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Statistical Analysis on the Effect of Machining Conditions towards Surface Finish during Edge Trimming of Carbon Fiber Reinforced Plastics (CFRP)

S. A. Sundi[1*], R. Izamshah[2], M. S Kasim[2], S. Ding[3] and M. F. Jaafar[2]

[1]*Faculty of Mechanical and Manufacturing Engineering Technology, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.*
[2]*Advanced Manufacturing Center (AMC), Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.*
[3]*School of Engineering, RMIT University, VIC 3083, Australia.*

ABSTRACT

The main aim of this work was to investigate the effect of machining conditions namely cutting speed (V_c) and feed per tooth (f_z) towards the surface finish during the edge trimming process on a specific CFRP material. The range of cutting speed (V_c) applied was 50 m/min (low), 100 m/min (middle) and 150 m/min (high) whilst for the feed per tooth (f_z); 0.05 mm (low), 0.10 mm (middle) and 0.15 mm (high). The CFRP panel is measured 3.25 mm in thickness and has 28 plies in total. Router or burr tool made of uncoated tungsten carbide with a diameter of 6.35 mm is used to perform the edge trimming process. The Taguchi technique has been adopted to plan the overall experimental process. Surface roughness measurement was taken using Mitutoyo Surftest SJ-410 and optical microscope Nikon MM-800 is utilized to further observe the quality of the trimmed surfaces. From the ANOVA analysis, both factors namely cutting speed, V_c and feed per tooth, f_z indicated a significant result towards the surface finish of the trimmed surfaces. The result is supported by the observation via optical microscopy which clearly exhibits uncut fibers, fiber pull-out and matrix degradation conditions. Detailed results are elaborated and discussed further in this paper.

Keywords: CFRP, Machining Conditions, Edge Trimming, Surface Finish.

1. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) laminates are extensively used in today's industries such as aerospace, defense, automotive and shipping industries due to their lightweight, high modulus and high specific strengths. 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). Although, composite components are often made near-net shape, some machining is often unavoidable. Machining is an indispensable process for shaping parts from stock composite materials and for finishing tight dimensional accuracy shapes.

Machining composite materials is hard to perform due to the mechanical, thermal properties and the high abrasiveness of the reinforcement constituents. The behavior of composites such as its inhomogeneity and interaction with the cutting tool whilst machining is a complex phenomenon to be understood. Machining may possibly cause quality issues of the machined composite part such as delamination, cracking, fiber pull-out, and burned matrices. All of these complexities which is related to the composites machining require great attention from researchers and industries in order to establish better a manufacturing environment [1]–[3].

*Corresponding Author: *syahrul.azwan@utem.edu.my*

Haddad et al. reported that defects on trimmed surface tend to increase with an increase in the feed speed. A few mechanical damages such as fiber pulled-out with matrix degradation in some areas were spotted through scanning electron microscope (SEM) images at high speed machining which was strongly believed to be due to thermal effects. Feed speed was found to be the major parameter affecting surface roughness under standard cutting conditions [4]. *Duboust et al.* proved that the feed rate and tool type had the most significant effect on the surface quality. Fiber orientation also plays an important role in the chip removal mechanism and surface damage [5], [6]. *Ahmet Can* presented the transverse and longitudinal arithmetic average of the surface roughness obtained by inclined machining position that is better than vertical machining in all cutting conditions. [7]. *Nor Khairusshima et al.* has performed an optimization study on milling of CFRP material applying statistical approach (RSM) presented that feed rate was the most significant factor affecting surface roughness and delamination of the CFRP material using end mill helical helix tool [8]. *Sheikh-Ahmad et al.* analyzed that surface roughness in the longitudinal direction increased with an increase in feed rate and a decrease in spindle speed, which was believed to be due to an increase in the effective chip thickness. Meanwhile, surface roughness in the transverse direction reported to show no clear trends and generally higher than the longitudinal direction [9]. Another study by *Haddad et al.* indicated that the quality of the machined surface is mainly affected by the cutting speed followed by the cutting distance. The increase of the feed speed or the cutting distance induces higher cutting forces [10]. *Haijin Wang et al.* concluded that cutting speed was the key factor which influences the cutting temperature in milling of CFRP composite materials, followed by feed rate and radial depth of cut. *Sundi et al.* revealed that the tool geometrical feature especially the variation number of teeth or flute for router type tool might affect the results of surface quality during edge trimming of a specific CFRP material [11], [12]. In more recent years, a comparison of Multi-tooth (MT) or burr tool and Up-Down or Compression Router (UD) on cryogenic condition was successfully examined by *Cunningham et al*. who concluded that cryogenic machining improves the average surface roughness as well as delamination length for both mentioned tool geometries [13].

The main objective of this study was to investigate the effect of machining conditions namely cutting speed (V_c) and feed per tooth (f_z) on the surface quality of edge trimming for a specific CFRP material utilizing burr tool. The trimmed surfaces were successfully analyzed by using surface tester measurement equipment in order to obtain the average surface roughness value, Ra. Moreover, further 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 CFRP panel measured 3.25 mm in thickness and the type of fabric was unidirectional (UD). Total number of plies was 28 in total. There were two thin layers of glass/epoxy woven fabrics 0.08 mm used at the top and bottom of the CFRP to protect the outer surfaces of the panel. The 26 unidirectional plies were made of carbon/epoxy preparation 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	Type of Fiber	CPT/Ply
Carbon	26	203 g/m^3	Unidirectional	0.125
Glass	2	107 g/m^3	Woven	0.08
Total thickness (mm)				3.25

2.2 Cutting Tool

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

Figure 1. Burr or router tool geometry; CAD model (top); actual tool (bottom).

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

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.

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

2.4 Design of Experiment

Taguchi method (Orthogonal Array L9) one of the statistical techniques has been adopted to plan the overall experiment. Analysis of variance (ANOVA) was successfully performed at the end of the data analysis to determine the significant factors / machining conditions which influenced the result of surface finish.
There were two variation of machining parameters focused on this work namely spindle speed (N) and feed rate (V_f). The range of spindle speed applied was 50 m/min (low), 100 m/min (middle), and 150 m/min (high) whilst for the feed per tooth, f_z; 0.05, 0.1, and 0.15 mm. Relationship between cutting speed (V_c), spindle speed (N), feed per tooth (f_z) and feed rate (V_f) are given by the formulas below. Table 4 represents the machining conditions applied in this research.

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

$$fz = \frac{Vf}{N} \tag{2}$$

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

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

2.5 Fixture Design & 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. 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 was performed with 100% 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. Down milling has been selected as the mode of machining configuration. Total travel distance of each run was 260 mm.

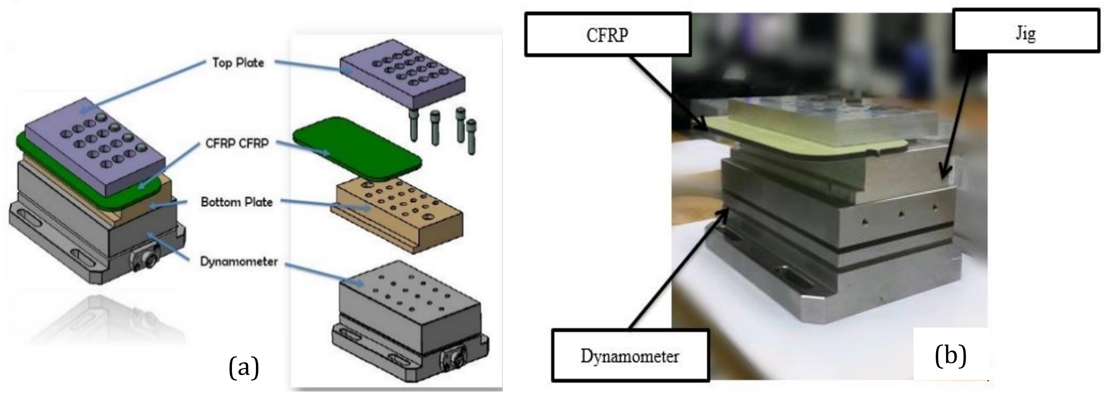

Figure 2. (a) CAD view of the jig with CFRP plate, (b) final fixture assembly preparation.

2.6 Surface Roughness Measurement

A surface roughness tester; Surftest SJ-410 manufactured by Mitutoyo was used to measure the surface finish of the workpiece. In this study, Ra (Arithmetical mean deviation) is referred to as the measure of surface roughness. Longitudinal surface roughness is being 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 was obtained to represent the result of surface finish on every specimen. Figure 3 indicates the SJ-410 roughness tester and the display unit.

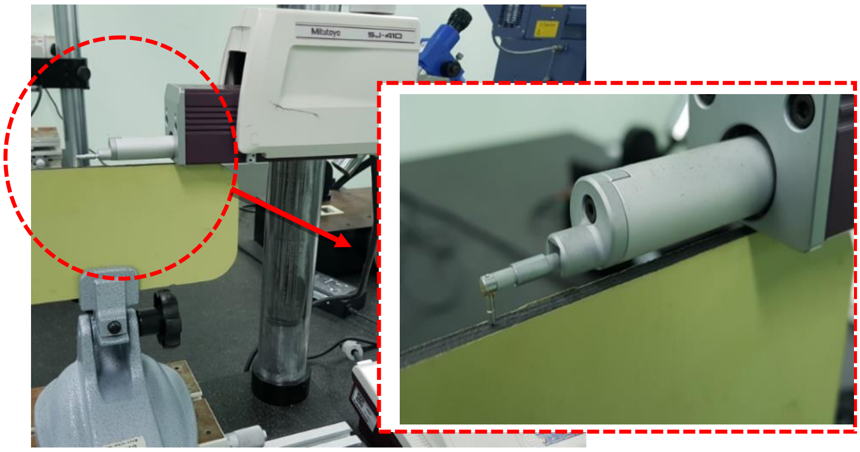

Figure 3. SJ-410 roughness tester and the display unit.

Meanwhile, Nikon MM-800 optical microscope was utilized to observe the details of the surface finish on every machined surface that were also observed by using the same microscope. The magnification range is between 1x magnification to 100x magnification. Therefore, it helps in identifying tool wear or damages as well as explains better what is really happening on the trimmed surfaces. Whilst the specimen was put under the microscope, the data processing software, E-max which was connected to a personal computer captured the required images. Figure 4 indicates the Nikon MM-800 microscope.

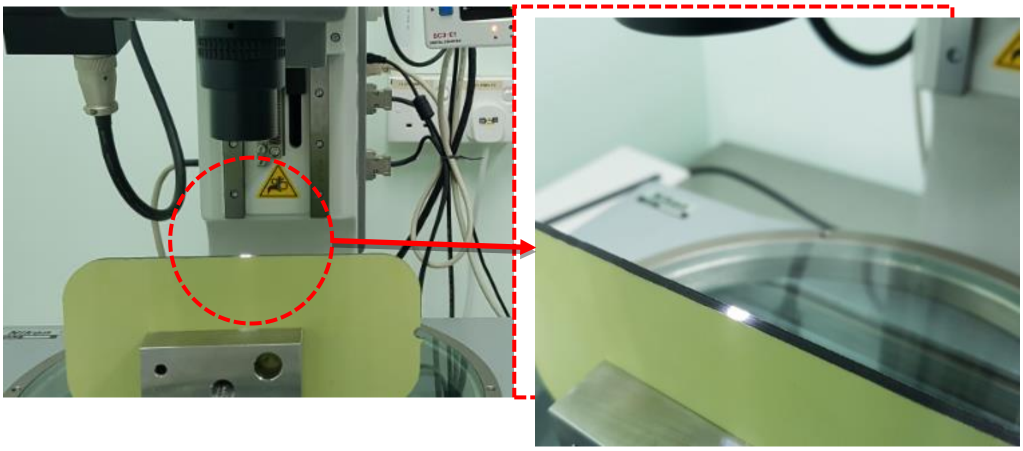

Figure 4. Observation of damages on trimmed surfaces by Nikon MM-800.

3. RESULT AND DISCUSSION

3.1 Surface Roughness Measurement and Observation

Figure 5 presents the results of averaged longitudinal surface roughness, Ra values for Run 1 (R1) until Run 9 (R9). The data has been grouped into three (3) groups of identical cutting speed, (V_c) which are group no.1; 50 m/min (R1, R3 & R8), group no. 2; 100 m/min (R4, R5 & R2) and group no. 3; 150 m/min (R7, R6 & R9). The sequences of Runs were arranged by feed per tooth, (f_z) settings ascendingly from left to right. The lowest averaged value (1.31μm) was obtained by Run 8 (R8) which the cutting speed, (V_c) applied was 50 m/min and feed per tooth, (f_z) at 0.15 mm. Meanwhile, the maximum value of surface roughness (12.62 μm) exhibited by the R9 which has the highest setting of cutting speed, (V_c) 150 m/min at the same feed per tooth, (f_z) as R8; 0.15 mm. In general, it could be seen that the higher the cutting speed, (V_c) the higher the surface roughness value is, Ra as illustrated by the dashed line. A similar trend could also be observed from the increases of the feed per tooth, (f_z). The quality of the trimmed surface showed a gradual decrease with the increase of the feed per tooth, (f_z) value. Therefore, an important conclusion could be drawn from this result; an increase in cutting speed, (V_c) as well as the feed per tooth, (f_z) shall worsen the surface quality of the trimmed surfaces on a specific CFRP material. This finding is in slight contrast with the research done by *M. Haddad et al.* which summarized that the quality of the machined surface was mainly affected by the cutting speed followed by cutting distance. Meanwhile, the increase of the feed speed or the cutting distance induces higher cutting forces [10]. In another study by *J.Y Sheikh-Ahmad and A.H Shahid,* it was *reported* that surface roughness and delamination depth increased with an increase in feed speed and a decrease in cutting speed. This was believed to correspond to the increase in effective chip thickness during trimming [14].

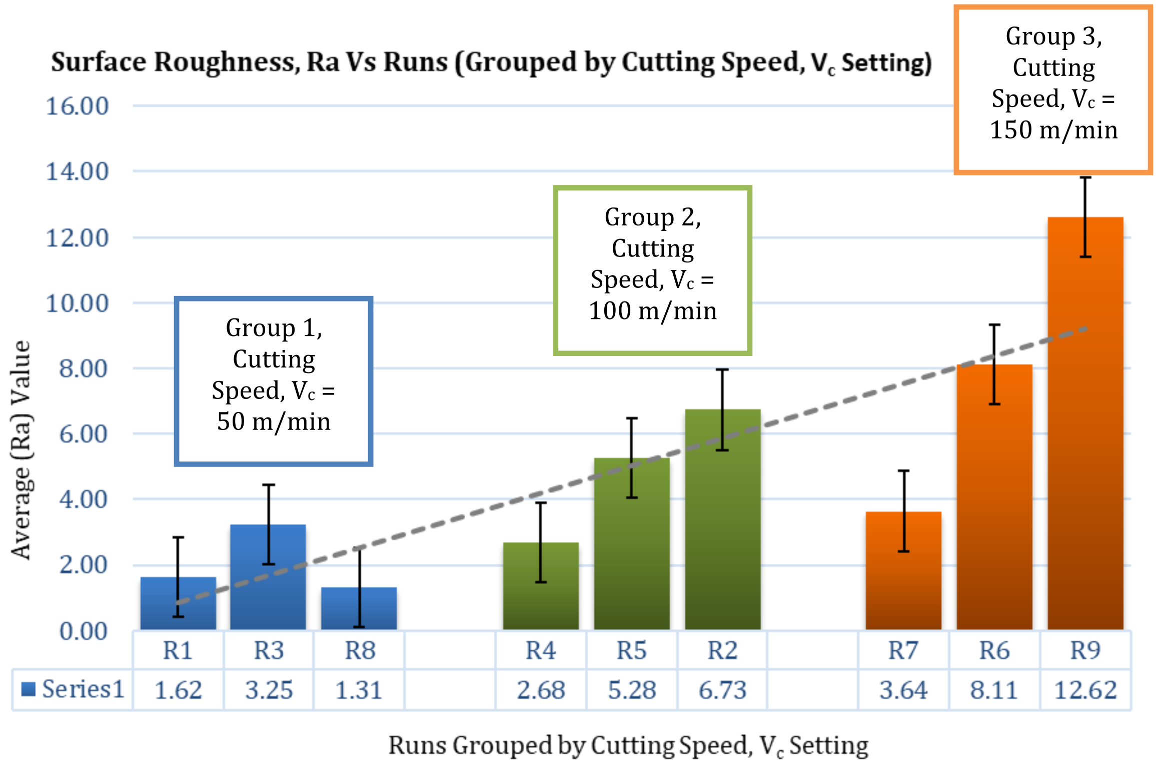

Figure 5. Surface roughness, Ra result grouped in cutting speed, V_c and arranged by feed per tooth, f_z ascendingly.

Figure 6 and 7 show the photomicrographs taken by the optical microscope to further explain the result of surface roughness, Ra as illustrated in Figure 5. It is obviously indicated that R9(**d**) at the highest cutting speed, (V_c) 150 m/min and feed per tooth, (f_z) 0.15 mm indicates obvious uncut fibers condition. The highest value of averaged Ra is possibly due to the amount of uncut fiber observed. On the other hand, a neat and better trimmed surface finish was obtained by the R8(**c**) which cutting speed, (V_c) applied was 50 m/min and feed per tooth, (f_z) 0.15 mm. Meanwhile, signs of severe matrix degradation were clearly identified on the visual of photomicrograph of R2(**a**). In addition, the visual of photomicrograph of R3(**b**) exhibits minor signs of matrix degradation and fiber pull-out. The cutting speed, (V_c) applied for R2 was 100 m/min and feed per tooth, (f_z) 0.15 mm. R3 had slower cutting speed, (V_c) 50 m/min as well as slower feed per tooth, (f_z) 0.10 mm. Significant defects such as fiber pull-out and matrix degradation were found mostly due to thermal effects [4], [15]. Due to increase of the friction between the cutting tool and the machined surface, the chip temperature increases. It gets higher when the feed per tooth is increased; with an increase in feed rate, the section of the chip becomes larger [16]. The chip is usually formed by plastic deformation of the respective material as its going through the shearing zone. When cutting polymers and their composites, elastic deformation plays a significant role in determining the cutting forces. Due to the elastic recovery, rubbing in this zone might be substantial and the resulting temperature rise may heat the polymer matrix above the glass transition temperature, T_g which may cause significant plastic flow in this region [1].

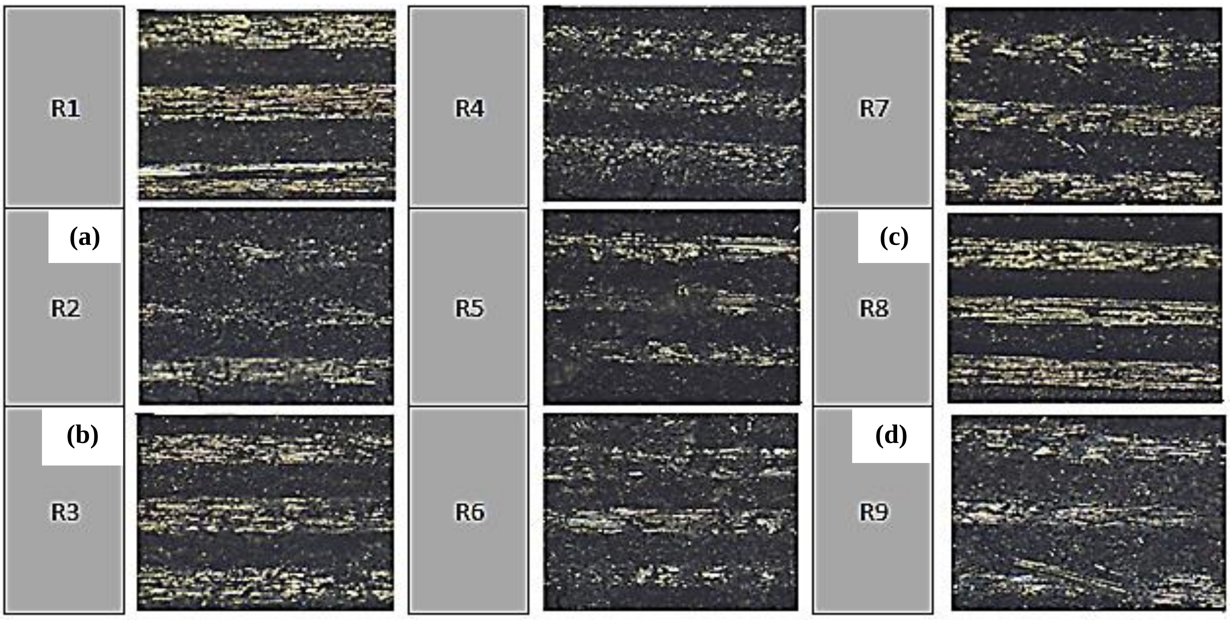

Figure 6. Photomicrographs taken by optical microscope on the trimmed surface.

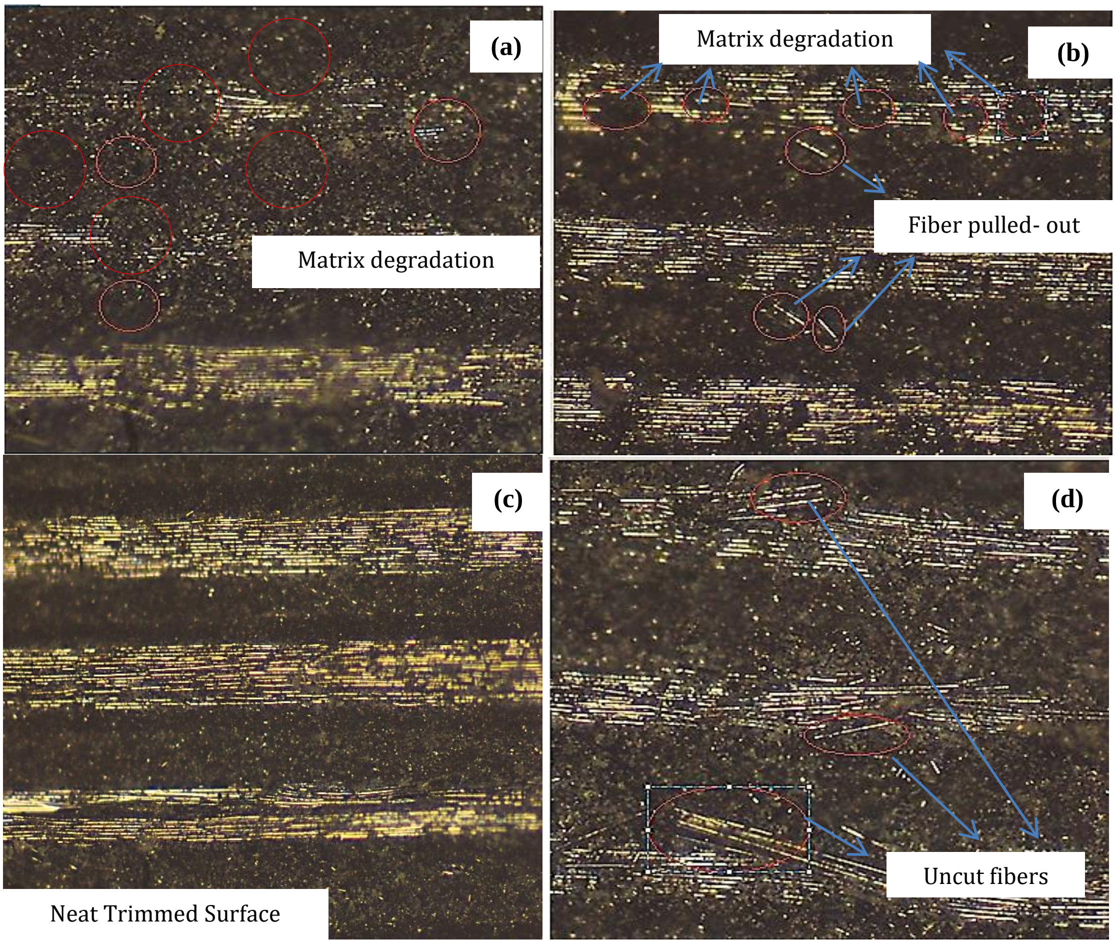

Figure 7. Enlarged of photomicrographs taken on the trimmed surface for various machining conditions; (a) V_c = 100 m/min, f_z = 0.15 mm (b) V_c = 50 m/min, f_z = 0.10 mm. (c) V_c = 50 m/min, f_z = 0.15 mm (d) V_c = 150 m/min, f_z = 0.15 mm.

3.2 Taguchi – ANOVA

Analysis of Variance (ANOVA) is carried out to determine which factor or machining parameter namely cutting speed, (V_c) and feed per tooth, (f_z) significantly affects the performance characteristics or selected response namely surface roughness. Tables 5 exhibits the result of ANOVA analysis for the average Ra values during the edge trimming process of a specific CFRP chosen as described in this work. This analysis was computed for a level of confidence of 95 %. The Model F-value shows 10.800 which implies the model is significant. There is only a 2.03% chance that a "Model F-Value" this large could occur due to noise. Thus, both factors; A = cutting speed and B = feed per tooth have significant effect to the chosen response; surface finish. Meanwhile, Figure 8 shows a 3D bar graph which summarized the effect of both factors, cutting speed, (V_c) and feed per tooth, (f_z) towards the surface quality of the trimmed surface for a specific CFRP material. The arrow indicates the most preferable point in order to get the best trimmed surface quality. Therefore, lower cutting speed and feed per tooth are the most preferable parameters to be chosen in order to obtain the minimum surface roughness.

Table 5 ANOVA Result for A = Spindle Speed, N and B = Feed per Tooth, F_z

Response	Surface Roughness				
		ANOVA for selected factorial model			
		Analysis of variance table			
	Sum of			Mean	
Source	Squares	df	Square	Value	Prob > F
Model	83.492	4	20.873	10.800	0.0203
A-Cutting Speed	31.120	2	15.560	8.0511	0.0396
B-Feed per Tooth	52.372	2	26.186	13.550	0.0165
Residual	7.7304	4	1.9326		
Cor Total	91.222	8			

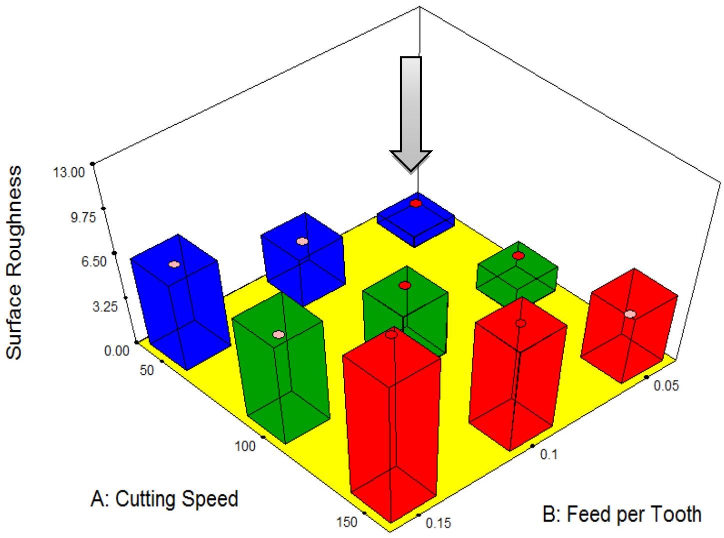

Figure 8. 3D bar graph illustrates the effect of cutting speed and feed per tooth towards surface roughness.

4. CONCLUSIONS

This paper presented results of surface roughness analysis, details of trimmed surface observations through optical microscopy as well as ANOVA analysis according to the Taguchi method (Orthogonal Array L9). The conclusions obtained from the investigation are as follows:

a) The minimum value of the averaged surface roughness (1.31μm) is obtained by (R8) in which the cutting speed, (V_c) applied was 50 m/min and feed per tooth, (f_z) at 0.15 mm. Meanwhile, the maximum averaged surface roughness value (12.62 μm) exhibited by the (R9) which has the highest setting of cutting speed, (V_c) 150 min/min and has a similar per tooth, (f_z) 0.15 mm.
b) The result above is supported by the observation of the trimmed surface through optical microscopy which clearly exhibits matrix degradation, uncut fiber and fiber pull-out on the (R9) enlarged photomicrograph. Clean and neat trimmed surface is indicated by the enlarged photomicrograph of (R8).
c) According to the ANOVA analysis, both factors namely cutting speed, V_c and feed per tooth, F_z concluded to be significant towards the focused response namely the surface finish.

Ultimately, this research has proven that the variation in cutting conditions impacted the result of surface finish during edge trimming of a specific CFRP material.

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