Effect of machining parameters on surface quality during edge trimming of multi-directional CFRP material: Taguchi method

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Abstract. In recent years, carbon fiber-reinforced polymer (CFRP) materials are gaining tremendous attention by industries especially in aerospace industry for product structures due to the superior material properties such as high strength, low weight and corrosion. This study presents a research on the influence of machining parameters utilizing uncoated tungsten carbide router or burrs tool towards surface quality during edge trimming of a specific CFRP material. CFRP panel of 10.31 mm in thickness with the total of 38 number of plies has been chosen to be the main study material. A famous statistical method namely Taguchi Method (L4) has been deployed to plan the overall experimental design. Two main factors investigated in this study were spindle speed and feed rate. Surface roughness measurement was taken using Mitutoyo Surftest SJ-410. Moreover, optical microscope Nikon MM-800 is utilized to further observe the trimmed surfaces. The result reveals that the spindle speed was the most influential parameter towards the trimmed surface quality. Run no. 3 (R3) generated approximately 2.5 times better Ra value than Run no. 3 (R2) at constant feed rate (1500 mm/min) but vary in spindle speed by the difference of 3000 rpm. From further observations of trimmed surface through optical microscope, obvious matrix degradation and wrench areas were spotted on the R2 trimmed surface compared to the R3. From ANOVA analysis, spindle speed was also indicated as the significant factor. Details results 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 thermostet 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% [16] as shown in Figure 1. 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 fatigue performance, and high static strength.

![Figure 1. Use of composites in the Boeing 787](image)

Machining composites is totally different from machining metals. The behavior of composite such as its inhomogeneity and interaction with the cutting tool whilst machining is a complex phenomenon to be understood. Machining may possibly cause the quality of the machined composite part such as delamination, cracking, fiber pull-out, and burned matrices. The abrasive nature of the reinforcement fibers and the need to shear them neatly bring to the additional requirements and constraints on the selection of the best tool materials, geometry as well as the cutting parameters [2]–[4]. Secondary processes such as trimming or milling to the final shape and drilling are typically necessary to facilitate component assembly as it exhibits surface roughness of the workpiece. Surface roughness and dimensional accuracy are closely related and it is generally necessary to specify a fine surface finish to maintain an acceptable tolerance in the finishing process. For many practical design applications, tolerance and strength requirements impose a limit on the maximum allowable roughness [5].

N. Duboussta et al. proved surface roughness increased with machining distance generally following a steady trend, while the tool wear was found to initially have a rapid wearing in period [6]. In the following year, the same authors developed a new optical method to measure surface roughness and damage of machined composite surfaces. They found that feed rate and tool type had the most significant effect on the surface quality [7]. Souhir Gara and Oleg Tsoumarev concluded 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 tothing 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 [8], [9]. Meanwhile, J. Sheikh-Ahmad et el. observed that surface roughness in the longitudinal direction increased with an increase in feed rate and a decrease in spindle speed, which corresponds to an increase in effective chip thickness. Surface roughness in the transverse
direction does not have clear trends and is generally higher than longitudinal direction [3], [10]. M. Haddad et al. agreed that whatever the tool geometry or the machining conditions, it is observed that the increase of the feed speed or the cutting distance induces higher cutting forces. However, increasing the cutting speed reduces the cutting forces [11]. The quality of the machined surface is mainly affected by the cutting speed followed by cutting distance [12]. On the other hand, P. Janardhan et al. summarized that the up milling in routing of CFRP composite material with burr tools provided better results than down milling in terms of machining damage, less delamination and surface roughness. Surface roughness in the longitudinal direction increased with an increase in feed rate and a decrease in spindle speed, corresponding to large effective chip thickness [13].

Despite the wealth of literature mentioned above, machining of composite materials enforces special attentions on the optimization of influence and interaction of machining parameters to minimize the defects of the surface produced by machining, which could drastically affect the strength the composite material. Hence, this research is initiated and successfully experimented to study the influence of cutting parameters towards the trimmed surface quality of a specific CFRP material.

2. Methodology

2.1 Material
The CFRP panel measured 10.31 mm in thickness and utilizing woven type fiber. The overall dimensions of the panel was 150 mm x 275 mm. It has 38 number of plies in total. The stacking sequence was given by $[\pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ, \pm 45^\circ, 0^\circ/90^\circ]$. 

2.2 Cutting Tool
The cutting tool used in this study was burrs or router type with the overall specification of the tool geometry is illustrated by Table 1. Figure 2 shows the overview of the actual geometry features of the mentioned tool.

| Table 1. Router or burrs tool geometry |
|--------------------------------------|
| Diameter (mm) | Number of teeth | Number of flute | Angle of helix (°) | Length (mm) |
| Pyramidal Type | 6 | 10 | 11 | 10 | 28 | 28 | 75 |

Figure 2. Scanned geometry of the router tool (a) actual router tool – side view (b) end / face view (c)

2.3 Machine Specification
The machine used to perform the edge trimming process was Hass CNC Gantry Router – 3 Axis GR-510. Specification of the machine is shown in Table 2.
Table 2. 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

Taguchi Orthogonal Arrays L4 has been applied in this research. Therefore, there were two ranges of spindle speed \((N)\) and feed rate \((V_f)\) were selected. Table 3 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 300 mm. The range for both machining parameters namely spindle speed and feed rate have been referred to the current practices applied by the local composite manufacturers.

Table 3. Machining parameters

| Spindle Speed, \(N\) (RPM) | Feed, \(V_f\) (mm/min) |
|-----------------------------|------------------------|
| R1                          | 7000                   | 1750                   |
| R2                          | 10000                  | 1500                   |
| R3                          | 7000                   | 1500                   |
| R4                          | 10000                  | 1750                   |

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. Figure 3 illustrates the CAD design as well as the final assembly of the 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.

2.6 Surface Roughness Measurement and Observation

Surface finish of the work piece 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. Stylus travel distance was set at 4 mm on each measurement to evaluate the longitudinal surface roughness. There were 5 points of measurement taken on every trimmed surface and final average Ra is obtained to represent the result of the surface finish on every specimen. Figure 4 indicates the SJ-410 roughness tester and longitudinal roughness measurement applied.

Figure 4. SJ-410 roughness tester is utilized to measure the surface quality of the trimmed surface

In addition, Nikon MM-800 microscope is utilized to observe further details of the surface finish on every machined surface. The magnification range is 1x magnification to 100x magnification. Therefore, it helped in identifying damages and described better understanding on the closed-up images captured. Whilst the specimen is under the microscope, the data processing software, E-Max which connected to a personal computer capturing the required images. Figure 5 exhibits the Nikon MM-800 microscope.
3. Result and Discussion

Figure 6 illustrates Run no.3 (R3) resulted the minimum surface roughness, Ra which ranged between 1.429 µm to 1.707 µm and followed by Run no.1 (R1) which ranged between 1.565 µm to 3.453µm. Meanwhile, Run no.2 (R2) exhibits the highest Ra values which stated the range between 3.685µm to 7.086 µm and followed by Run no.4 (R4) which stated the Ra value ranged between 3.414 µm to 4.762 µm. In average, the minimum Ra value was generated by R3 at 1.60 µm and the maximum averaged Ra value was obtained by R2 at 5.48µm. The difference between R3 and R2 is approximately 3.88 µm or approximately 2.43 times better. It appears that R3 and R2 were sharing the same feed rate which was 1500 mm/min. Therefore, an important summary could be drawn here which stating that the spindle speed is the most influential factor towards surface finish in edge trimming CFRP material. This finding is consistent with previous study reported by Haddad et.al which confirmed the quality of the machined surface is mainly affected by the cutting speed or spindle speed followed by the cutting distance [11], [12]. However, N. Doboust et al. who developed the new optical method to measure surface roughness and damage of machined composite surfaces summarized that the feed rate and tool type had the most significant effect on the surface quality and not the spindle speed [7]. In other work done by J. Sheikh-Ahmad et al. they concluded that surface roughness in the longitudinal direction increased with an increase in feed rate and a decrease in spindle speed, which corresponds to an increase in effective chip thickness as the main reason contributed to the final result of surface roughness [3].

Figure 5. Nikon MM-800 is used to further observe the trimmed surface
The result obtained was then investigated further under optical microscope. Photomicrographs were taken along the trimmed surface and the significant ones were captured to be analysed further. Figure 7 and 8 illustrate the comparison of photomicrographs taken for each run. Images from R2 (marked by red dotted line box) obviously indicate matrix degradation phenomenon where the horizontal layers of laminated fibres were hardly seen. Moreover, areas known as wrench areas also clearly spotted from the images. These same damages were also identified in high speed trimming of multi-directional CFRP which was also using the router or burrs tool. At high speed trimming, few mechanical damages such as the form of fiber pulled-out with matrix degradation in some areas were really visible which was believed due to thermal effects. Under standard cutting conditions, feed speed was found to be the major parameter affecting surface roughness [14], [15]. Meanwhile, from the photomicrographs taken for the trimmed surface of R3 (marked by blue dotted box) a neat laminated fibers laid horizontally were obviously exhibited which indirectly supporting the result obtained by the Ra values.

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Figure 6. Surface finish (Ra) result for all Runs (R) of machining parameter

| Table 4. Result of Ra (µm) values |
|----------------------------------|
|       | 1   | 2   | 3   | 4   | 5   | Avg. |
| R1    | 2.954 | 1.565 | 2.955 | 3.453 | 2.797 | 2.74 |
| R2    | 4.756 | 3.685 | 7.003 | 7.086 | 4.866 | 5.48 |
| R3    | 1.61  | 1.707 | 1.429 | 1.649 | 1.603 | 1.60 |
| R4    | 3.414 | 3.807 | 3.998 | 4.762 | 4.558 | 4.11 |
3.1 Taguchi – ANOVA

Analysis of Variance (ANOVA) is carried out to determine which of the factor or machining parameter (spindle speed, \( N \) and feed rate, \( V_f \)) significantly affect the performance characteristics or selected responses namely surface roughness. Tables 5 and 6 show the results of the ANOVA with the average Ra values for edge trimming of a specific CFRP chosen in this study. This analysis was computed for a level of confidence of 95 %.

The Model F-value from Table 5 shows 320.06 which implies the model is significant. There is only a 3.95% chance that a "Model F-Value" this large could occur due to noise. Thus, factor A = spindle speed has significant effect to the first response; surface finish. Meanwhile, Table 6 indicates the "Model F-value" of 0.12 which implies the model is not significant relative to the noise. There is a 90.15 % chance that a "Model F-value" this large could occur due to noise. Hence, factor B = feed rate has no significant factor towards the first response; surface finish.

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**Figure 7.** Photomicrographs at 100X magnification on the trimmed surface

**Figure 8.** Obvious matrix degradation and wrench areas spotted on R2 trimmed surface, \( N=10\,000 \) rpm; \( V_f=1500\,\text{mm/min} \) (left); Neat trimmed surface observed on R3 trimmed surface, \( N=7000 \) rpm; \( V_f=1500 \) mm/min (right)
Table 5. ANOVA Result for \(A=\text{Spindle Speed, N}\)

| Source | DF | Squares | Mean | Value  | Prob > F | F  |
|--------|----|---------|------|--------|----------|----|
| Model  | 2  | 4.232825| 8.46565| 320.06238| 0.0395  | significant |
| A      | 1  | 6.890625| 6.890625| 521.03025| 0.0279  |    |
| AB     | 1  | 1.575025| 1.575025| 119.09452| 0.0582  |    |
| Residual| 1 | 0.013225| 0.013225|    |          |    |
| Cor Total| 3| 8.478875|        |       |          |    |

Table 6. ANOVA Result for \(B=\text{Feed Rate, V}_f\)

| Source | DF | Squares | Mean | Value  | Prob > F | F  |
|--------|----|---------|------|--------|----------|----|
| Model  | 2  | 0.794125| 1.58825| 0.115247| 0.9015  | not significant |
| B      | 1  | 0.013225| 0.013225| 0.001919| 0.9721  |    |
| AB     | 1  | 1.575025| 1.575025| 0.228575| 0.7161  |    |
| Residual| 1 | 6.890625| 6.890625|    |          |    |
| Cor Total| 3| 8.478875|        |       |          |    |

4. Conclusion
This paper presented results of surface roughness analysis, \(R_a\) for edge trimming of CFRP composite utilizing router or burrs tool with various machining parameters. The following points emerged from the present investigation are as follows:

i. From the surface roughness result, it was shown that R3 generated the minimum averaged \(R_a\) value with 2.43 times better than R2 at constant feed rate, \(V_f\) (1500 mm/min) but 3000 rpm slower in spindle speed, \(N\). Therefore, spindle speed was found to be the main influential factor towards surface finish in edge trimming CFRP material.

ii. The observation of trimmed surface via optical microscopy clearly indicated matrix degradation and wrench areas on the R2 trimmed surface compared to the R3 which indirectly translating the result obtained above (i).

iii. From ANOVA analysis, spindle speed has shown the significant factor which again indirectly supporting the mentioned above results.

Ultimately, this work has contributed to our knowledge about the effect of machining parameters namely spindle speed and feed rate towards surface roughness in edge trimming of specific CFRP composite.

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