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Study on tool wear and workpiece surface integrity following drilling of CFRP laminates with variable feed rate strategy

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Abstract

Drilling carbon fibre reinforced plastic (CFRP) composites is often accompanied by workpiece delamination particularly at hole exit, which is dependent to a large extent on the applied feed rate/thrust force. In this paper, a variable feed rate strategy was investigated where drill feed was decreased from a maximum of 0.3 mm/rev to 0.01 mm/rev for the final 2 mm of hole depth, in order to reduce thrust force and minimise hole exit damage but without severely impacting process productivity. A full factorial experiment involving two variable factors (CFRP lay-up configuration at two levels and primary feed rate at three levels) was performed using diamond coated carbide tools. All tests achieved the 384 drilled hole criterion with tool flank wear ranging from 114 to 193 µm, chipping/delamination of the coating and abrasion were the principal tool wear modes. Delamination factor values at hole entry generally increased with primary feed rate and number of holes drilled by up to ~23%, with limited difference in exit delamination factor between the first and last holes drilled (maximum of 0.04). The reduced feed rate regime immediately prior to hole exit led to lower surface roughness by up to ~6.46 µm Ra compared with the entry location together with reduced fibre pull out and cavities compared to the rest of the hole when drilling with a new tool. Surface quality was however less apparent with increased numbers of holes drilled and tool wear.

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Keywords: CFRP laminate; Drilling; Surface integrity

1. Introduction

Carbon fibre reinforced plastic (CFRP) composites are commonly used for structural aerospace components including floor beams, frame panels and wing segments, as well as the majority of vertical and horizontal sections of the tail. Joining of such parts is mainly realised by mechanical bolting/ riveting, which can be compromised by the quality of machined holes. Consequently, the integrity of drilled fastener holes in CFRP is paramount, with assessment metrics including hole surface roughness, out of roundness and cylindricity as well as the incidence and level of workpiece delamination/flaws. However, CFRP composites have relatively poor machinability due chiefly to the abrasive nature of the fibres leading to rapid tool wear and the inhomogeneous/anisotropic material properties relating to the dissimilar constituent phases, varying fibre orientation and lay-up process [1-2].

When drilling polymer composites, entry/exit delamination, fibre pullout and poor surface finish are not uncommon [3]. Various forms of hole defect/damage including porosity/cavities (due to loss/absence of matrix material between layers), internal cracks (fibre/matrix cracking), resin/fibre loss etc. are usually observed. Such defects are principally due to the fibrous nature of the workpiece material and the differences in thermal/mechanical properties between reinforcement and matrix material [4]. Several researchers have concluded that damage is strongly affected by drilling feed rate, which has a significant effect on the ensuing thrust force [5-8].

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Khashaba et al. [6] reported the presence of delamination at both hole entry and exit even when drilling GFRP at a relatively low feed rate of 0.056 mm/rev and cutting speed of 20 m/min using 13 mm diameter carbide tools. The severity of delamination was typically found to increase with tool wear and rising cutting temperatures, which can promote softening of the matrix and induce weakening of the interlaminate bond strength [8-10]. A comparison of hole surface roughness produced using new and worn tools when drilling GFRP composites highlighted the deterioration of hole surface quality due to higher thrust forces generated by the worn drills, together with elevated temperatures resulting from the low conductivity of the composite workpiece [6, 11]. Not surprisingly, surface roughness also increased by up to 50% as feed rate increased from 0.056 to 0.45 mm/rev, however there appeared to be minimal effect when cutting speed was varied from 6.4 to 50.6 m/min.

According to Brinksmeier et al. [12], hole surfaces with no discernible damage (except for minor bending of 0° orientation fibres) was observed when drilling CFRP at low cutting speed (40 m/min) and high feed rate (0.2 mm/rev). In contrast, subsurface cracks extending up to 50 µm below the surface were found when operating at high cutting speed (120 m/min) combined with low feed rate of 0.026 mm/rev. However, hole surface roughness was below 1.6 µm Ra, which was attributed to smearing of fibre dust and matrix material caused by the comparatively high temperatures generated (191.6ºC). Ramulu et al. [13] studied the effect of fibre orientation on surface roughness when edge-trimming graphite/epoxy composite. It was found that machined surface roughness and breakage of fibre bundles were highly dependent on fibre direction, while crushed fibres reduced with increasing fibre angle. The current paper details work to study the effect of variable feed rate strategy on tool wear together with surface roughness and integrity following drilling of CFRP composites using diamond coated carbide tools.

2. Experimental work

2.1. Workpiece materials and cutting tools

The CFRP laminates employed for the experiments involved two different lay-up configurations denoted as Type 2 and Type 3 respectively. The former (Type 2) was 9.36 mm thick comprising 36 unidirectional (UD) prepreg layers (each 0.26 mm thick), while the Type 3 material was made up of 40 plies resulting in a thickness of 10.4 mm. All of the workpieces were manually laid up and autoclave cured with stacking sequences of $[45/0/135/0/90/0/135/0/45]_{2S}$ and $[45/0/135/135/135/90/45/45/45/0/135/135/90/45/45/0/135/135/90/45]_{S}$ for the Type 2 and Type 3 laminates respectively. The prepreg sheets consisted of intermediate modulus (IM), high tensile strength carbon fibres impregnated within an epoxy resin matrix and had a fibre weight fraction of between 64 and 68% post curing. The CFRP panels were supplied in the form of plates having dimensions of 100 × 100 mm to fit a bespoke designed drilling jig, pre-fabricated with 9 mm diameter clearance holes. Each plate accommodated an array 64 holes (8 × 8) at a pitch distance of 10 mm.

The tools used for the tests were chemical vapour deposited (CVD) diamond coated tungsten carbide (WC) twist drills with a double cone geometry; see Fig. 1. The 6 mm diameter drills were designed with a helix angle of 30° together with primary and secondary point angles of 130° and 60° respectively. The thickness of the CVD-diamond layer was ~7-11 µm, with a hardness of 8000-10000 $HV_{0.05}$, coefficient of friction 0.02-0.1 and surface roughness of 0.1-0.4 µm Ra.

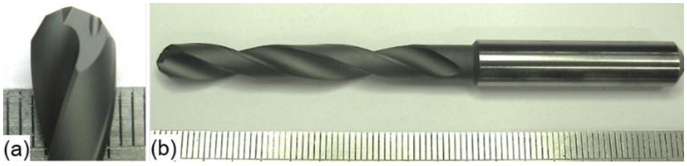

Fig. 1. CVD-diamond coated tool; (a) drill point and (b) full length view.

2.2. Experimental design, test procedure and equipment

A full factorial experimental design was undertaken involving variation in CFRP laminate configuration at 2 levels and feed rate at 3 levels, with the test array detailed in Table 1. The drilling trials were initially carried out at the respective primary feed rate levels of 0.1, 0.2 and 0.3 mm/rev, which reduced to 0.01 mm/rev for the final 2 mm of the hole. Cutting speed was fixed at 90 m/min for all tests. Drill wear (mean of maximum flank wear from both flutes) together with thrust force and torque were measured after the first hole and at subsequent intervals of 32 holes. The tool life criterion was either 384 holes drilled or a mean maximum flank wear of 300 µm. Micrographs of the hole entry and exit were recorded for both the first and last holes drilled in each test.

Table 1. Full factorial test array.

Test no.	Workpiece material	Primary feed rate (mm/rev)	
1	Type 2	0.10	Reduced to 0.01 mm/rev for final 2 mm
2	Type 3	0.10	
3	Type 2	0.20	
4	Type 3	0.20	
5	Type 2	0.30	
6	Type 3	0.30	

Trials were carried out on a Matsuura FX-5 vertical high speed machining centre with a maximum spindle rotational speed of 20,000 rpm rated at 15 kW. The machining centre was fitted with a Renishaw probe and tool length setter as well as a dust extraction system capable of removing particles down to 0.3 µm. Fig. 2 shows the experimental setup on the Matsuura FX-5. Chilled air (~8°C) was generated and delivered by a Nex-Flow vortex tube at a pressure of 0.4 bar. Thrust force and torque were measured using a Kistler 9123B 4-component piezoelectric rotating dynamometer mounted on the machine spindle via a quick change toolholder. The force signals were relayed to a PC installed with Dynoware software for analysis via a Kistler type 5221A stator and type

5223A multichannel signal conditioner. Drill flank/chisel wear was evaluated using a WILD M3Z toolmakers microscope integrated with a X-Y digital micrometer platform having a resolution of 1 µm. Optical images of workpiece delamination/damage at hole entry/exit locations for the first and last holes drilled in each test, were captured using a digital camera mounted on the toolmakers microscope. Corresponding delamination factor, F_d (ratio of maximum damaged diameter to nominal drilled hole diameter) was then calculated, with the respective diameters measured from the micrographs using Autodesk software.

The first and last holes drilled in each test were subsequently sectioned notionally along the hole centerline using an Extec Labcut 300 abrasive disc cutting machine equipped with a recirculating coolant system and alumina based disc. Hole surface roughness was characterised using a Taylor Hobson Form 120 Talysurf having a vertical resolution of 10 nm and stylus tip radius of 2 µm. Cut-off and evaluation lengths were 0.8 mm and 4.0 mm respectively, with measurements obtained near the entry, exit and middle sections of the hole. Additionally, the surface quality of the machined holes were assessed using a high resolution JEOL 6060 scanning electron microscope (SEM).

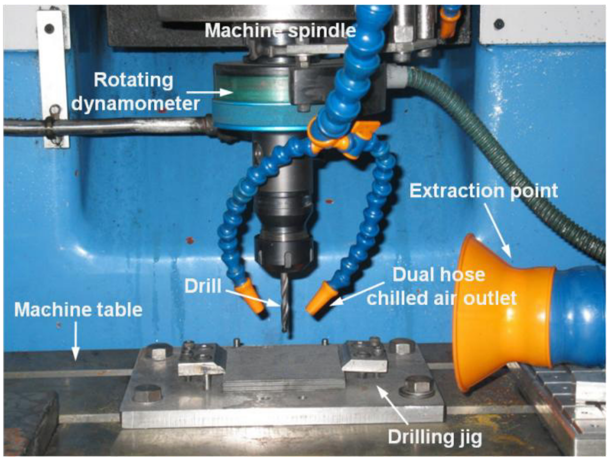

Fig. 2. Experimental drilling setup in Matsuura FX-5.

3. Results and discussion

3.1. Tool wear and life

Fig. 3 details the evolution of tool flank wear against number of holes drilled for all tests. All of the drills produced 384 holes, with flank wear ranging between 114 µm (Test 5) and 193 µm (Test 2). Tool wear at test cessation was typically lower by up to ~41% when drilling the Type 2 laminates and operating at higher feed rates. This was due in part to the larger thickness of the Type 3 workpieces as well as the shorter tool-workpiece contact time. It was observed that abrasion (prior to removal of coating layer) and delamination of the CVD-diamond coating were the principal tool wear modes, as shown in the wear scar micrographs from Tests 2 and 5 in Fig. 4.

Analysis of variance (ANOVA) of the data revealed that none of the main factors were statistical significant with respect to tool wear, although this was possibly due to the fact that the majority of tool-workpiece contact time (~70-88%) was confined to the final 2 mm of the hole when feed rate was reduced to 0.01 mm/rev. This may also have contributed to the relatively high residual level (~75%), with workpiece material having a percentage contribution ratio (PCR) of 24.54% while the corresponding PCR for primary feed rate was negligible.

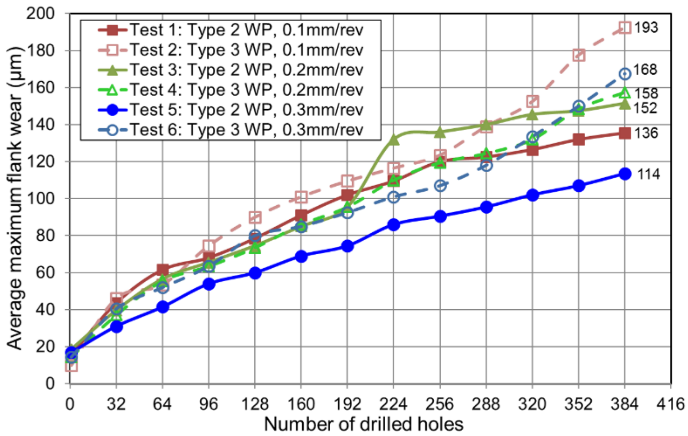

Fig. 3. Flank wear curves for all tests against number of drilled holes.

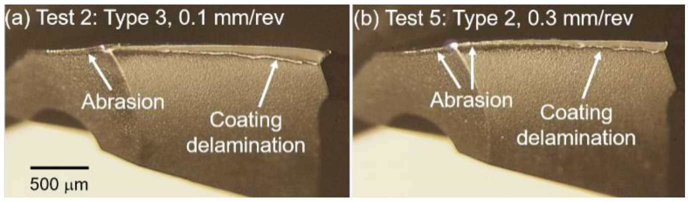

Fig. 4. Tool wear scar at test cessation in (a) Test 2 and (b) Test 5.

3.2. Hole entry and exit quality

Fig. 5 shows micrographs of hole entry and exit for the first and last holes drilled in trials involving the Type 2 workpiece materials (Tests 1, 3 and 5). In terms of hole entry quality, minor damage in the form of fuzzing and limited uncut fibres was observed in the first holes drilled, while greater levels of fuzzing, uncut fibres and delamination were apparent for the last holes drilled, irrespective of primary feed rate and workpiece type. Despite application of the decreased feed rate (0.01 mm/rev) strategy for the final 2 mm of the workpiece, the damage at hole exit was generally similar or more pronounced than the corresponding entry location, see Fig. 5. However, a reduction in exit damage was evident when compared to holes drilled at a constant feed rate of 0.1 mm/rev [14].

Fig. 6 shows the typical thrust force and torque profiles obtained when drilling the last hole in each test. Both parameters increased rapidly during the first stage of drilling (primary feed rates of 0.1-0.3 mm/rev), with thrust force and torque peaking at 591 N and 111 N.cm respectively in Test 6, but subsequently dropped by up to ~80% in the second stage of operation where feed rate was considerably reduced (0.01 mm/rev). Thrust force increased by ~98-155% over the test duration when drilling the Type 3 composite while the corresponding rise was limited to ~56-67% in trials involving the Type 2 material.

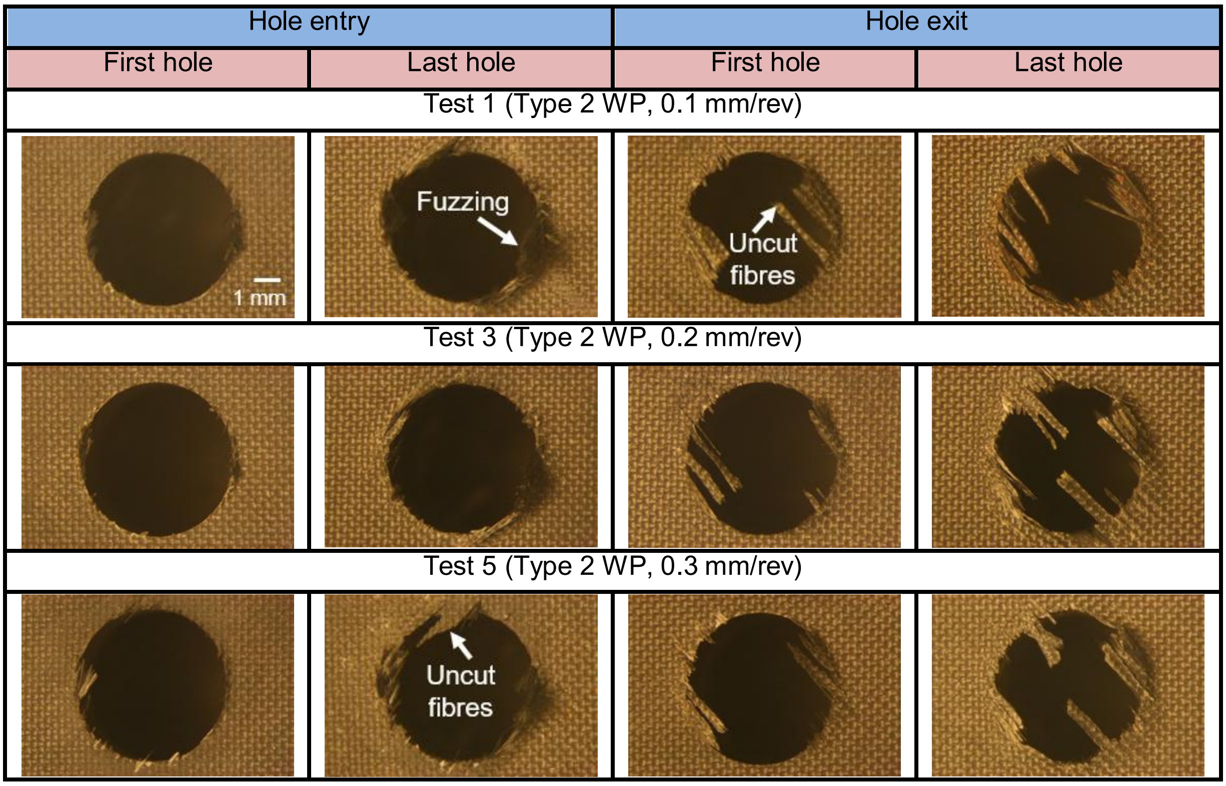

Fig. 5. Hole entry and exit quality of the first and last holes in tests involving Type 2 workpiece material.

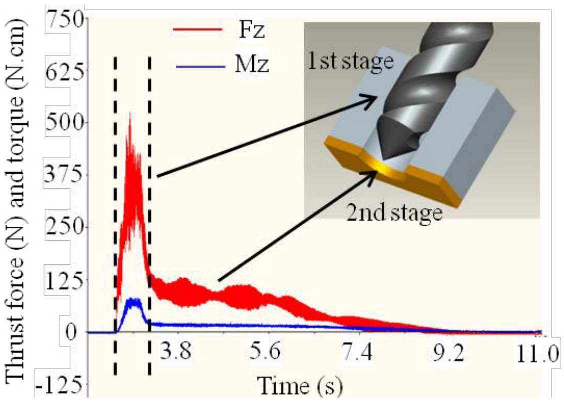

Fig. 6. Typical force and torque profile at the last hole (hole 384) drilled.

The calculated delamination factors at hole entry and exit positions for the first and last hole drilled in each test are detailed in Fig. 7. In general, F_d was found to be greater (by up to 0.18) at test cessation compared with the first hole drilled for both entrance and exit locations. Delamination factor values at hole entrance generally increased with feed rate with a maximum of 1.35 observed in Test 5 (Type 2, 0.3 mm/rev). For the exit delamination factor, Type 2 workpiece normally produced lower values (up to 0.16 lower) than the Type 3 material, except for the last hole drilled when operating at 0.3 mm/rev (Test 5). Understandably, the influence of varying primary feed rate on exit delamination factor exhibited no apparent trend. According to the associated ANOVA, feed rate was found to be a statistically significant factor (at the 5% level) affecting the entrance F_d of the first hole drilled with a PCR of 87.9%, which was in agreement with the observations of other researchers [7]. There was limited discrepancy between exit F_d values of the first and last holes drilled, which suggests that the lower feed rate used had a more dominant effect than tool wear level on hole exit damage.

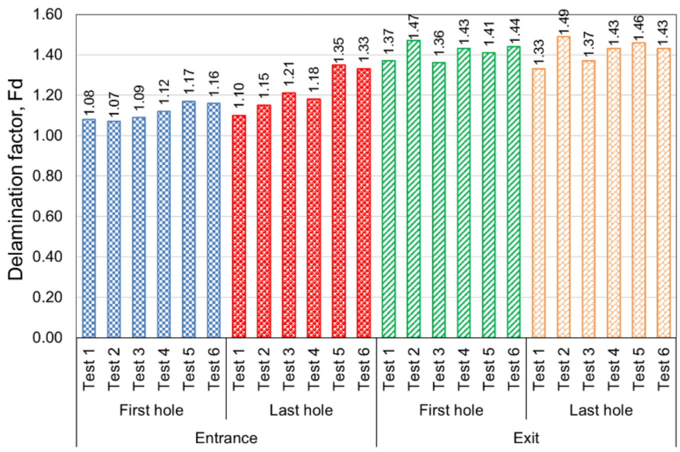

Fig. 7. Delamination factor at hole entry and exit for first and last holes drilled in all trials.

3.3. Workpiece surface roughness

Fig. 8 outlines the hole surface roughness (Ra) values measured at the entry and exit positions of both the first and last holes drilled in all tests. In general, the roughness values were typically higher in Type 3 workpieces (Tests 2, 4 and 6) compared to the Type 2 configuration machined at equivalent feed rate levels. This was due to the larger number of plies orientated at 135° in the former (14).

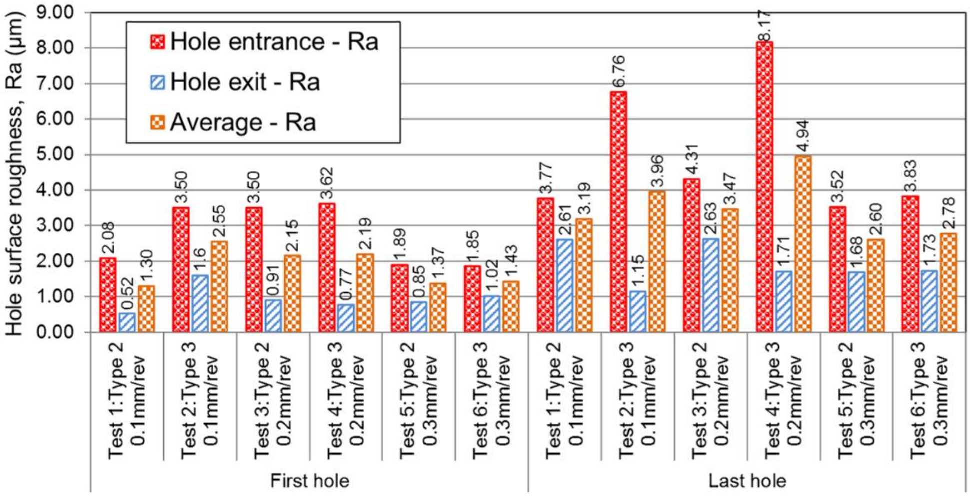

Fig. 8. Surface roughness (Ra) of hole entry and exit section of the first and last holes drilled in all tests.

Increasing feed rate from 0.1 to 0.3 mm/rev led to lower surface roughness (by ~44% in terms of average Ra) in all of the first holes drilled in Type 3 laminates, which was attributed to the decrease in tool wear when operating at higher feed rates, as a result of the shorter drill-workpiece interaction period. Conversely, there was no apparent correlation between the hole surface roughness and feed rate for the last holes drilled, possibly due to the comparatively high levels of tool wear at test cessation. Furthermore, the roughness measured in the vicinity of the hole exit location was consistently lower (by up to ~80%) than the entrance section, probably due to a 'ploughing/'polishing' effect when operating at the extremely low feed rate of 0.01 mm/rev.

3.4. Hole surface morphology

Fig. 9 shows SEM micrographs of the machined surfaces for the first holes drilled in Tests 1, 3 and 5 involving the Type 2 workpieces. Defects in the form of fibre and matrix loss/void formation were evident particularly in the 135º direction plies around the vicinity of the hole entry regardless of the primary feed rate level (0.1-0.3 mm/rev) and despite the drills being in the new condition. Several other researchers have also reported that damage was typically severe in plies orientated at 135º due to the cutting mechanism being dominated by shearing, leading to macro fracture of the fibres [15-16]. In contrast, surfaces with limited flaws were observed near the hole exit due to the lower feed rate (0.01 mm/rev) employed over the final 2 mm of drilling. Considerable deterioration in surface quality over the entire hole however was visible at test cessation; see Fig. 10. Here, reducing feed rate to 0.01 mm/rev near the hole exit provided no appreciable benefits, which suggests that tool condition had a more prominent influence than feed rate during the latter stages of a test. Surprisingly, increasing the primary feed rate to 0.3 mm/rev did not appear to exacerbate the level of damage compared to results when drilling at 0.1 mm/rev. Similar results and trends were seen with the Type 3 lay-up.

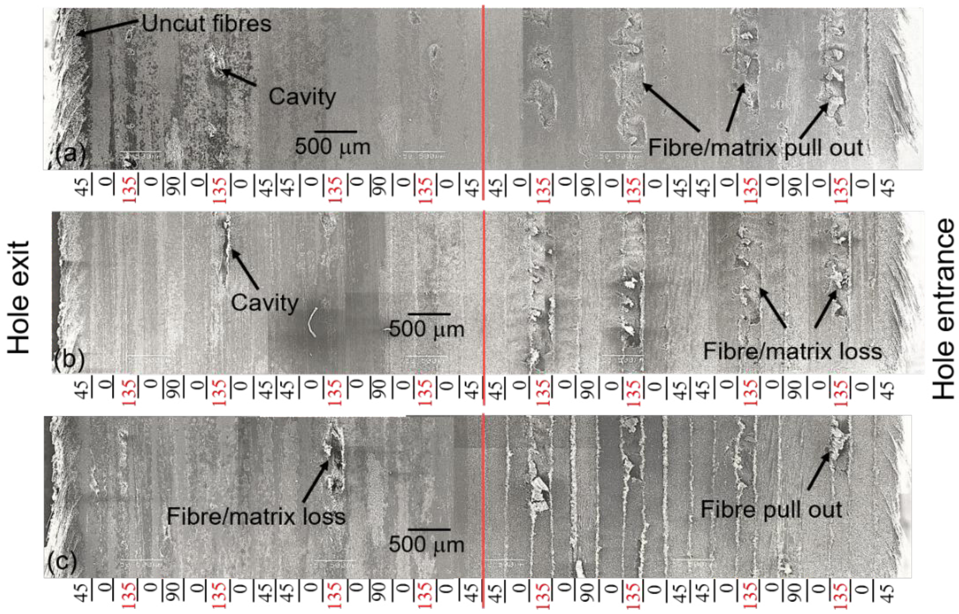

Fig. 9. SEM micrographs of hole surfaces for the first hole in (a) Test 1 (0.1 mm/rev), (b) Test 3 (0.2 mm/rev) and (c) Test 5 (0.3 mm/rev).

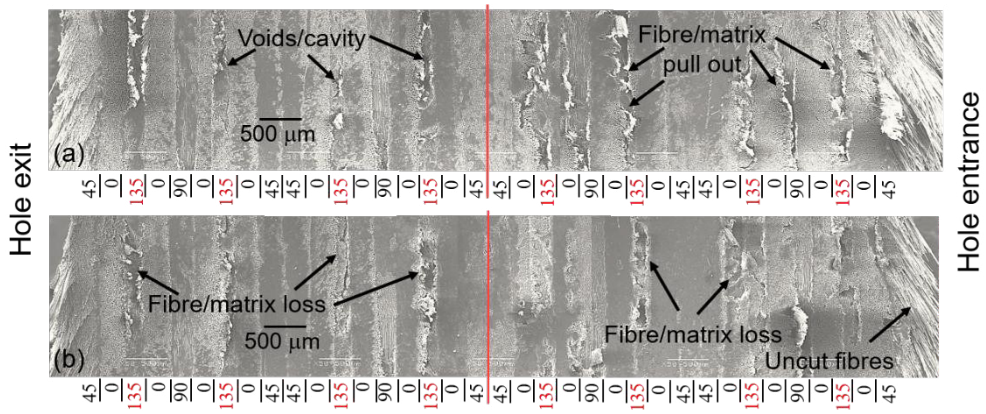

Fig. 10. SEM micrographs of hole surfaces for the last hole in (a) Test 3 (0.2 mm/rev) and (b) Test 5 (0.3 mm/rev).

4. Conclusions

- All tests achieved the 384 hole criterion with corresponding tool flank wear ranging from 114 (Test 5) to 193 μm (Test 2). Tool-workpiece contact time decreased by ~20% as primary feed rate increased from 0.1 (3.78 s) to 0.3 mm/rev (3.03 s) for each hole.
- Increasing primary feed rate led to higher entrance F_d in the first holes drilled and was a statistically significant factor with a PCR of 87.9%. However, the difference in the exit delamination factors of the first and last holes drilled was minimal, most likely due to the reduced feed rate of 0.01 mm/rev utilised for the final 2 mm in all tests.
- Drilling with the variable feed rate strategy resulted in improved hole surface quality at the exit section in terms of reduced fibre pull out and damage/voids compared to the entrance position, but at the expense of productivity.
- Hole surface roughness near the exit was consistently lower than at the entrance position due to the lower feed rate applied as the drill approached the end of the hole. Additionally, average hole roughness was up to ~96% higher in the Type 3 composite due to the greater number of plies orientated in the 135° direction compared to the Type 2 workpiece.

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