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Influence of Router Tool Geometry on Surface Finish in Edge Trimming of Multi-Directional CFRP Material

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Abstract. The use of carbon fibres reinforced plastic (CFRP) composites material for product structures has been steadily increasing due to the superior material properties such as high strength, low weight and corrosion resistance especially in aerospace industry. This work presents a research on the influence of various router or burrs tool geometrical feature towards surface roughness in edge trimming process on a specific CFRP material. CFRP panel which measured in 3.41mm thickness with 28 plies in total has been chosen to be the main study material. Three various geometrical features of router tool made of uncoated tungsten carbide material with diameter of 6.35mm which vary in number of flute and helix angle were utilized to investigate the effect of surface roughness in edge trimming of CFRP material. Surface roughness measurement was taken using Mitutoyo Surftest SJ-410. Furthermore, optical microscope Nikon MM-800 is utilized to further observe the trimmed surfaces. The result reveals that tool type 3 (T3) resulted the lowest surface roughness with respect to the overall averaged Ra value which ranged between 2.22µm to 5.29µm whilst tool type 1 (T1) obtained the highest Ra values ranged between 2.86µm to 19.36µm. On the other hand, the tool type 2 (T2) falls in the middle between the rests of two others type of tool which stated the range of Ra average value was between 3.91µm to 5.28µm. This result is also supported by photomicrographs observation taken by optical microscope which elaborated and discussed further in this paper.

1. Introduction

Composites are materials established by combining two or more distinctly different materials. In most cases, the composite is made by a mixture of matrix and reinforcement materials. The matrix material may be made from metals, ceramics, or polymers. Meanwhile, polymer matrices are normally reinforced with glass, carbon, and aramid fibers [1]. The polymer matrix such as thermoset and thermoplastic binds the fibers together then transferring the load to the reinforced fibers and protect the fibers from the environmental attack [2]. In recent years, fiber-reinforced polymers (FRPs) materials are gaining tremendous attention by industries especially in aerospace industry. The consumption of composite materials has increased more than 50% in newly designed commercial aircrafts. The *Boeing 787 Dreamliner* for instance, exhibiting gradual increases in usage of composite materials which stated 50% [36]. There are two main reinforcement fibers used in aero-structural manufacturing namely Glass Fiber

Reinforced Polymer (GFRP) as well as Carbon Fiber Reinforced Polymer (CFRP). CFRP are extensively used in today's aerospace industry due to their lightweight, high fracture toughness, good fatigues performance and high static strength.

Components fabricated from composite materials are usually manufactured to the near-net shape of the desired design. A process used in manufacturing composite components is called lamination process which a process of building layer by layer out of contoured two-dimensional plies that closely capture the final shape of the product. Although, composite components are often made near-net shape, some machining is often unavoidable. Machining is also an indispensable process for shaping parts from stock composite materials and for finishing tight dimensional accuracy shapes. Among the common machining processes used are edge trimming and routing, milling, drilling, countersinking, and grinding [1]. Machining composite materials is hard to be performed due to the mechanical, thermal properties and the high abrasiveness of the reinforcement constituents. These properties typically resulted in damages being introduced into the work material and in very rapid wear development in the cutting tool. Hence, there are several types of cutting tool materials as well as geometries available in the market. The ultimate reason for this variety in tooling is the multiple characteristics of the composite materials deriving from the various forms, types of reinforce material, matrices used and methods applied to manufacture certain composites. There are two main types of tools suitable for routing or trimming CFRP materials, namely polycrystalline diamond (PCD) inserts and solid or coated carbide end mill which categorized into helical spiral type and router or burrs type. Tool geometrical design especially the number of tooth has direct relationship with machining parameters according to the fundamental formula.[3]–[9].

Tool materials in machining composites should be capable of withstanding the abrasiveness of fibres and debris resulting from machining. The tool geometry should provide a keen edge capable of neatly shearing the fibers. These two requirements are distinctively different from those expected of a cutting tool in metal machining [1]. *Prakash R. et al.* conducted an experiment to study the effect of various tool geometry. They reported T1 generated lower cutting force and moderate surface roughness with no delamination. The trapezoidal geometry shape allows more cutting area and creates lower surface damages. T2 generated higher cutting force and surface roughness. The cutting tooth has small flat edged pyramidal form that creates more indentations to the work piece. T3 resulted the highest cutting forces and worst delamination where the continuous flutes with higher helical angle cause the pulling action of the extreme top and bottom plies of the laminate which results in delamination [7]. On the other hand, *M. Haddad et al.* reported that burr tool seems to minimize defects on trimmed surface. However, these defects tend to increase with an increase in the feed speed. A few mechanical damages such as fibre pulled-out with matrix degradation in some areas were spotted through scanning electron microscope (SEM) images at high speed machining which strongly believed due to thermal effects. Feed speed was found to be the major parameter affecting surface roughness under standard cutting conditions. Tool geometry and the cutting parameters which impacted the formation of the chip thickness were the two main factors discovered affecting the mass of harmful particles [10]. *N. Duboust et al.* proved the surface roughness increased with machining distance generally following a steady trend. They also concluded that diamond coated tool with multiple cutting teeth or also known as burrs tool was able to produce a good quality surface although at high feed rate in comparison with polycrystalline diamond (PCD) tool [11], [12]. *Ondrej Bilek et al.* studied eight different types of tool on the cutting force, surface roughness and dimensional accuracy. They summarized that PCD-coated tools for CFRPs machining has a lower cutting efficiency due to a different friction characteristic. Meanwhile, tools with left-hand and right-hand spirals which is also known as burrs or router tool was recommended for edge trimming or side milling [13]. *Souhir Gara and Oleg Tsoumarev* found that the transverse roughness does not depend on cutting conditions, it depends only on tool geometry. Contrary to the longitudinal roughness which was not only depending on the tool geometry but also the cutting conditions. Feed per tooth presents the highest statistical and physical influence on the surface roughness for knurled or burrs tool. Fine toothing of burrs tool exhibited the most suitable tool for the slotting of CFRP material due to the minimum damages generated from the machined specimens in comparison to the smooth and coarse toothing [14], [15].

Having said that, the effect of various geometrical feature mainly for router or burrs tool towards surface roughness and tool wear in edge trimming process on a specific CFRP material is initiated and successfully explained in this work.

2. Methodology

2.1 Material

The work piece material (CFRP panel) for the experiment was provided by local aerospace composite manufacturing industry. The CFRP panel measured 3.41 mm in thickness and the type of fabric was unidirectional (UD). It has 28 number of plies in total which consist of 2 Glass plies on the bottom and the top of the panel play the role of protecting the outer surfaces of the panel. The stacking sequence is illustrated by Table 1.

Table 1: CFRP stacking sequence

Ply or Part Number	Orientation (°)
P2	45
P3	135
P4	90
P5	90
P6	0
P7	90
P8	0
P9	90
P10	0
P11	135
P12	45
P13	45
P14	135
P15	45
P16	135
P17	90
P18	90
P19	0
P20	90
P21	0
P22	90
P23	0
P24	135
P25	45
P26	45
P27	135

Table 2: CFRP details

Composite composition	No of Ply	Areal Density	Fabric Type	CPT/Ply
Carbon	26	203 g/m^3	Unidirectional	0.125
Glass	2	107 g/m^3	Woven	0.08
			Total thickness (mm)	3.41

2.2 Cutting Tool

There were three types of router or burrs tool with different geometrical features have been chosen and investigated in this work. Type 1 (T1) is defined as fine, Type 2 (T2) is medium and Type 3 (T3) is smooth. These three tools were made of tungsten carbide (uncoated) and has diameter 6.35mm but slightly different in the overall length (*refer Table 3*). Figure 1 indicates the types of router or burrs tool used in this research.

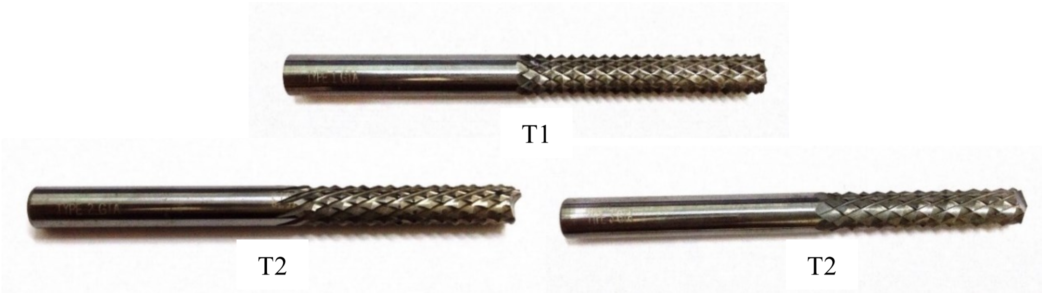

Figure 1: Three different geometrical feature of router or burrs tool

Table 3: Router or burrs tool properties

	Diameter (mm)	Number of teeth	Number of helix		Angle of helix (°)		Length (mm)
			Right	Left	Right	Left	
Type 1	6.35	12	12	12	28	28	75.3
Type 2	6.35	10	11	10	26	26	72.0
Type 3	6.35	9	7	9	19	32	80.2

2.3 Machine Specification

The machine used for this experiment is a Hass CNC Gantry Router – 3 Axis GR-510. Specification of the machine is given in Table 4.

Table 4: CNC Router Specifications

Parameters	Specifications
Max Spindle Speed	10 000 rpm
Horse Power of the Spindle	15 hp
Max Feed Rate	53.3 m/min
Maximum X-axis travel distance	3073 mm
Maximum Y-axis travel distance	1549 mm
Maximum Z-axis travel distance	279 mm
Work Surface/Table	3099 mm × 1346 mm

2.4 Machining Parameters

The range of spindle speed (N) applied for each type of chosen router tool was between 2526 rpm to 7579 rpm. Meanwhile, the cutting feed was varied from 126 mm/min to 1137 mm/min. Table 5 represents the machining parameters applied in this work. Down milling has been selected as the mode of machining configuration. Total travel distance of each run was 260 mm.

Table 5: Machining parameters

		Tool Type	Vc (m/min)	Spindle Speed, N (RPM)	Feed/Rev, Fz	Feed Rate, Vf (mm/min)
T1	R1	Fine	50	2526	0.05	126
	R2	Fine	100	5053	0.1	505
	R3	Fine	150	7579	0.15	1137
T2	R1	Medium	50	2526	0.1	253
	R2	Medium	100	5053	0.15	758

	R3	Medium	150	7579	0.05	379
T3	R1	Smooth	50	2526	0.15	379
	R2	Smooth	100	5053	0.05	253
	R3	Smooth	150	7579	0.1	758

2.5 Fixture Design and Edge Trimming

The fixture to hold the CFRP specimen panel for edge trimming process in the experimental phase was designed by Computer Aided Design (CAD) model and Computer Aided Manufacturing (CAM) of Catia V5 software. Two separate plates namely top and bottom plate are used to firmly secure the specimen right in the middle with enhancement of four M8 screws. The holes of the bottom plate were designed to fit in with the dynamometer initial holes dimension. Figure 2 below illustrates the CAD design as well as the final assembly of fabricated fixture before the real physical edge trimming process. In this work, the edge trimming process performed with 100% of tool diameter or step width (a_e) and the depth of cut (a_p) was taken in full thickness of the selected composite panel. This is to replicate the actual industrial practice done by composite manufacturers.

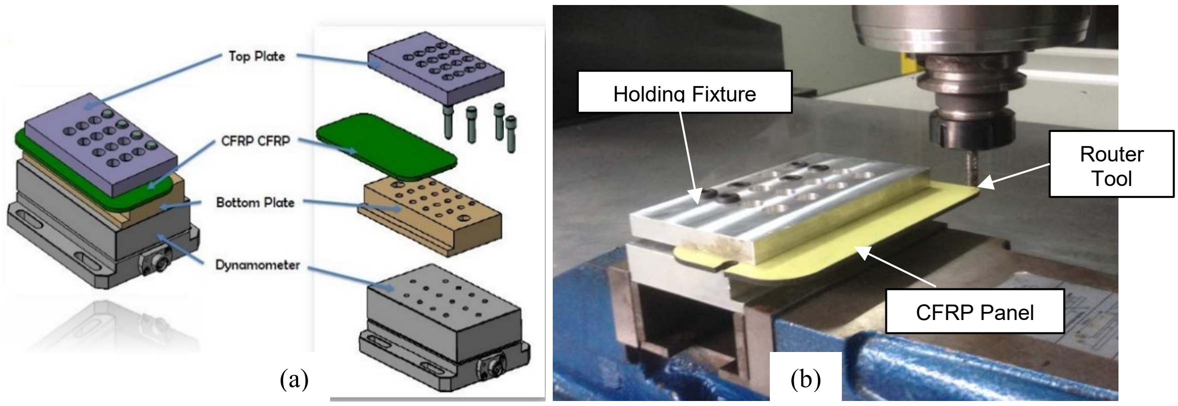

Figure 2: (a) CAD view of the jig with CFRP plate, (b) final fixture assembly preparation

2.6 Surface Roughness Measurement and Observation

Surface finish of the workpiece was measured using surface roughness tester Surftest SJ-410 manufactured by Mitutoyo which is capable to measure up to 0.0001 µm. In this study, Ra (Arithmetical mean deviation) is used to measure the surface finish. Longitudinal surface roughness is evaluated in this work with the stylus travel distance set at 4 mm on each measurement. There were 5 points of measurements taken on every machined surface and final average Ra is obtained to represent the result of surface finish on every specimen. Figure 3 shows the SJ-410 roughness tester and the display unit.

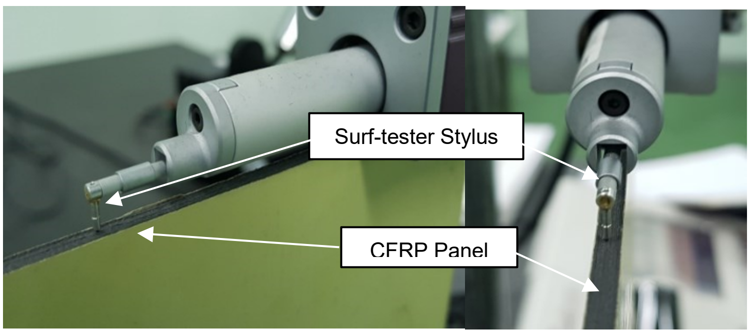

Figure 3: SJ-410 roughness tester and the display unit

On the other hand, Nikon MM-800 microscope is utilized to observe the tool wear for each type of chosen router tool. Moreover, further details of the surface finish on every machined surface is also observed by using the same microscope. The magnification range is 1x magnification to 100x magnification. Therefore, it helps in identifying tool wear or damages as well as explains better on things occurred on the trimmed surfaces. Whilst the specimen is under microscope, the data processing software, E-max which connected to a personal computer capturing the images needed. Figure 4 indicates the Nikon MM-800 microscope.

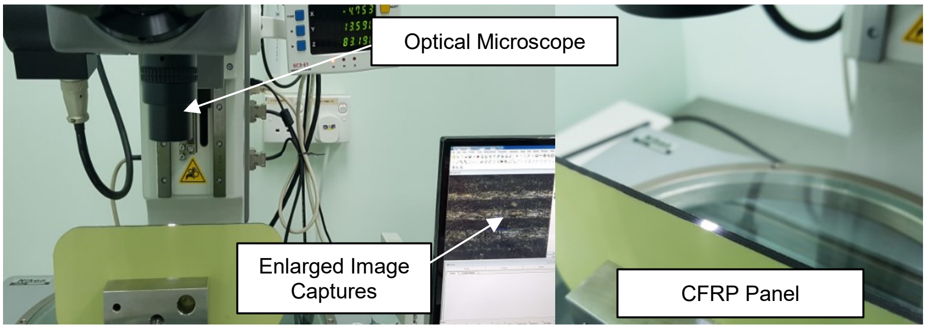

Figure 4: Nikon MM-800 is utilized to further observe the trimmed surface

3. Result and Discussion

From the result it is obviously seen that the Type 3 (T3) tool resulted the best surface roughness, Ra which ranged between 2.22µm to 5.29µm. Meanwhile, Type 1 (T1) tool shows the highest Ra values ranged between 2.86µm to 19.36µm. On the other hand, Type 2 (T2) tool falls in the middle between the rests of two others type of tool which stated the range of Ra value was between 3.91µm to 5.28µm. In general, T3 resulted the lowest surface roughness exhibited by the Run no. 1 (R1) which the machining parameter applied was spindle speed, N at 2526 rpm and feed rate, V_f 379 mm/min. In contrast, T1 has presented the highest surface roughness, Ra value indicated by the Run no. 3 (R3) which the machining parameter applied was spindle speed, N at 7579 rpm and feed rate, V_f 758 mm/min. An enormous difference of Ra value obtained by the R3 of T1 and T3 which is approximately (*19.36µm - 3.78µm = 15.58µm or almost 400% or 4 times different*) which provides an evidence that the difference in tool geometrical feature impacted the trimmed surface quality. Spindle speed, N was maintained at 7579 rpm but only slight difference on the feed rate, V_f (*1137 mm/min – 758 mm/min = 379 mm/min or 33.33%*). Therefore, it could be predicted that the surface quality trimmed by tool T3 shall generate better than the T1 tool if the same feed rate, V_f is being applied. This result also supported by further observation of the trimmed surface by optical microscope which is illustrated by Figure 5.

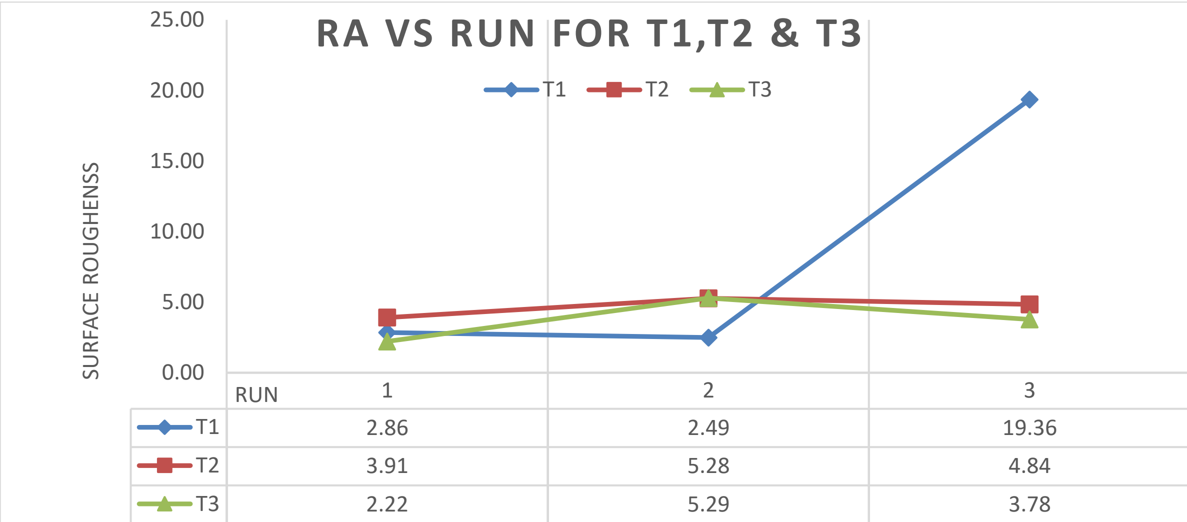

Figure 5: Average surface roughness, Ra result for all the types of router tool

Table 6: Result of Ra values

		1	2	3	4	5	Avg. (µm)
	R1	3.167	3.77	3.074	3.529	0.755	2.86
T1	R2	2.409	2.174	2.57	2.33	2.991	2.49
	R3	16.174	25.828	17.662	9.693	27.43	19.36
	R1	4.093	7.11	3.493	0.564	4.292	3.91
T2	R2	6.694	5.818	5.634	3.98	4.249	5.28
	R3	4.397	4.872	4.966	3.76	6.225	4.84
	R1	2.47	2.248	2.593	1.46	2.335	2.22
T3	R2	4.808	5.466	5.916	6.643	3.625	5.29
	R3	2.632	2.402	4.791	3.785	5.287	3.78

Figure 6 and 7 illustrate the photomicrograph taken by optical microscope to explain further the result of surface roughness, Ra as described in Figure 5. It appears that the trimmed surface by T1 with the spindle speed, N 7579 rpm and feed rate, V_f 1137 mm/min clearly exhibits uncut fibers and fibers pull-out condition compared to the trimmed surface by T3 with same spindle speed but only little difference on feed rate applied which stated at 758 mm/min. Significant defects such as fiber pull-out and matrix degradation were found mostly to due to thermal effects [6], [10]. By looking at the details of the tool geometry for both mentioned tools (T1 & T3), T1 has more number of flutes compared to the T3 (*refer Table 3*). On the other hand, T1 has the same helix angle for both right and left flutes whilst T3 has various helix angle for both flutes. Therefore, an important conclusion could be drawn from the finding of this work which concluded that tool geometrical feature especially the variation number of teeth or flute for router type tool might affecting the result of surface quality during edge trimming of a specific CFRP material. This finding is consistent with findings of past studies by Souhir Gara and Oleg Tsoumarev, which reveals that the transverse roughness does not depends on cutting conditions, it depends only on tool geometry. Contrary to the longitudinal roughness which was not only depending on the tool geometry but also the cutting conditions. They also found that feed per tooth presents the highest statistical and physical influence on the surface roughness for knurled or router tool [14]–[16].

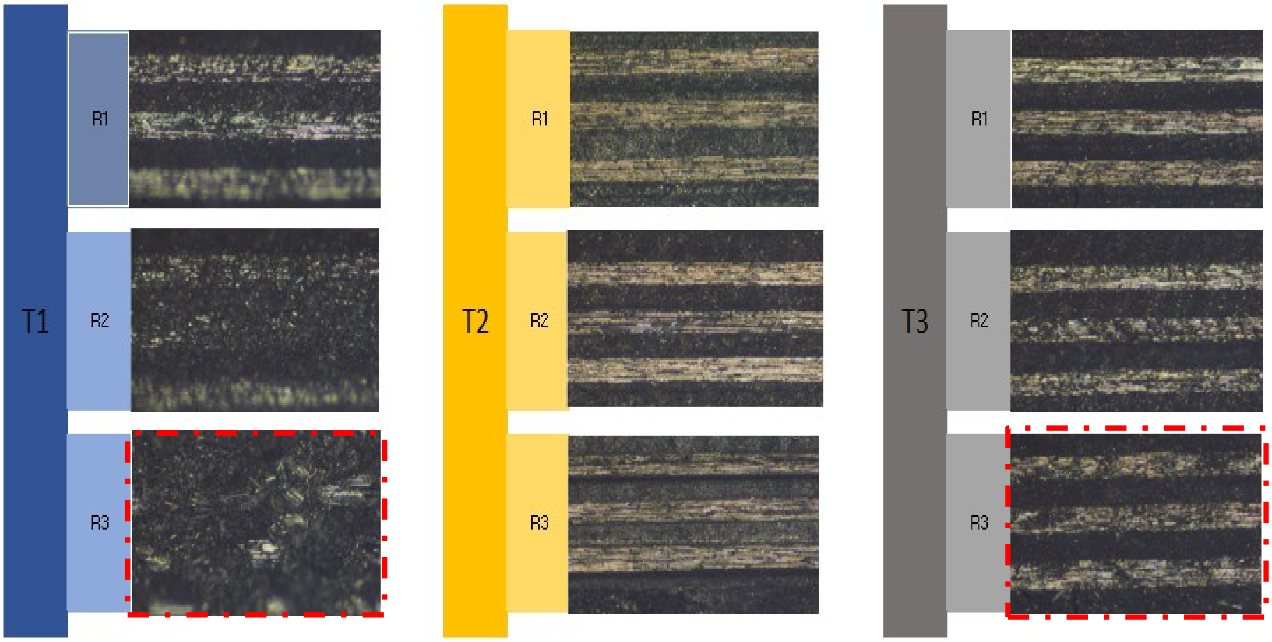

Figure 6: Photomicrographs taken by optical microscope with 100X magnification on the trimmed surface

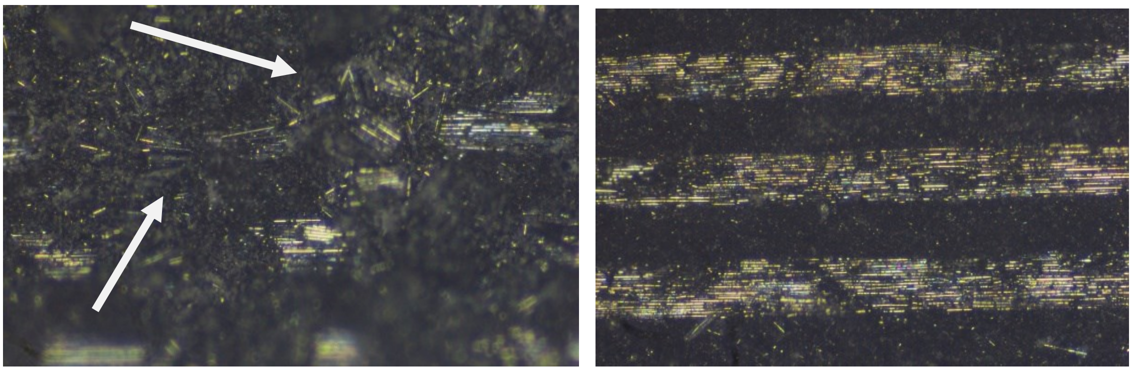

Figure 7: Obvious uncut fibers and fibers pull-out condition observed in R3 (T1) (left); better trimmed surface with slight uncut fibers observed in R3 (T3)

4. Conclusion

This paper presented results of surface roughness analysis, Ra as well as further trimmed surface observation utilizing optical microscopy method on edge trimming of CFRP composite with various tool geometrical features (router or burrs tool). The following points emerged from the present investigation are as follows:

i. At the same spindle speed applied, the surface roughness result based on the averaged Ra value at Run no. 3 (R3) for tool type T3 was approximately 4 times better than tool type T1 although the feed rate applied was only 379 mm/min or 33.33% different.
ii. From further observation carried out via optical microcopy, uncut fibers and fibers pull-out condition were clearly spotted on the trimmed surface of T1 but not so obvious on the trimmed surface of T3.
iii. Looking at the tool geometrical feature, T1 has more number of flutes compared to the T3 as well as same helix angle for both right and left flutes whilst T3 has various helix angle for both flutes.

Ultimately, the tool geometrical feature especially the variation number of teeth or flute for router type tool might affecting the result of surface quality during edge trimming of a specific CFRP material.

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