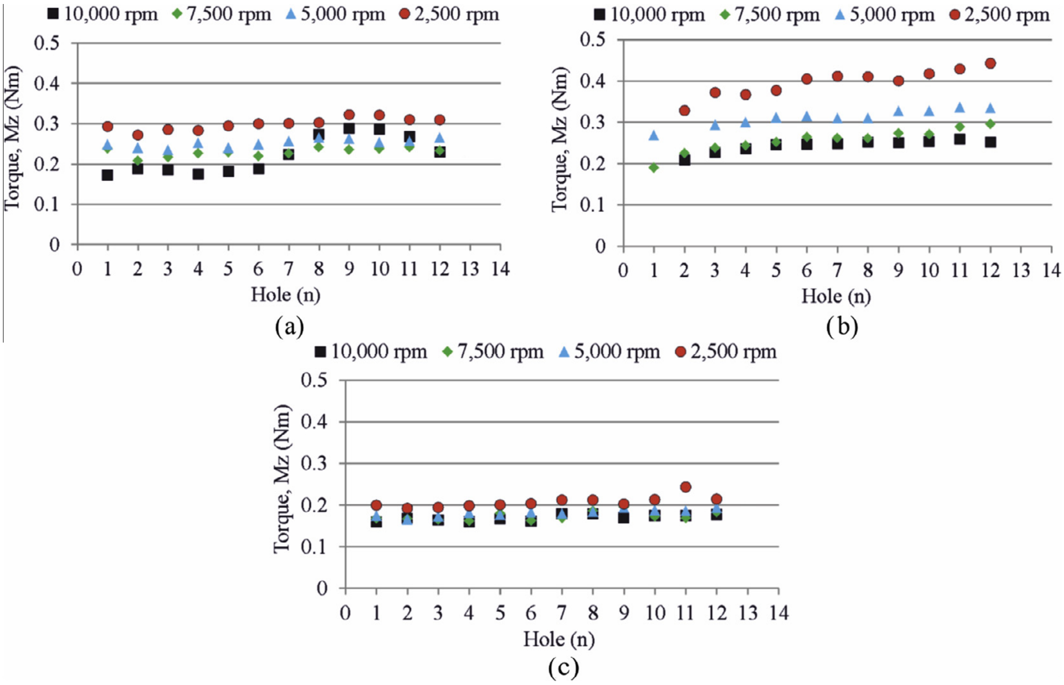

Fig. 6. Evolution of the maximum torque developed in drilling each hole in (a) MTM44-1 CF0300, (b) MTM44-1 CF2216 and (c) MTM28B CF0300 composite systems, at the considered cutting speeds.

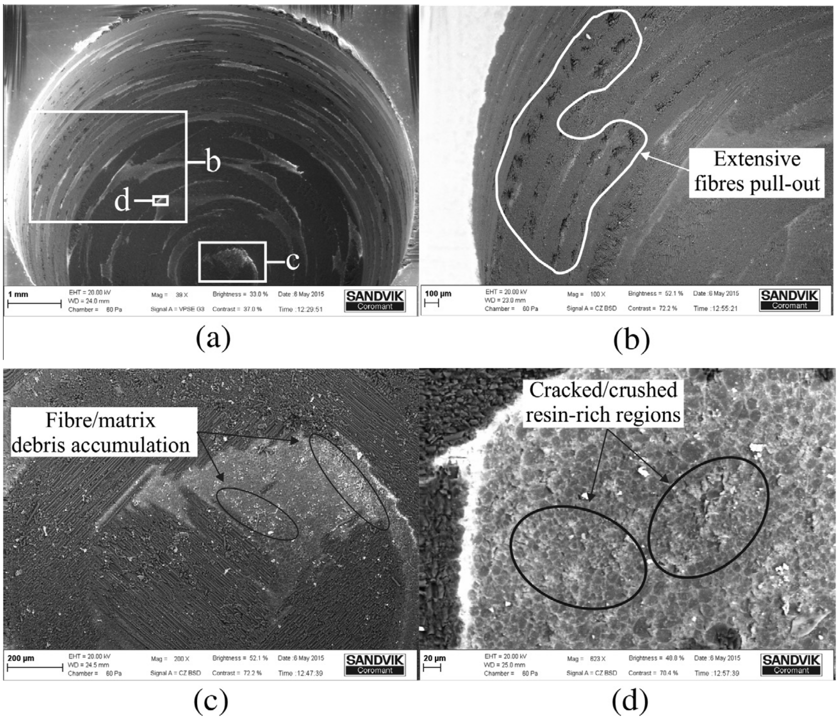

Fig. 7. SEM micrographs showing the machined surface in a blind hole, (a) general view, where regions having different CF orientations and fibre/resin phases can be distinguished due to different scattering of secondary electrons and electron charging (resin phases), (b) ±45° fibre orientation regions showing extensive fibres pull-out, (c) bottom of the hole showing 0/90° fibre orientations and resin-rich regions and (d) damaged resin-rich area.

The maximum torque curves obtained exhibited characteristic features in common for all the drilled composite systems. The influence of resin and number of consecutive holes drilled on the maximum torque can be explained in the same terms as explained above in the case of thrust force (i.e. the opposing effects of temperature and tool wear). However, unlike in the case of the maximum thrust force, cutting speed exhibited significant impact on the maximum torque developed. Cutting speeds within the low-mid range (50–100 m/min) yielded higher torque than those in the mid-high range (150–200 m/min), therefore indicating an inverse cutting speed-torque correlation. Furthermore, Fig. 6 shows that the composite reinforced with HM CF fabric (CF2216) exhibited to be more sensitive to the changing cutting speed compared to those featuring HS CF (CF0300) fabrics. This behaviour can be explained due to the impact of cutting speed on the drilling temperatures, strain rate and CF fabric failure.

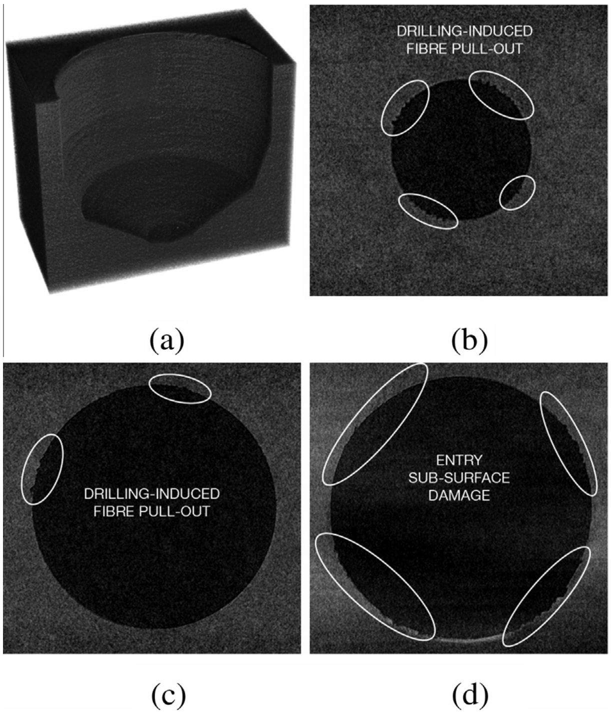

Fig. 8. X-ray µCT scans of a blind hole showing (a) a cross-section view of a 3D reconstruction obtained from the radiographs, drilling-induced damage (b) when the primary cutting edge engages the workpiece, (c) when the secondary cutting edge engages the workpiece and (d) damage below the hole entry surface.

Lower cutting speeds, which imply lower strain rates and longer machining times, allow improved matrix-fibre load transfer compared to higher cutting speeds, thus yielding higher torque values. As explained in previous work carried out by the authors [13], at T_g the resin maintains its nominal elastic modulus, thus preserving its ability to transfer the load to the reinforcement. Table 5 showed that whilst the systems reinforced with HS CF fabrics (MTM28B CF0300 and MTM44-1 CF0300) developed maximum drilling temperatures above T_g, the composite reinforced with HM CF fabrics (MTM44-1 CF2216) developed maximum drilling temperatures on the T_g of the resin. This suggests that those CF composites developing maximum drilling temperatures less than or equal to ($\leqslant$) T_g are more sensitive to the effects of strain rate on torque.

Inefficient matrix-fibre load transfer, combined with elevated drilling temperatures and the characteristic failure behaviour of each type of CF and fibre orientation, contribute to machining-induced surface defects, as illustrated in Fig. 7. Regions with ±45° fibre-cutting edge orientations developed extensive fibres pull-out, which created crater-type surface defects, as depicted in Fig. 7(b). The brittle fracture behaviour of CFRP composites, especially $\leqslant T_g$, promotes the generation of fine debris formed by a mixture of crushed resin and micron/sub-micron size CF segments

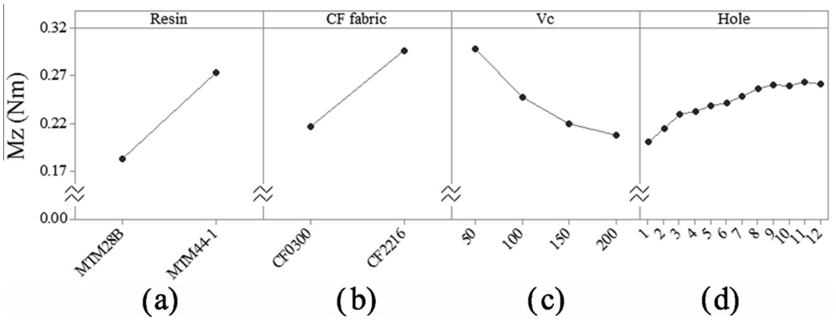

Fig. 9. Factors main effects on the maximum torque developed in CFRP drilling.

(Fig. 7(c)). This debris can act as a highly abrasive element in a three-body abrasion tribosystem, causing further damage on the softer resin-rich regions, which can also develop cracking (Fig. 7(d)) due to the cutting forces applied and the limited load transfer in the machining direction.

The through-thickness damage assessment using X-ray μCT showed damage induced at different stages during the drilling operation (Fig. 8). The initial stage, which corresponds to the engagement of the primary cutting edge into the workpiece, initiated fibre pull-out in the ±45° fibre-cutting relative angles (Fig. 8(b)). The following cutting stage, which corresponds to the engagement of the secondary cutting edge into the composite, generated the same type of damage to a lesser extent (Fig. 8(c)). The reason for this lower damage generation can be explained by the higher reinforcement-cutting edge relative angle compared to the earlier stage, which promotes a cleaner cutting of the fibres, thus reducing the fibre pull-out. Once the tool is fully engaged into the workpiece, fibre pull-out is still present but limited in depth, forming localised crater-type damage. However, in the vicinity of the surface, the extent of the induced damage increases due to the lack of support and stability, generating further sub-surface damage and, ultimately, delamination (Fig. 8(d)). Further details about this damage inspection using X-ray μCT are available in the Supplementary Video file provided.

The statistical analysis (Table 6) and the factors main effects (Fig. 9) of the results discussed above found that all the factors considered had a significant influence on the maximum torque (p-values < 0.001) and confirmed the inverse and direct effects of cutting speed and number of holes on the maximum torque (Fig. 9(c) and (d)), respectively. As in the case of the maximum thrust force, the model fitted can explain this relationship with good precision ($R^2 = 82.2\%$).

The results discussed agree with the reported literature about failure mechanics of CFRP composites. Due to the nature of the drilling operation, the rotating cutting edges are constantly changing their relative position respect to the reinforcement and advancing through the thickness helically and the cutting edges apply the load off-axis and off-plane, where matrix failure modes dominate. Therefore, despite CF fabrics and yarns are considered strain-insensitive [25,26], the mechanical properties of CF fabrics can also exhibit strain-rate dependency [27–29].

3.2. Discussion

This work investigated the impact of workpiece constituents, number of consecutive holes drilled and cutting speed on the cutting forces developed in the drilling of carbon/epoxy composites. The most significant fact found in this investigation is that the resin was the factor exhibiting the highest impact on the maximum thrust force, the maximum torque and the machining temperatures. Provided that load (in this case represented by thrust force and the frictional component of torque), friction, abrasiveness and wear are terms closely correlated, this ultimately suggests that resin will also have a significant impact on the abrasiveness of the composite (despite the low abrasiveness of resin itself) and tool wear.

The main reason given to explain the impact of resin was that in the drilling of CFRP composites the forces are always applied in off-axis directions to the reinforcement (perpendicularly in the case of thrust force and following an helical path in the case of torque). This prevents the matrix from properly transferring the load to the fibres, thus reducing the strength of the composite in machining. In the case of torque, the ability of the resin to transfer the load to the reinforcement is also affected by the drilling temperature and the changing strain rate, which exhibited an inverse strain rate-torque correlation. In this situation, a part of the load is still transferred to the fibres, therefore explaining both the dissimilar strain rate sensitivity exhibited by the CF fabrics considered and the correlation with between CF fabric and torque.

As mentioned above, these results indicate the type of resin also influences both the abrasiveness of the composite, the machining temperatures and the tool wear in drilling. Based on the outcomes obtained in this investigation, cutting speed selection has to be considered with other factors, such as number of consecutive holes drilled and plate thickness. Cutting speeds around 100 m/min (5000 rpm) provide a good balance between machining times, tool wear rate and torque (which affects the amount of energy utilised in the drilling operation and, ultimately, hole quality). Higher cutting speeds up to 150 m/min (7500 rpm) can also be considered for laminates thinner than those considered in this study or for short drilling intervals, as the impact of tool wear is minimised.

The results obtained in this investigation present valuable insights into the influence of resin on the machining temperatures, the tool-composite friction and the abrasiveness of the composite, factors that will be further explored in future work.

4. Conclusions

This paper investigated the impact of cutting speed and workpiece constituents on the forces developed in CFRP drilling by machining three carbon/epoxy systems, combining two types of thermosetting resins and two types of woven CF fabrics. From the results obtained in this investigation and their analyses, the following conclusions can be drawn:

- The type of resin and the number of consecutive holes drilled exhibited significant impact on the maximum thrust force, whereas the influence of both the type of CF fabric and cutting speed were found negligible. The contribution of resin is explained by the dominance of the thermomechanical properties of the resin in the feed direction, which are higher for those resins with higher degrees of cross-linking (improved elastic modulus and T_g.

- The contribution of the number of consecutive holes drilled on the maximum thrust force actually combines the contrasting contributions of two subfactors: machining temperatures and tool wear. Machining temperatures over T_g of the matrix produce a decrease of the elastic modulus of the composite (as shown in previous work carried out by the authors [13]), therefore the maximum thrust force would also decrease. However, this is exceeded by the increase of the maximum thrust force produced by the increasing tool wear, which implies an increase of the tool-workpiece contact surface.
- All of the factors considered (workpiece constituents, number of holes and cutting speed) showed a significant impact on the maximum torque. The contributions of resin and number of holes can be explained in the same terms as in the case of thrust force. However the part of the contribution of resin on the maximum torque is related to the impact of the resin properties on the chip formation and the tool-composite friction, which will be investigated in future work.
- The maximum torque exhibited significant sensitivity to cutting speed, especially the composite reinforced with HM CF fabric. This behaviour can be explained by the characteristic helical cutting direction followed in drilling, the strain rate sensitivity of CFRP laminates in off-axis directions, the machining temperatures and the mechanical behaviour of thermosetting resins at different temperatures. In these directions, where the composite failure behaviour is mostly dominated by the matrix failure mechanisms, high strain rates prevent a proper load transfer from the matrix to the fibres, thus explaining the inverse cutting speed-maximum torque correlation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.compstruct.2016.01.008.

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