Tribology Online
Japanese Society of Tribologists
http://www.tribology.jp/trol/

Vol. 15, No. 2 (2020) 53-59.
ISSN 1881-2198
DOI 10.2474/trol.15.53

Article

Effect of Machining Parameters on Surface Roughness in Edge Trimming of Carbon Fiber Reinforced Plastics (CFRP)

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Manuscript received 22 March 2019; accepted 02 December 2019; published 30 April 2020
Presented at the International Tribology Conference Sendai 2019, 17-21 September, 2019

Abstract

The main aim of this research was to investigate the effect of machining parameters towards surface quality during edge trimming process on a specific CFRP material. There were two variation of machining parameters focused in this work namely spindle speed (N) and feed rate (V_f). The CFRP panel is measured 3.25 mm in thickness and the type of fabric was unidirectional (UD). It has 28 number of plies in total and were arranged multi-directional. Router or burr tool geometry made of uncoated tungsten carbide with a diameter of 6.35 mm was used to perform the edge trimming process. 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 the smallest value of the surface roughness (1.31 μm) is obtained by Run 8 (R8) which the spindle speed, N applied was 2506 rpm and feed rate, V_f at 376 mm/min. Meanwhile, the highest surface roughness value (12.62 μm) exhibited by the R9 which had the highest setting of spindle speed, N 7518 rpm and the highest feed rate, V_f 1128 mm/min. The result is supported by the observation of trimmed surface through optical microscopy which clearly exhibits uncut fibers and matrix degradation condition. Details results elaborated and discussed further in this paper.

Keywords

CFRP, machining parameters, edge trimming, surface roughness

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. 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.

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 [3–8]. 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.

Koplev et al. and W. Konig et al. were among the earliest researchers who performed experimental studies in composite machining. They have recommended that routers with the "diamond cut" / burrs tool geometry for glass and carbon fibers and opposed helical design for aramid fibers generated the best results. Authors also agreed the practical problems of machining FRP were the avoiding of material damages like burning and delamination issues [9]. They also observed that during machining of Unidirectional (UD) CFRP perpendicular to the fiber, the surface is destroyed and cracks are formed. Machined or trimmed surface was found to be smoother and the cracks reached one or two of fiber diameters into the composites when the CFRP is machined parallel to the fiber [10]. In another research carried out by M. Ucar and Y. Wang discovered that the chips removed from CFRP are in discontinuous scrap or powder forms because CFRP is brittle and the removed chips are fractured instead of being elastically and plastically deformed. In addition, surface roughness was found to decrease as the cutting speed, V_c increased and as the feed rate, V_f decreased. The larger the feed rate the larger the cutting force due to the chip thickness [11]. M.K. Nor Khairusshima et al. has performed optimization study on milling of CFRP material applying statistical approach (RSM) utilizing helical helix tool geometry. They reported that the feed rate, V_f was the most significant factor affecting surface roughness and delamination factor of the CFRP [12]. Haijin Wang et al. concluded that cutting speed, V_c was the key factor which influences the cutting temperature in milling of CFRP composite materials, followed by feed rate, V_f and radial depth of cut. Meanwhile, feed rate, V_f was the key parameter which influences the cutting force in milling of CFRP composite materials, followed by cutting speed, V_c and radial depth of cut, a_e. As for the Polycrystalline Diamond (PCD) tool, low cutting speed, minimum feed rate, and maximum radial depth of cut are preferred to obtain good surface quality and high material removal rate (MRR) [13]. In different work by S. Ghafarizadeh et al. discovered that by utilizing a PCD two-flute ball nose end mill, the surface roughness increases with an increase in the feed rate, V_f as well as the cutting forces. Negative lead angle led to increases of instability of the roughness result. In contrary, positive lead angle produces higher cutting forces [14]. In more recent year Nor Farah Huda Abd. Halim et al. carried out an experimental investigation on Ultrasonic Assisted Machining (UAM) and Conventional Machining (CM) using three fluted polycrystalline-diamond (PCD) tools employing constant cutting speed, V_c (500 m/min) and feed rate, V_f (0.8 m/min). Authors discovered that tool wore out faster during UAM than conventional milling. This was believed due to the effect of ultrasonic vibration on the cutting tool generated more friction effect between the tool and cutting surface. In addition, average surface roughness reported for UAM was higher between 5 to 25% than conventional milling [15].

In different research by 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 or feed rate, V_f. 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 (HSM) which strongly believed due to thermal effects. Feed rate 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 [16]. N. Duboust et al. introduced the new optical method to measure surface roughness and damage of machined composite surfaces. Authors proved the surface roughness increased with machining distance generally following a steady trend. They also reported 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, V_f in comparison with polycrystalline diamond (PCD) tool [17, 18]. Souhir Gara and Oleg Tsoumarev performed a series of comparison study on a few different micro-grain of burr tool which categorized into fine, medium and coarse type in slotting CFRP material. Authors discovered 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, F_z was found to be the highest statistical and physical influence on the surface roughness for knurled or burr tool. Fine toothing of burr 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 [19, 20].

It is quite apparent from the reviews above that there is a paucity of research efforts that provide a clear insight into the relationship between surface finish of the trimmed surfaces with machining parameters namely spindle speed, N / cutting speed, V_c and feed speed / feed rate, V_f in edge trimming of CFRP material. This research initiated was to investigate the effect of the two chosen machining parameters (spindle speed, N and feed rate, V_f) towards trimmed surface quality of a specific CFRP material utilizing burrs tool geometry. The trimmed surfaces were successfully analysed by using surface tester measurement equipment to obtain the average surface roughness value, Ra. Moreover, a thorough observation has been carried out by adopting microscopy equipment to understand what was really happening on the machined surfaces.

2 Methodology

2.1 Material

The workpiece material (CFRP panel) for the experiment was provided by local aerospace composite manufacturing industry. The CFRP panel measured 3.25 mm in thickness and the type of fabric was unidirectional (UD). It has 28 number of plies in total which consist of 2 thin layer of glass/epoxy woven fabrics 0.08 mm were then used at the top and bottom of the CFRP laminate play the role of protecting the outer surfaces of the panel. The 26 unidirectional plies were made of carbon/epoxy prepreg manufactured by Hexcel Composite Company. The stacking sequence was $[45/135/90_2/0/90/0/90/0/135/45_2/135]s$. The nominal fiber volume fraction is 60%. Table 1 illustrates the overall specification of CFRP material used in this work.

Table 1 CFRP details

Composite composition	No of Ply	Areal Density	Fabric Type	CPT/Ply
Carbon	26	203 g/m³	Unidirectional	0.125
Glass	2	107 g/m³	Woven	0.08
Total thickness (mm)				3.25

2.2 Cutting tool

The type cutting tool used in this work was router or burr tool made of tungsten carbide (uncoated) and diameter 6.35 mm (refer Table 2). Figure 1 indicates the geometrical feature of the burrs tool used in this research.

2.3 Machine specification

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

2.4 Machining parameters

There were two variation of machining parameters focused in this work namely spindle speed (N) and feed rate (V_f). The range of spindle speed applied was 2506 rpm (low), 5012 rpm (moderate), and 7518 rpm (high) speed whilst for the feed rate was between 125 mm/min to 1128 mm/min depending on the feed per revolution, f_z; 0.05, 0.1, and 0.15 mm/rev. Relationship between cutting speed (V_c), spindle speed (N), feed per revolution (f_z) and feed rate (V_f) are given Equations below. Table 4 represents the machining parameters applied in this work.

$$V_c = \frac{\pi \times D \times N}{1000} \tag{1}$$

$$f_z = \frac{V_f}{N} \tag{2}$$

Where, V_c = cutting speed, D = diameter of cutting tool, N = spindle speed, f_z = feed per revolution, V_f = feed rate,.

2.5 Fixture design and preparation

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 illustrates the CAD design as well as the final assembly of fabricated fixture before the real physical edge trimming process.

2.6 Surface roughness measurement

Surface roughness plays a major role in specifying surface finish of machined CFRP material in production. Machining processes can rapidly change the surface layer, which results in a change of mechanical properties of the composite. Spindle speed / cutting speed, feed rate, cutting forces as well as tool geometry were among the highly-influenced factors affecting the surface quality. Surface roughness tester; Surftest SJ-410 manufactured by Mitutoyo is used to measure the surface finish of the workpiece. In this study, Ra (Arithmetical mean deviation) is referred to measure the surface roughness. Longitudinal surface roughness is evaluated with the stylus travel distance set at 4 mm on each measurement. There were 5 points of measurement taken on every machined surface and final average Ra is obtained to represent the result of surface finish on every specimen. Figure 3 indicates the SJ-410 roughness tester and the display unit.

Table 2 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	10	10	10	30	30	75

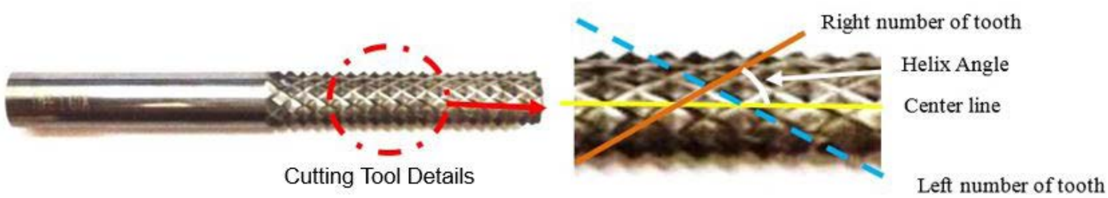


Fig. 1 Details of tool geometrical design

Table 3 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

Table 4 Machining parameters

Run (R)	Cutting Speed, V_c (m/min)	RPM	Feed per Tooth, f_z (mm)	V_f mm/min
1	50	**2506**	0.05	**125**
2	100	**5012**	0.15	**752**
3	50	**2506**	0.1	**251**
4	100	**5012**	0.05	**251**
5	100	**5012**	0.1	**501**
6	150	**7518**	0.1	**752**
7	150	**7518**	0.05	**376**
8	50	**2506**	0.15	**376**
9	150	**7518**	0.15	**1128**

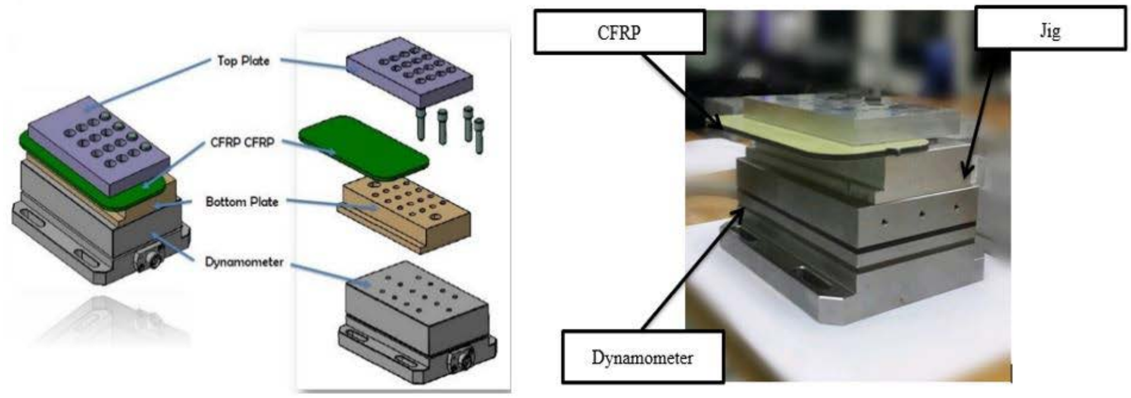


Fig. 2 (a) to (left) CAD view of the jig with CFRP plate, (b) to (right) final fixture assembly preparation

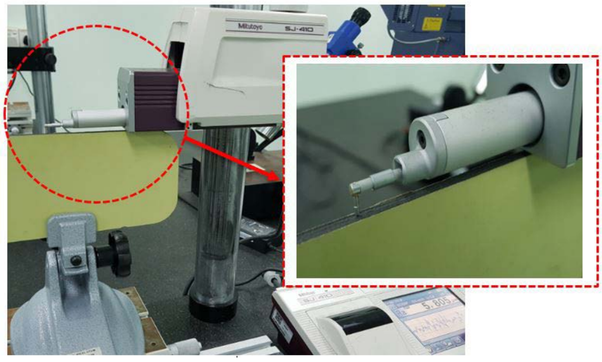


Fig. 3 SJ-410 roughness tester and the display unit

Meanwhile, Nikon MM-800 optical microscope is utilized to observed the details of the surface finish on every trimmed surface. The magnification range is between 1x magnifications to 100x magnification. Therefore, it helps in identifying tool wear or damages as well as explains better on what is really happening 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.

3 Result and discussion

Figure 5 presents the result of averaged longitudinal surface roughness, Ra values for Run 1 (R1) until Run 9 (R9) from the data obtained shown by Table 5. It is obviously seen that the smallest value (1.31 μm) of the surface roughness is obtained by Run 8 (R8) which the spindle speed, N applied was 2506 rpm and feed rate, V_f at 376 mm/min. Meanwhile, the highest surface roughness value (12.62 μm) exhibited by the R9 which has the highest setting of spindle speed, 7518 rpm and the highest feed rate, 1128 mm/min. Looking at the two sets of identical feed rate (R2 & R6 = 752 mm/min, R7 & R8 = 376 mm/min) it could be summarized that an increase in spindle speed will increase the value of surface roughness. In other words, surface roughness increases proportionally with increase in spindle speed.

Figures 6 and 7 illustrate the photomicrograph taken by optical microscope to describe further the result of surface roughness, Ra as illustrated in Fig. 5. It appears that the trimmed surface of R9 at spindle speed, N 7518 rpm and feed

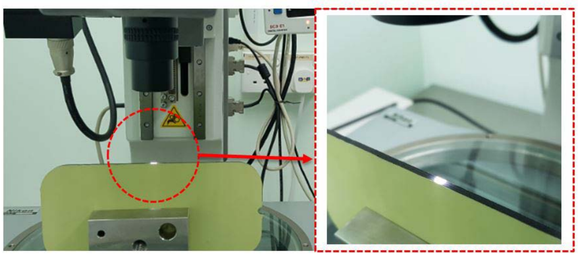


Fig. 4 Observation of damages on trimmed surfaces by Nikon MM-800

Table 5 Overall surface roughness data

RUN	1	2	3	4	5	Avg.
R1	1.95	1.28	0.94	2.80	1.11	**1.62**
R2	7.57	7.79	6.50	9.35	2.44	**6.73**
R3	4.59	4.14	2.43	2.43	2.63	**3.25**
R4	2.50	2.46	2.42	2.95	3.06	**2.68**
R5	2.80	3.92	8.09	6.98	4.59	**5.28**
R6	7.43	7.55	9.23	7.45	8.89	**8.11**
R7	2.30	3.66	3.93	3.97	4.34	**3.64**
R8	1.07	1.33	0.98	1.41	1.77	**1.31**
R9	15.72	13.33	10.68	13.33	10.03	**12.62**

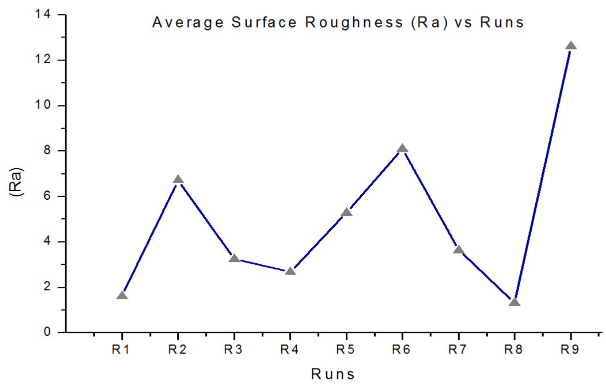


Fig. 5 Surface roughness, Ra result (averaged Ra values)

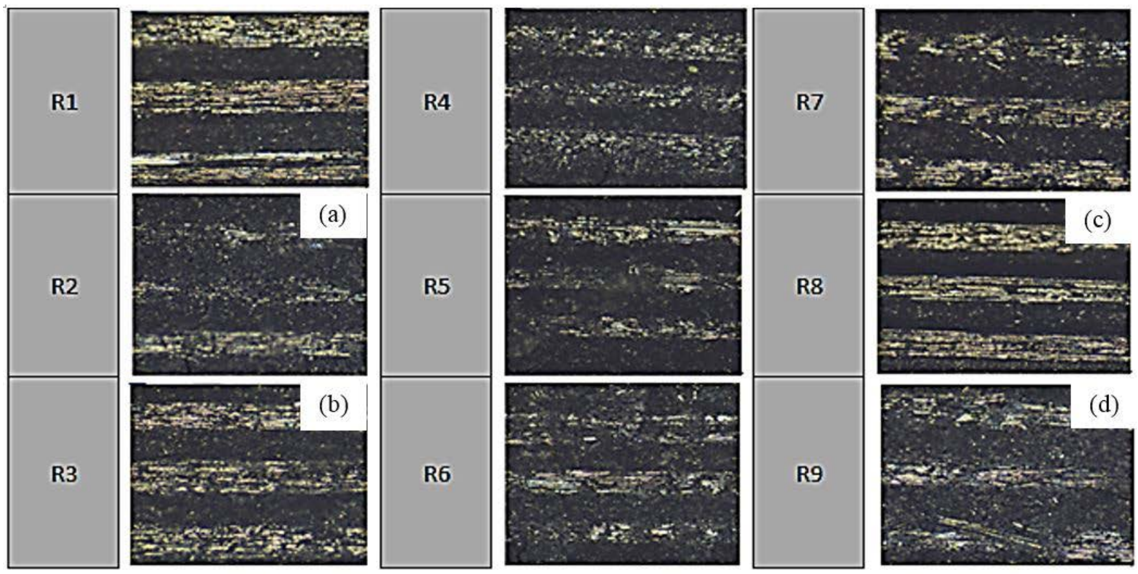


Fig. 6 Photomicrographs taken by optical microscope on the trimmed

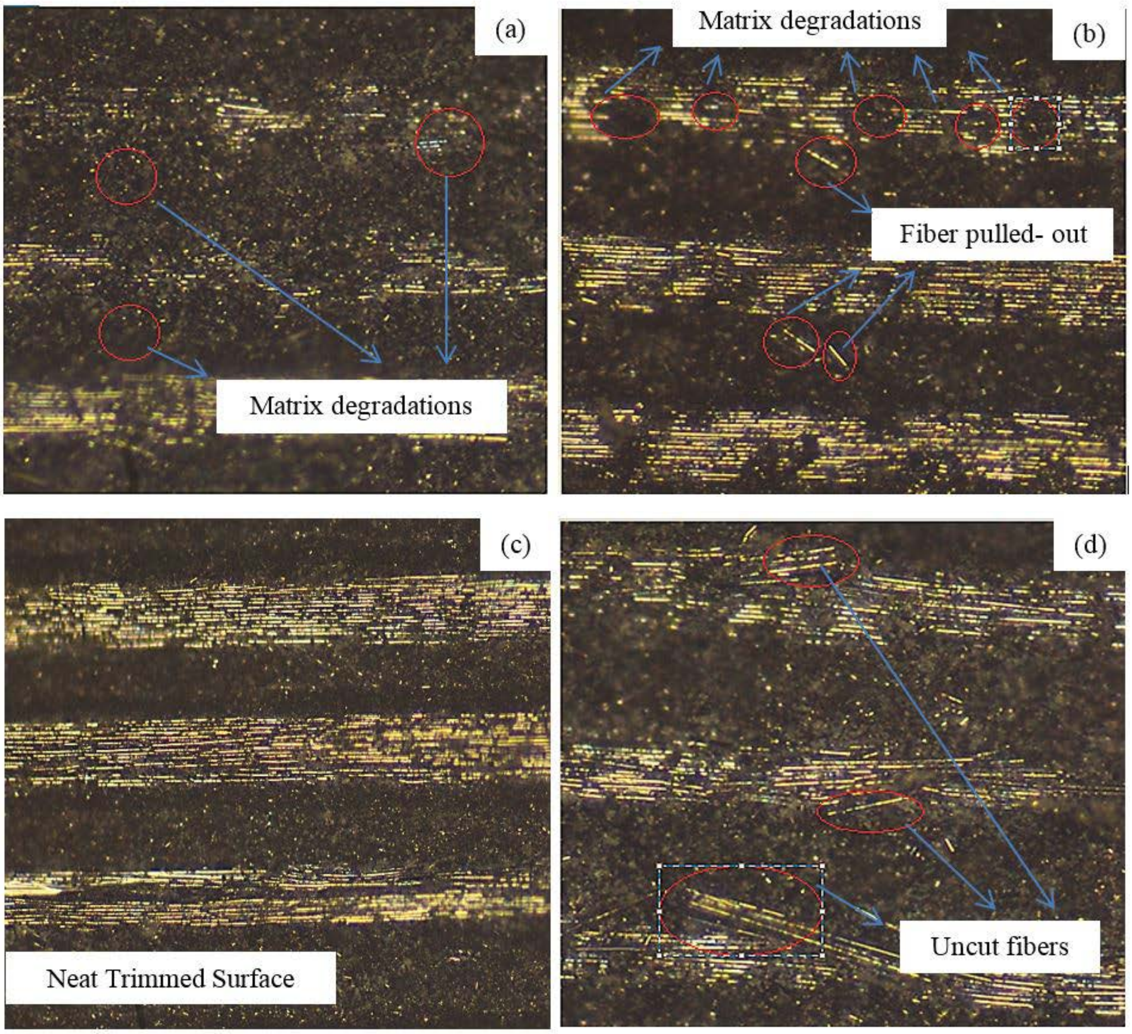
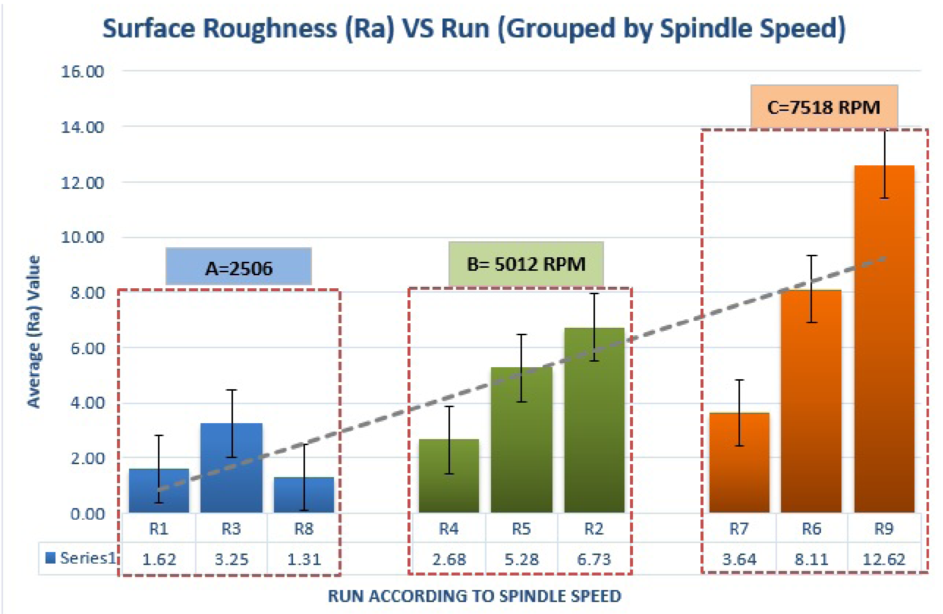


Fig. 7 Enlarged of photomicrographs taken on the trimmed surface for various machining parameters; (a) N = 5012 rpm, V_f = 752 mm/min (b) N = 2506 rpm, V_f = 251 mm/min (c) N = 2506 rpm, V_f = 376 mm/min (d) N = 7518 rpm, V_f = 1128 mm/min



Run	RPM	mm/min
1	2506	125
2	5012	752
3	2506	251
4	5012	251
5	5012	501
6	7518	752
7	7518	376
8	2506	376
9	7518	1128

Fig. 8 Ra data grouped into spindle speed & feed rate

rate, V_f 1128 mm/min clearly exhibits uncut fibers condition. Signs of matrix degradation, uncut fiber and fiber pull-out were obviously spotted on the visual of photomicrograph of R2 and R3. The spindle speed applied for R2 was 5012 rpm and feed rate at 752 mm/min. R3 had approximately half of the spindle speed, 2506 rpm and lower feed rate 251 mm/min. Significant defects such as fiber pull-out and matrix degradation were found mostly due to thermal effects [6, 16]. A neat and better trimmed surface finish was obtained by the R8 which the spindle speed and feed rate applied were 2506 rpm and 376 mm/min respectively. This finding provides evidence that spindle speed is the most prominent factor effecting the trimmed surface quality of CFRP material which indirectly supporting the result presented by Fig. 5. This finding is consistent with findings of past study by S.A Sundi et al (2019) which reported that spindle speed was found to be the main influential factor towards surface finish in edge trimming CFRP material [21, 22].

Figure 8 presents three (3) groups of Run according to the identical spindle speed, N which are labelled by A; 2506 rpm (R1, R3 & R8), B; 5012 rpm (R4, R5 & R2) and C; 7518 rpm (R7, R6 & R9). The sequence of groups were arranged ascending based on the spindle speed and feed rate, V_f applied. Dashed-line across the figure indicates the overall trend obtained when increasing the spindle speed, N and the feed rate, V_f towards the Y-axis (the surface roughness value, Ra) in edge trimming of CFRP material. In general, an important conclusion could be drawn from this result; an increases in spindle speed as well as the feed rate decreases surface quality of the trimmed surfaces. Therefore, minimum spindle speed and feed rate settings are preferred to obtain better trimmed surface quality. This finding is seems to be agreed with the research done by M. Haddad et al. which summarized that the quality of the machined surface is mainly affected by the cutting speed, V_c or spindle speed, N (refer Eq. (1)) [23]. In addition, feed speed or feed rate, V_f was found to be the major parameter affecting surface roughness under standard cutting conditions [16].

4 Conclusions

This paper presented results of surface roughness analysis, further trimmed surface observation utilizing optical microscopy method, tool wear observation and cutting forces on the edge trimming of CFRP composite with burrs tool geometry. The following points emerged from the present investigation are as follows:

a) The smallest value of the surface roughness (1.31 μm) is obtained by Run 8 (R8) which the spindle speed, N applied was 2506 rpm and feed rate, V_f at 376 mm/min. Meanwhile, the highest surface roughness value (12.62 μm) exhibited by the R9 which has the highest setting of spindle speed, 7518 rpm and the highest feed rate, 1128 mm/min.
b) The result above is supported by the observation of trimmed surface through optical microscopy which clearly exhibits the sign of matrix degradation, uncut fiber and fiber pull-out on the R9 photomicrograph. Contrary, a neat and better trimmed surface finish was shown by the R8 photomicrograph.

Ultimately, this research has proven that the variation in cutting parameters impacted the result of damages during edge trimming of CFRP material. Furthermore, lower spindle speed, N and feed rate, V_f settings are preferred to obtain a minimized surface quality in edge trimming of a specific CFRP material.

Acknowledgments

Authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) and Ministry of Education (MOE) for their financial support. The research was funded by Fundamental Research Grant (FRGS) Grant No. FRGS/2018/FKP-AMC/F00378.

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