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2nd CIRP Conference on Surface Integrity (CSI)

Influence of lay-up configuration and feed rate on surface integrity when drilling carbon fibre reinforced plastic (CFRP) composites

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Abstract

Experimental data is presented relating to surface roughness (2D and 3D) and workpiece integrity when drilling unidirectional CFRP laminates with varying lay-up configurations (Type 1, 2 and 3) at different feed rates (0.2 and 0.4mm/rev) using diamond coated carbide tools. Drill feed rate was ramped down to 0.01mm/rev for the final 0.5mm in all trials. Surface roughness at hole exit was typically lower (up to 4.04µm Ra) compared with the entry section in all tests due to the lower feed rate applied. High resolution SEM micrographs and 3D topographic maps showed that Type 2 ([45/0/135/0/90/0/135/0/45]_{2S}) lay-up gave the lowest roughness of ~1.16µm Sa after 384 holes at a cutting speed and feed rate of 90m/min and 0.4mm/rev respectively. Cavities, smearing of matrix material and adhered/deposited fibre dust were observed near the exit location at test cessation.

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Keywords: Drilling; Fibre reinforced plastic; Surface roughness; Material orientation

1. Introduction

The use of carbon fibre reinforced plastic (CFRP) composites has shown a marked increase in recent years, particularly in the aerospace industry. This has been reflected in the upsurge of CFRP utilisation for commercial passenger aircraft from < 5% (Boeing 757/767) in the 1980's to almost 50% of total weight in the latest Boeing 787 Dreamliner [1]. Specific components include floor beams and frame panels, as well as the majority of vertical and horizontal sections of the tail. Joining of such parts is mainly dependent on mechanical bolting/riveting. Consequently, the quality of drilled fastener holes in CFRP is paramount, with metrics relating to hole surface roughness, roundness and cylindricity as well as the level of workpiece delamination/flaws.

Khashaba et al. [2] suggested that surface roughness (Ra) could be used as a parameter for detecting internal

workpiece delamination as deep valleys were typically observed at the damage location. They compared SEM micrographs with corresponding surface roughness profiles when drilling GFRP composite. Ramulu et al. [3] reported that 3D roughness parameters provided a better indication of machined surface quality and were recommended over 2D measures such as Ra and Rt in milling of graphite/epoxy composite, as the surface roughness and profile were found to be highly dependent on both fibre orientation and measurement direction. The influence of fibre orientation on surface quality when milling of CFRP was demonstrated by El-Hofy et al. [4], who showed that wavy surfaces were generally found at plies in the 45° direction while matrix cracking and fibre pullout were more prevalent at the 90° and 135° orientation.

Hole entry/exit delamination is a damage mode commonly observed when drilling composites, which can lead to deterioration in workpiece properties and performance. It can be minimised/avoided by reducing

thrust forces during the drilling process, which is largely influenced by feed rate levels [5, 6]. In terms of cutting environment, machining of fibre reinforced polymers are typically conducted dry, as use of water based cutting fluid/emulsion can cause swelling of the material as well as induce chemical reactions with certain functional groups of macro molecules, leading to form and geometrical errors [7]. Similarly, natural or synthetic oils are not recommended as they can combine with the resulting CFRP dust to produce a heavy sludge that can damage the coolant system, and which may have to be removed from the machined parts [8]. Elevated temperatures during drilling however can cause a reduction in fibre-matrix interfacial shear strength followed ultimately by matrix burn and fibre pull out [9]. The paper details work to study the effect of variable feed rate and lay-up configuration on surface roughness and integrity following drilling of CFRP composites under chilled air conditions.

2. Experimental design, workpiece materials, equipment and test procedure

Autoclave cured CFRP laminates with 3 different configurations/fibre orientations were employed. These involved manually laid up unidirectional (UD) pre-pregs (0.26mm thick) with Type 1 and Type 3 laminates comprising 40 plies with a thickness of 10.4mm, whereas Type 2 laminates were 9.36mm thick consisting of 36 plies. The lay-up sequences were [45/0/135/90]_{5S}, [40/0/135/0/90/0/135/0/45]_{2S} and [45/0/135/135/135/90/45/45/45/0/135/135/90/45/45/0/135/135/90/45]_S for Types 1, 2 and 3, respectively. The CFRP laminates were made of intermediate modulus (294GPa), high tensile strength (5880MPa) carbon fibre impregnated with epoxy resin resulting in a fibre weight fraction of 64 to 68%. The fibre volume of the CFRP composite following curing was 60%, with an overall tensile strength and modulus of 2950MPa and 154GPa respectively [10]. Plates measuring 100×100mm were produced for the trials. Tools employed for the work were 6.38mm diameter CVD-diamond coated tungsten carbide (WC) drills, having optimised double point geometry (130° and 60° angles) designed for improved chip breaking and enhanced chip evacuation [11], see Fig. 1.

All tests were carried out on a Matsuura FX-5 vertical high speed CNC machining centre with a variable spindle capable of up to 20,000rpm rated at 15kW. The machine was fitted with a Filtermist dust extraction system for removing airborne CFRP dust particles $\geq 0.3\mu\text{m}$. A chilled air environment ($\sim 8^\circ\text{C}$) was utilised in each trial and was generated using a Nex-Flow vortex tube (type 56030FD), which was directed to the cutting zone through two adjustable nozzle hoses at a pressure

of 0.4 bar. The CFRP workpieces for tool wear/life testing were held in a bespoke drilling jig with an array (10×10) of pre-fabricated 7mm diameter clearance holes, see Fig. 2 for experimental setup.

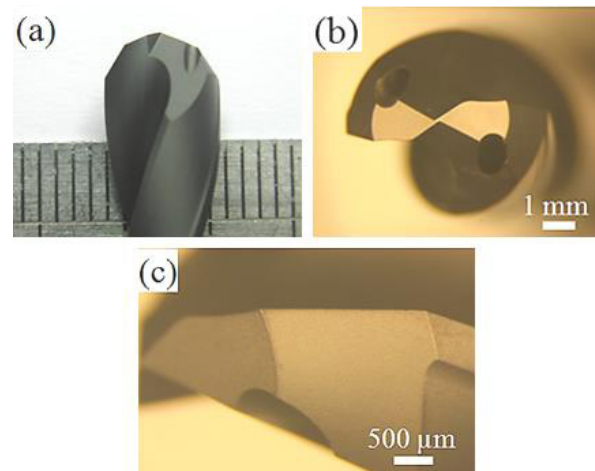


Fig. 1. Diamond coated drill tip (a) side view; (b) end view; (c) cutting lip

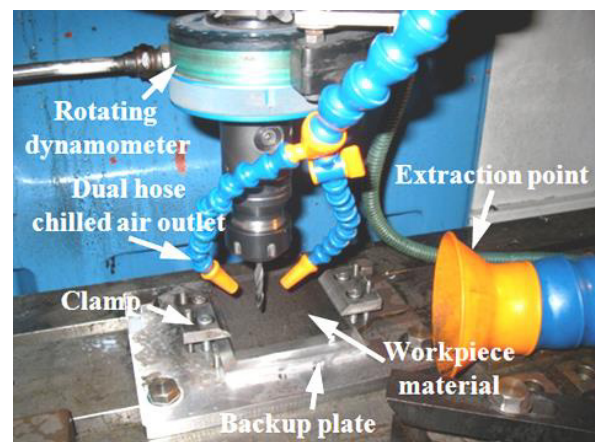


Fig. 2. Drilling experimental setup

The end of test criteria was a maximum flank wear (VB_{max}) of 0.3mm or drilling of 384 holes. The first and last holes drilled from each trial were sectioned (approximately along the centre of the hole) using a diamond slitting saw for subsequent machined surface analysis, see schematic in Fig. 3. Workpiece surface roughness (2D parameters) at the hole entrance and exit were evaluated using a Taylor Hobson Talysurf 120L with cut-off and evaluation lengths of 0.8 and 4mm respectively (replicated twice) while 3D topographic maps were obtained over a scan area of $8 \times 1\text{mm}$ at $\sim 1\text{mm}$ beneath the hole entrance. Tool flank wear was measured using a toolmaker's microscope equipped with a micrometre stage (0.001mm resolution) and corresponding wear scar images captured using a digital

camera. Hole surfaces and associated workpiece damage were assessed with a JEOL 6060 scanning electron microscope (SEM). Cutting speed was kept constant at 90m/min for all tests.

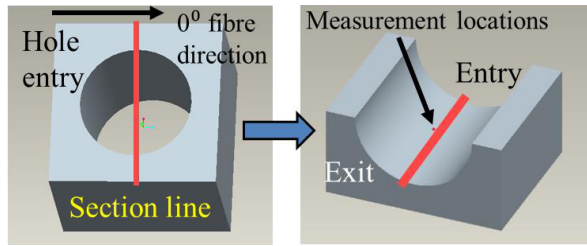


Fig. 3. Schematic of hole sectioning and surface measurement locations

A full factorial experimental array was employed involving 2 variable factors; one at three levels and the other at two levels giving a total of 6 tests. The factors and their corresponding levels are detailed in Table 1. In addition, a variable feed rate regime was applied for each hole in order to reduce thrust force as well as delamination at the hole exit. The feed rate was initially set at 0.2 or 0.4mm/rev and reduced to 0.01mm/rev in last 0.5mm prior to drill exit from the workpiece.

Table 1. Test array with variable factors and corresponding levels

Test no.	Workpiece material	Feed rate (mm/rev)*
1	Type 1	0.2
2	Type 2	0.2
3	Type 3	0.2
4	Type 1	0.4
5	Type 2	0.4
6	Type 3	0.4

*reduced to 0.01mm/rev in final 0.5mm prior to exit

3. Results and discussion

Tool wear progression followed a similar trend irrespective of feed rate or workpiece configuration, with all trials achieving 384 holes. The highest flank wear recorded at test cessation was 123 μ m in Test 3 while Test 4 showed the lowest flank wear level with a VB_{max} of 102 μ m. The relatively low variation (21 μ m) in tool wear levels between tests was most probably due to the difference in tool-workpiece contact time, which was 1.33 and 1.00s per hole when operating at 0.2 and 0.4mm/rev respectively. Abrasion and chipping/peeling of the CVD diamond coating (at the cutting edge corner) were the primary wear modes for all of the drills inspected, and was similar to that shown in Fig. 4(a). In preliminary testing at a feed rate of 0.6mm/rev, both

cutting lips experienced catastrophic fracture at the flank surface after drilling only one hole as shown in Fig. 4(b), due to the high thrust force experienced (~1304N).

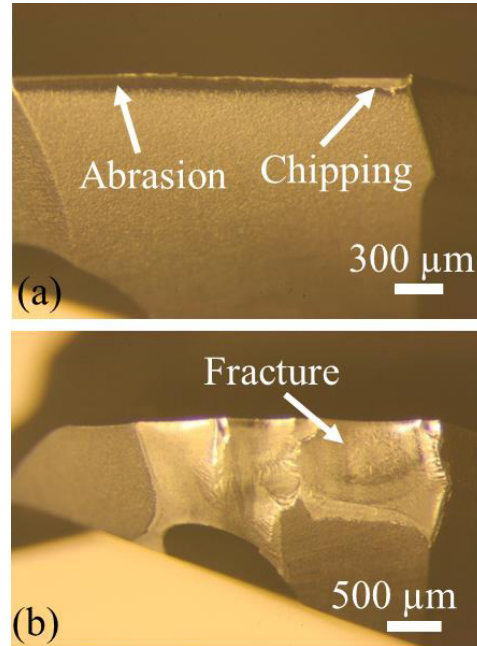


Fig. 4. Drill wear scar in (a) Test 3 after 384 holes; (b) preliminary test at a feed rate of 0.6mm/rev after 1 hole

Fig. 5 details surface roughness (R_a) values measured at the entry and exit positions in both the first and last holes drilled for all tests. Hole roughness was generally higher in Type 3 workpieces (Tests 3 and 6) at both feed rate levels, which was due to the larger number of plies (14) orientated at 135°. Increasing feed rate from 0.2 to 0.4mm/rev led to lower R_a in all of the samples analysed, which was attributed to a decrease in tool wear when operating at higher feed rates, as a result of the shorter interaction period between the tool and workpiece [6]. Furthermore, the R_a measured in the vicinity of the hole exit location was consistently found to be lower (by up to ~80%) compared to the entrance section, which was possibly due to a 'ploughing' or 'polishing' effect when operating at the very low feed rate of 0.01mm/rev. An analysis of skewness (R_{sk}) showed that all values were negative, indicating that the machined surfaces were typically dominated by sharp/deep valleys, most likely the result of fibre pull out/matrix loss. Conversely, the relatively high kurtosis (R_{ku}) values recorded (> 3) suggests the presence of sharp peaks on the measured profiles, which was likely from uncut/re-deposited fibres on the hole surfaces.

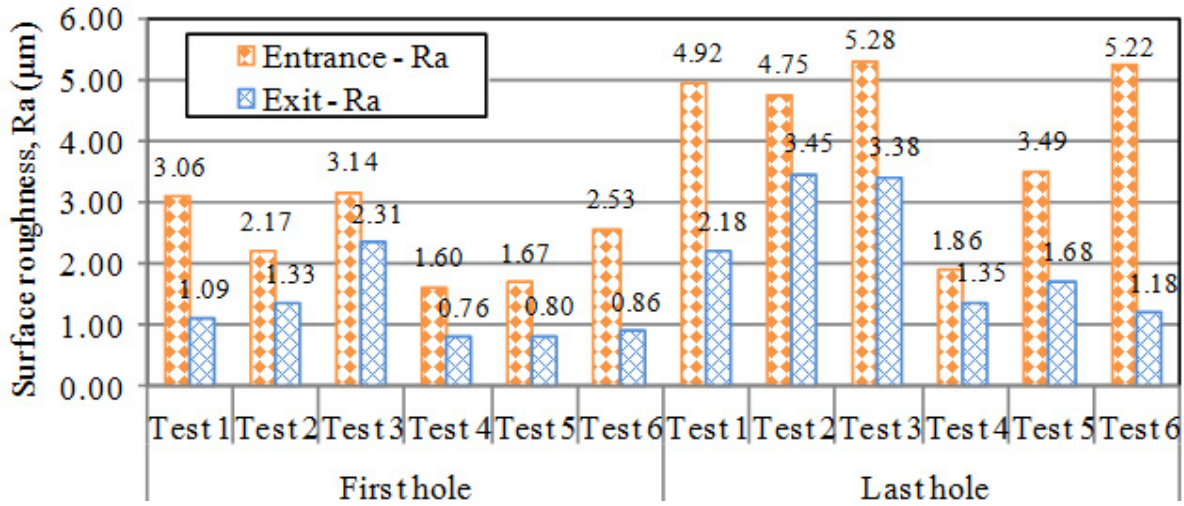


Fig. 5. Surface roughness (Ra) results for all tests at entrance and exit location for the first and last hole

Fig. 6 details the measured 3D roughness parameters (Sa and St) for the first and last holes drilled in each of the experiments (all tests drilled 384 holes). The trends were largely similar to corresponding Ra data with hole surface quality generally deteriorating as tool wear increased (up to ~ 150% higher Sa value at test cessation in Test 5) and when operating at the lower feed rate level (deviation of ~ 21 – 72%). In terms of CFRP lay-up configuration, the Type 2 material was found to give the lowest roughness with minimum Sa values of 0.46 and 1.16μm when utilising new and worn tools respectively in Test 5. An analysis of variance (ANOVA) showed that both workpiece material and feed rate were statistically significant at the 5% level with respect to Sa,

lay-up having the greater effect with a percentage contribution ratio (PCR) of 83.7% compared to only 16.2% for feed rate. In addition, the variation in St (total height of the surface) was similar to that of the Sa parameter with a maximum of 143.0μm for the last hole in Test 3.

Fig. 7 shows 3D surface topography maps of the first hole produced in Tests 2 and 3. Substantial grooving/voids were clearly visible particularly at the 135° orientated plies in both workpiece samples despite drilling with new tools. Damage was also more severe in the Type 3 workpiece due to the presence of adjacent 135° plies, which would explain the poorer surface roughness observed previously.

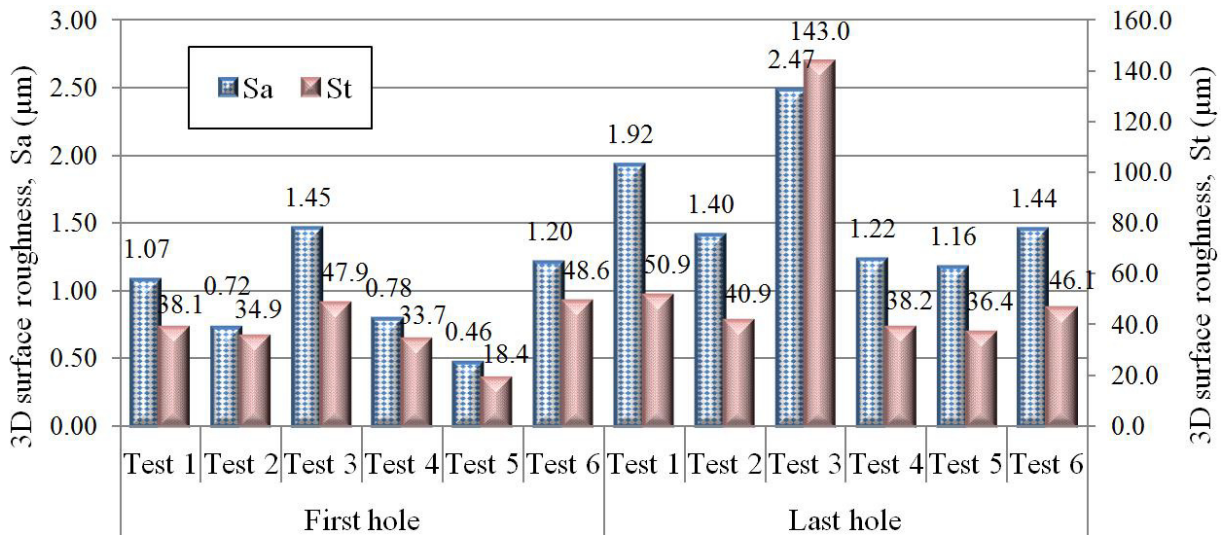


Fig. 6. Surface roughness (Sa and St) results for first and last holes in all tests

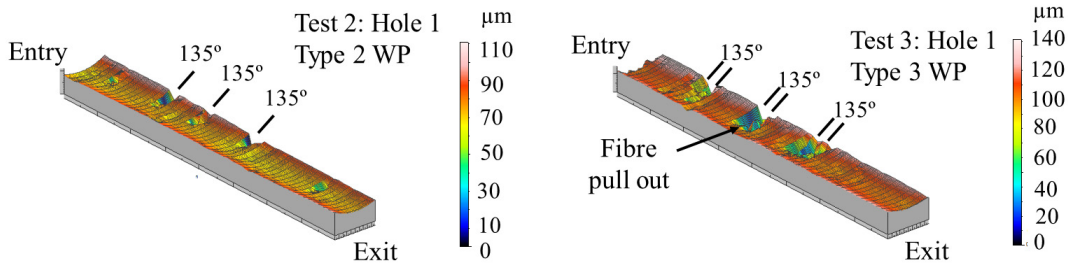


Fig. 7. Three dimensional (3D) topography maps of the first hole in Tests 2 and 3

Subsequent SEM analysis of selected cross sectioned hole surfaces confirmed that cavities due to fibre/matrix loss were primarily concentrated at plies with 135° orientation, while those at 0°, 45° and 90° were largely free of damage, see Fig. 8. The surface quality of holes machined using new drills was significantly better towards the exit location, with minimal signs of defects even at the 135° ply; see Fig. 8(a) and Fig. 8(b), as a result of the 0.01mm/rev feed rate employed. When assessing the last hole drilled however, workpiece damage was evident even at the exit position, which suggests that tool wear/edge condition was the dominant factor affecting hole surface quality; see Fig. 8(c). During machining, fibres in the 135° direction were typically subjected to intense elastic bending (instead of shearing) by pressure from the tool cutting edge. As the load exceeded the fibre yield strength, failure occurred below the cutting plane/surface with the debris removed as the tool passed, thereby creating a cavity/groove on

the surface. In contrast, fibres in the 0° direction suffered cracking due to buckling or were ‘peeled off’/separated and slid up the tool rake face while fibre fracture typically initiated at the tool tip (without elastic bending) for plies in the 45° and 90° orientations [1].

Fig. 9 shows sample SEM micrographs of surfaces near the hole exit location (drilled at feed rate of 0.01mm/rev). Observations showed that smearing of melted matrix material was prevalent when drilling with new tools. This was possibly due to the increased tool-workpiece contact time at the low feed rate resulting in relatively higher interface temperatures. The poor thermal conductivity of CFRP was a further contributory factor in relation to resin melt, which typically occurs at 300 - 400°C [12]. Conversely, adhered or re-deposited fibre dust and fibre/matrix cracking similar to that shown in Fig. 9(b) was evident as tool wear increased, with severity highly dependent on ply orientation and drill edge sharpness.

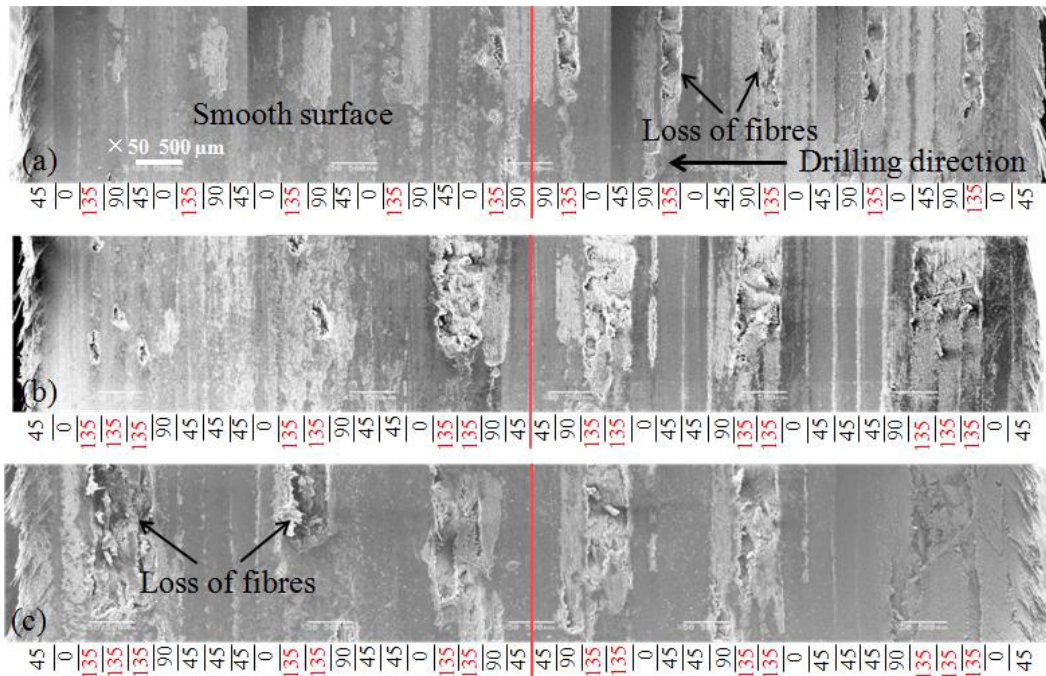


Fig. 8. Hole surface integrity in (a) Test 4 - hole 1; (b) Test 6 - hole 1; (c) Test 6 - hole 384

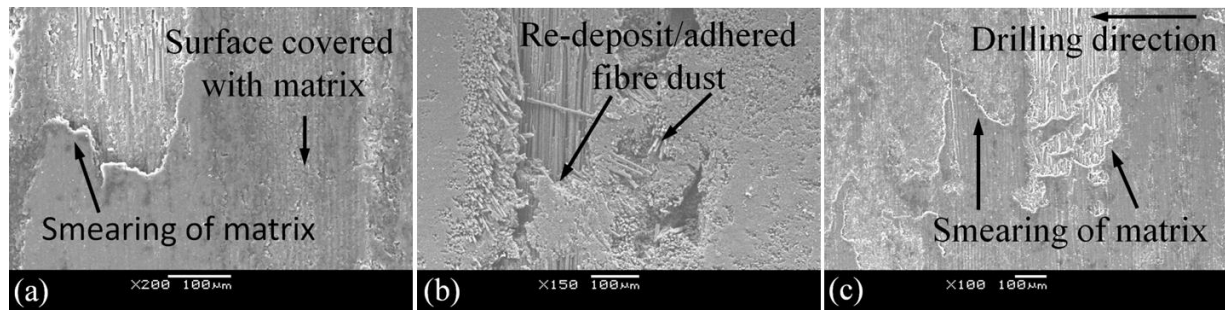


Fig. 9. SEM micrographs showing surfaces near the exit location in (a) Test 1 - hole 1; (b) Test 1 - hole 384; (c) Test 5 - hole 1

4. Conclusions

- Drill flank wear did not exceed $123\mu\text{m}$ in all tests even after machining 384 holes, with abrasion and chipping of the CVD diamond coating being the principal tool wear modes.
- Surface roughness near the bottom of the hole was typically lower (maximum value recorded $4.04\mu\text{m}$ Ra) compared with the top section in all tests due to the reduced feed rate prior to the drill exiting the workpiece. Type 2 CFRP workpiece material produced the lowest Sa value ($1.16\mu\text{m}$) at a feed rate of 0.4mm/rev while Type 3 gave the highest roughness value ($2.47\mu\text{m}$ Sa) at test cessation.
- Surface defects in the form of grooves/cavities were generally observed at 135° plies irrespective of cutting parameters and tool condition, while those at 0° , 45° and 90° showed comparatively limited damage when utilising new drills. Due to the anisotropic nature of the material and influence of fibre direction on workpiece damage, 3D topographic/areal parameters are necessary for assessing machined surface quality in CFRP workpieces.
- SEM observations showed smearing of matrix material and adhered/deposited fibre dust in the surface cavities when drilling with the very low feed rate (0.01mm/rev) near the exit location.

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