INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOLUME 23, ISSUE 1, 2026, 13434 - 13445
DOI: https://doi.org/10.15282/ijame.23.1.2026.14.1012

RESEARCH ARTICLE

Effect of machining conditions for enhanced surface integrity and cutting temperature in trimming hybrid fibre-reinforced polymer composites

S.M.F. Syed Hassan[1], **S.A. Sundi**[1]*, **M.H. Mohd Ramaly**[1], **I.A. Abdul Hakim**[1], **M. Ahmad**[1], **R.I. Raja Abdullah**[1], **I.S. Othman**[1], **R. Loh**[2]

[1]Faculty of Industrial and Manufacturing Engineering and Technology, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2]Evertools Industrial Supply Sdn. Bhd. 7, Jalan Perusahaan Sungai Lokan 3, Taman Industri Sungai Lokan, 13800 Butterworth, Pulau Pinang

Abstract – This study aims to evaluate how cutting parameters influence surface quality and cutting temperature during the trimming of Hybrid Fibre Reinforced Polymer (HFRP) used in aerospace components. Although HFRP is increasingly adopted in aircraft structures, it remains difficult to machine because trimming can trigger delamination, matrix degradation, and non-uniform heat generation across the laminate. To address this, a Taguchi L9 Orthogonal Array was applied to systematically examine the effects of spindle speed and feed per tooth on two key outcomes: surface roughness (R_a) and maximum cutting temperature (T_{max}). Trimming experiments were performed on a Roland MDX540 CNC router, and surface integrity was assessed using optical microscopy, thermal imaging, and analysis of variance. Two parameter settings emerged as optimal, depending on the targeted response. The lowest surface roughness was achieved at 7518 RPM with 0.10 mm per tooth (R_a = 2.44 µm), whereas the lowest cutting temperature occurred at 5012 RPM with 0.15 mm per tooth (T_{max} = 110.2 °C). Since surface integrity is the primary quality requirement for aerospace trimming, the condition of 7518 RPM / 0.10 mm per tooth was selected as the most practical optimum. This setting provides a noticeably improved surface finish while keeping the cutting temperature at a moderate level (approximately 115 °C), which remains safely below the threshold for polymer matrix degradation. Analysis of variance results further indicate that feed per tooth is the dominant factor governing surface roughness, while spindle speed has the strongest influence on cutting temperature. Overall, the findings support a dual-objective optimisation approach that balances mechanical surface integrity and thermal control, providing practical parameter guidance for consistent, high-quality trimming of HFRP aerospace parts.

Article History

Received	:	21 July 2025
Revised	:	12 September 2025
Accepted	:	9 December 2025
Published	:	12 March 2026

Keywords
HFRP
Spindle speed
Feed per tooth
Surface quality
Cutting temperature
Taguchi orthogonal array

1. Introduction

The aerospace industry is undergoing a major shift towards greater use of advanced composite materials, particularly Hybrid Fibre Reinforced Polymer (HFRP). These materials combine fibres, such as carbon, glass, or aramid, with a polymer matrix, making them high-strength, lightweight, corrosion-resistant, and highly flexible [1-2]. HFRP has been widely used in key aircraft components, including wing panels, fuselages, and interiors [3]. For example, the Airbus A330 and Boeing 787 Dreamliner use HFRP to reduce aircraft weight by up to 800 kg, improve fuel efficiency, and reduce carbon emissions, in line with global sustainability goals [3-4] (Refer to Figure 1). While HFRP offers numerous advantages, machining this material presents unique challenges. Its heterogeneous nature, which combines a polymer matrix with fibres, often leads to delamination, fibre pull-out, and matrix cracking during cutting [5-7]. However, the inherently heterogeneous composition of HFRP, comprising multiple fibre types and orientations embedded in a polymer matrix, introduces significant complexity to the machining process, particularly in achieving high surface integrity and managing thermal interactions [8-9]. Furthermore, HFRP materials containing metallic elements make uniform machining more difficult because of variations in their thermal and mechanical properties [10]. Previous research has explored several approaches to reduce machining-related defects in HFRP. In general, surface roughness and delamination are highly sensitive to cutting parameters, including feed rate, spindle speed, depth of cut, and tool geometry. When these parameters are properly optimised, machining-induced damage can be minimised, and surface integrity improved [9,11-12]. For example, Wang et al. [13] reported that a low feed per tooth reduces the likelihood of surface damage. At the same time, a higher spindle speed can improve stability by reducing vibration. Tool design also plays a major role: Sundi et al. [14] showed that tools with suitable geometries, such as helical and router-type cutters, can enhance surface quality and reduce tool wear. Similarly, Ozkan et al. [15] found that increasing the feed rate tends to increase Ra, whereas higher cutting speed often leads to lower Ra values.

*CORRESPONDING AUTHOR | S.A Sundi | ✉ syahrul.azwan@utem.edu.my

Despite these advantages, machining HFRP remains a major concern, particularly for aerospace applications where quality and reliability are stringent requirements. The laminated, anisotropic structure of HFRP leads to non-uniform fibre–matrix interactions during cutting, often resulting in defects such as delamination, fibre pull-out, and matrix cracking. In addition, abrasive reinforcements, such as carbon and glass fibres, increase friction and accelerate tool wear, shortening tool life and compromising machining consistency. Trimming and routing become even more challenging when HFRP includes hybrid features such as metallic layers or honeycomb cores. These layers alter heat transfer and the distribution of the cutting load, making the machining response more complex. As a result, careful, precise parameter selection is essential to maintain both surface quality and process stability. Beyond surface roughness, cutting temperature is another key factor that strongly affects machining performance. According to Gara et al. [16], excessive temperature, often associated with high cutting speed, can degrade the polymer matrix and weaken bonding between layers (including fibre layers and core structures such as honeycomb), leading to defects that are difficult to repair. Studies by Khashaba and El-Keran [17] and Wang et al. [18] also observed that temperature peaks may approach the resin's glass transition temperature (Tg), particularly at high spindle speeds and low feed rates. While such thermal softening can sometimes reduce cutting resistance and suppress delamination, it also increases the risk of resin softening and matrix degradation if thermal control is insufficient. This highlights an important trade-off in HFRP machining: thermal assistance can improve cutting, but excessive heat can permanently damage the matrix and the fibre–matrix interface. Therefore, selecting spindle speed and feed per tooth within moderate ranges is critical to generate sufficient heat for smoother cutting while avoiding thermal damage.

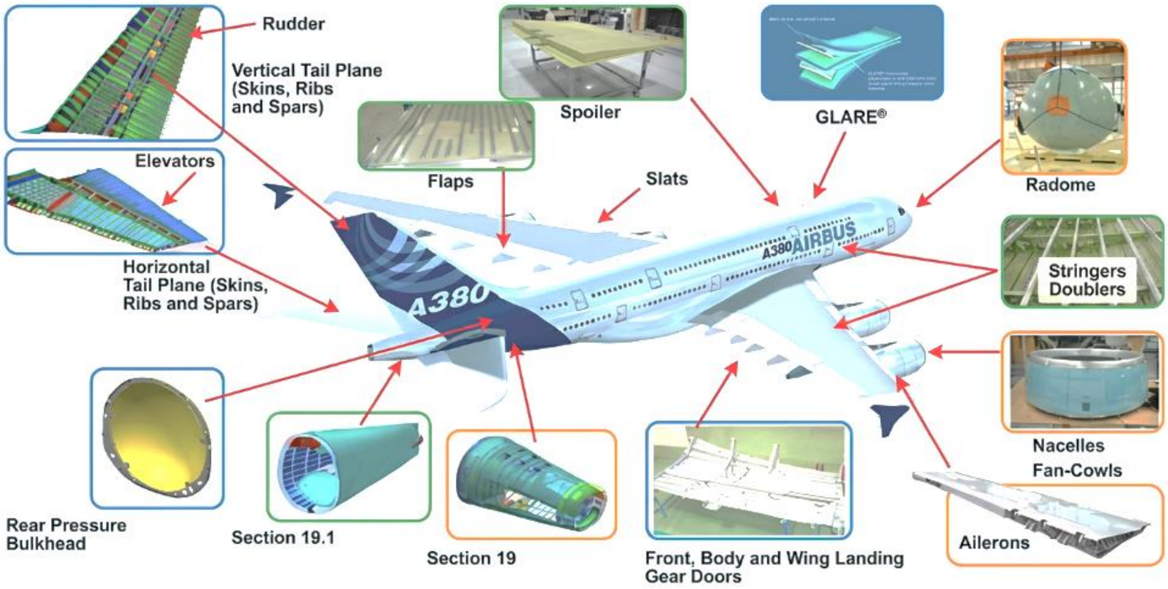


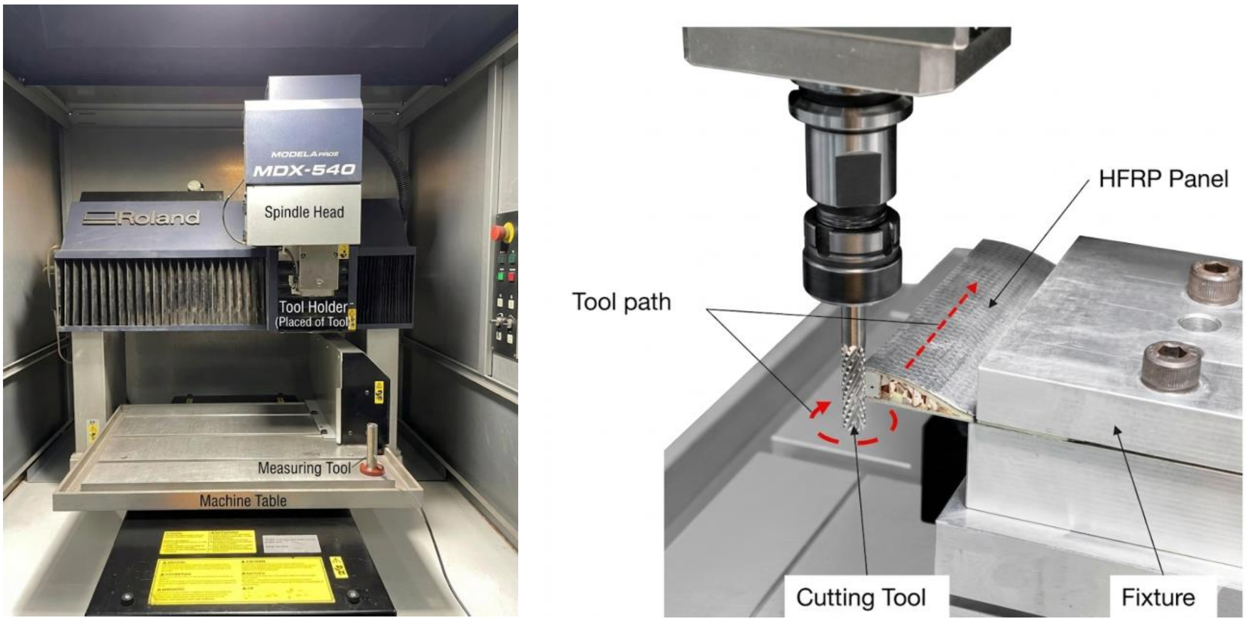
Figure 1. Structural components of the Airbus A380 were manufactured using hybrid fibre-reinforced composite materials [4]

The literature emphasises machining parameters such as spindle speed, feed per tooth, and cutting temperature. For instance, Caggiano et al. [12] reported that temperature increases with spindle speed, potentially accelerating tool wear. Meanwhile, Sundi et al. [14] showed that higher feed rates can also significantly raise cutting temperature, contributing to matrix degradation and fibre–matrix debonding during trimming. Several researchers have also adopted statistical approaches to improve parameter selection. A study by Sundi et al. [19] demonstrated that methods such as the Taguchi L9 Orthogonal Array combined with ANOVA are effective for identifying optimal parameter settings. Likewise, Sundi et al. [20] highlighted that this approach not only helps determine the best parameter combination but also reduces variability in machining outcomes, particularly for surface roughness and peak cutting temperature. However, much of the existing work tends to focus on a single output, such as surface roughness or tool wear, without fully addressing the interaction between surface integrity and thermal response. This lack of dual-objective optimisation limits understanding of how cutting temperature influences surface quality under realistic aerospace trimming conditions. Although some integrated optimisation frameworks have been introduced for composite machining, their suitability for HFRP remains insufficiently studied, indicating a clear need for further validation and refinement [21-23]. To address this gap, the present study proposes a Taguchi-based experimental framework that simultaneously evaluates surface roughness and cutting temperature to identify optimal trimming conditions for aerospace-grade HFRP. The novelty of this work lies in integrating thermal–mechanical correlation under dry-trimming conditions using a Taguchi L9 Orthogonal Array, providing a practical, reproducible strategy to improve machining performance while minimising tool wear and material degradation. Accordingly, this study investigates the influence of spindle speed and feed per tooth on surface roughness and examines how surface quality correlates with cutting temperature during trimming. To better understand the mechanisms underlying surface formation, high-resolution microscopy was also performed to assess the trimmed-edge features. The remainder of this paper is organised as follows: Section 2 outlines the methodology and experimental setup;

Section 3 presents the results and discusses surface roughness and cutting temperature; and Section 4 concludes the study and highlights key industrial implications.

2. Materials and Methods

The experiments were planned using a Taguchi L9 Orthogonal Array, which enables efficient evaluation of several machining factors with only a small number of trials. This design enabled the study to pinpoint the cutting-parameter combination that delivers the best surface finish while keeping the cutting temperature under control.

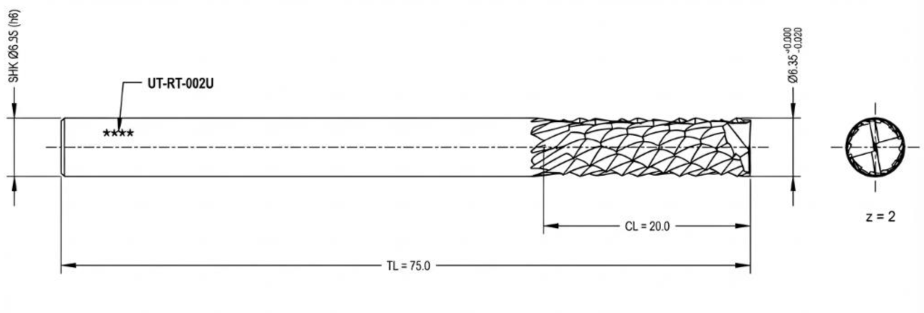


(a) MDX-540 CNC router (b) Actual trimming setup

Figure 2. MDX-540 CNC router and actual trimming setup

2.1 Experimental Design

A Taguchi L9 Orthogonal Array was used to evaluate two key cutting parameters: spindle speed (10024, 7518, and 5012 RPM) and feed per tooth, fz (0.05, 0.10, and 0.15 mm). This L9 design was chosen over a full factorial or response surface approach because it substantially reduces the number of experimental runs while still providing statistically reliable insights. The selection is also consistent with earlier CFRP trimming studies that adopted similar Taguchi-based strategies [13, 19]. These parameter combinations yielded 9 distinct experimental sets. Each combination was tested on HFRP material using a Roland MDX540 CNC Router with a 6.35 mm-diameter tungsten carbide router/burr cutting tool (see Figure 2). The cutting process was performed in climb milling mode to ensure stability and reduce vibration. Climb milling was chosen for its superior surface finish and reduced tool deflection compared to conventional milling, as reported by Hafeez et al. [24]. A total of nine (9) new tungsten carbide router/burr-type cutting tools with a diameter of 6.35 mm were used for the nine experimental runs, with each run utilising a fresh tool to eliminate the influence of tool wear on the results. Figure 3 shows the schematic diagram of the router tool, and Table 1 shows its specifications.



a) Schematic design with dimensions

b) Physical tool prototype

Figure 3. a) Router tool geometry, b) Actual router cutting tool

Table 1. Router Tool Specification

Tool geometry	Details
No. of flute (Right)	6
No. of flute (Left)	6
Helix angle (Right)	20
Helix angle (Left)	20
Diameter	6.35 mm
Tool length	75 mm

2.2 Preparation of Materials and Equipment

The HFRP material used in this study was supplied by a research collaborator, a leading manufacturer of composite aerostructures, and consisted of laminated panels with a honeycomb core. This material has a quasi-isotropic lay-up of 19 layers, including one aluminium layer. The structure of this material is shown in Figure 4 and Table 2. Sample preparation involved cutting rectangular specimens (100 × 50 × 5 mm) using the same Roland MDX-540 CNC router to ensure dimensional consistency and prevent misalignment during subsequent trimming tests. Environmental conditions were kept consistent throughout the experiments at 26 ± 1 °C and 60 ± 5% relative humidity to minimise the influence of ambient temperature fluctuations. Trimming was performed using a Roland MDX-540 CNC router, with cutting temperature continuously monitored using a Fluke Ti400 thermal camera to capture reliable thermal responses during machining. Surface quality was then examined in detail using a Nikon MM-800 microscope. Together, these controlled conditions and complementary measurement tools ensured that the collected data were both accurate and sufficiently comprehensive to support the study's objectives.

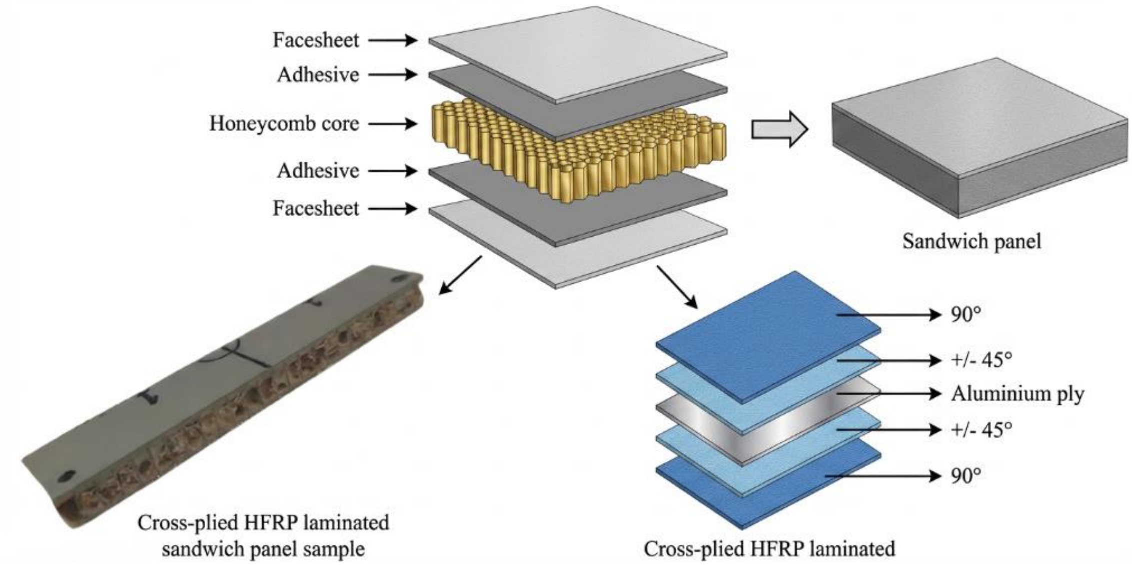


Figure 4. Structure of honeycomb core in HFRP panel

Table 2. Stacking sequence HFRP material

Ply number	Orientation	Ply number	Orientation
P1	0°/90°	P11	0°/90°
P2	0°/90°	P12	0°/90°
P3	0°/90°	P13	0°/90°
P4	0°/90°	P14	0°/90°
P5	+/- 45°	P15	+/- 45°
P6	0°/90°	P16	+/- 45°
P7	0°/90°	P17	0°/90°
P8	0°/90°	P18	0°/90°
P9	0°/90°	P19	0°/90°
P10	+/- 45°		

2.3 Measurements and Observations

2.3.1 Surface quality

Surface roughness (Ra) was measured using a Shodensha GR4300 at a point 30 mm from the specimen centre. To ensure reliable results, the instrument was calibrated before each measurement session using a certified reference block (Ra =

3.00 µm ± 0.05 µm). For each specimen, Ra readings were collected at 10 evenly spaced locations along the trimmed edges, with 5 points on the right edge and 5 on the left, for a total evaluation length of approximately 60 mm. The ten values from each experimental run were averaged to obtain a single mean Ra, which was used for the ANOVA and optimisation analysis. This measurement strategy improves representativeness by capturing surface variability along the trimmed region (see Figures 5-6).

2.3.2 Cutting temperature

Cutting temperature was monitored with a Fluke Ti400 thermal imager to assess how the selected cutting parameters influence the thermal response during trimming. This monitoring is important because excessive heat can accelerate polymer matrix degradation and compromise surface integrity. In each test, the HFRP specimen was securely clamped to a custom jig and positioned on the MDX-540 CNC router's working table. The thermal camera was positioned at an appropriate angle and distance to continuously capture temperature changes throughout the cutting operation (see Figure 7). Before testing, the camera was calibrated using a 100 °C blackbody reference, and the emissivity was set to 0.95 in line with the manufacturer's guidance for polymer composites. The recorded thermal footage was then processed in SmartView software to obtain the maximum (T_{max}) and average cutting temperatures for each experimental run.

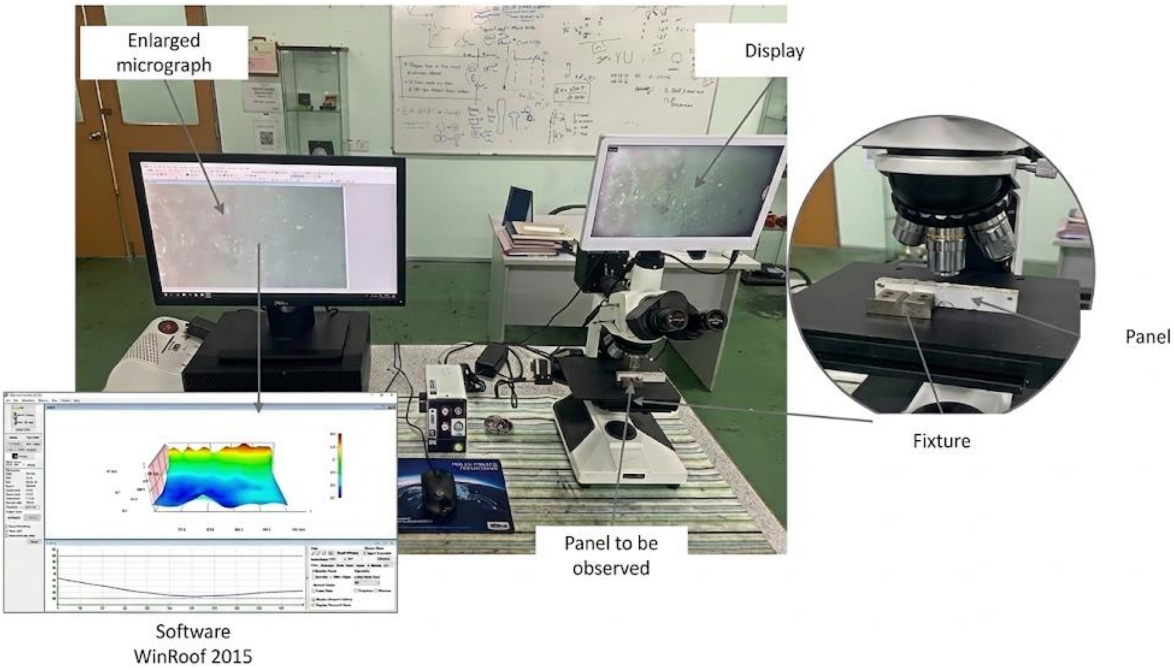


Figure 5. 3D profilometer Shodensha GR4300

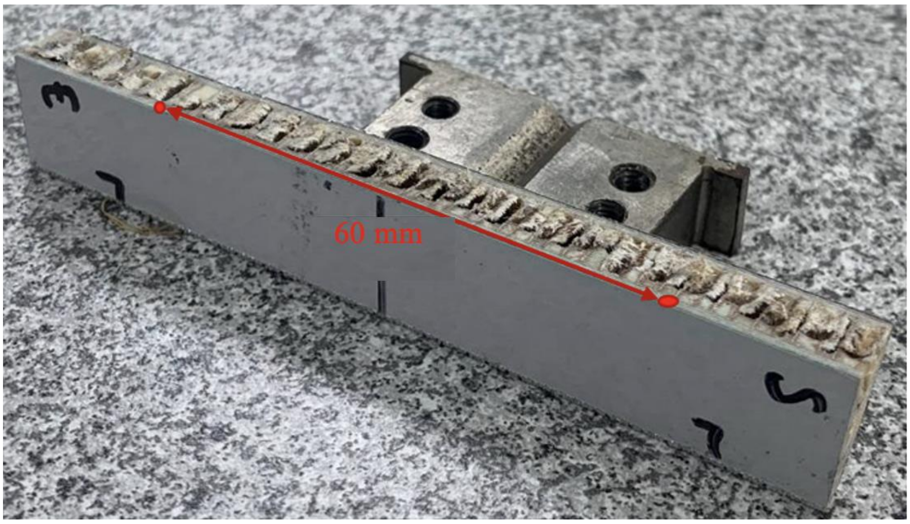


Figure 6. Surface roughness measurement procedure used in this study

2.4 Data Analysis

The collected data were analysed using ANOVA to identify which cutting parameters most strongly influence surface quality and cutting temperature. The Signal-to-Noise (SN) ratio was also used in the analysis to determine the optimal parameter combination, given the "smaller is better" characteristic of surface roughness and temperature. The experimental outcomes from this section form the basis for the dual-response trade-off analysis discussed later in Section 3.5.

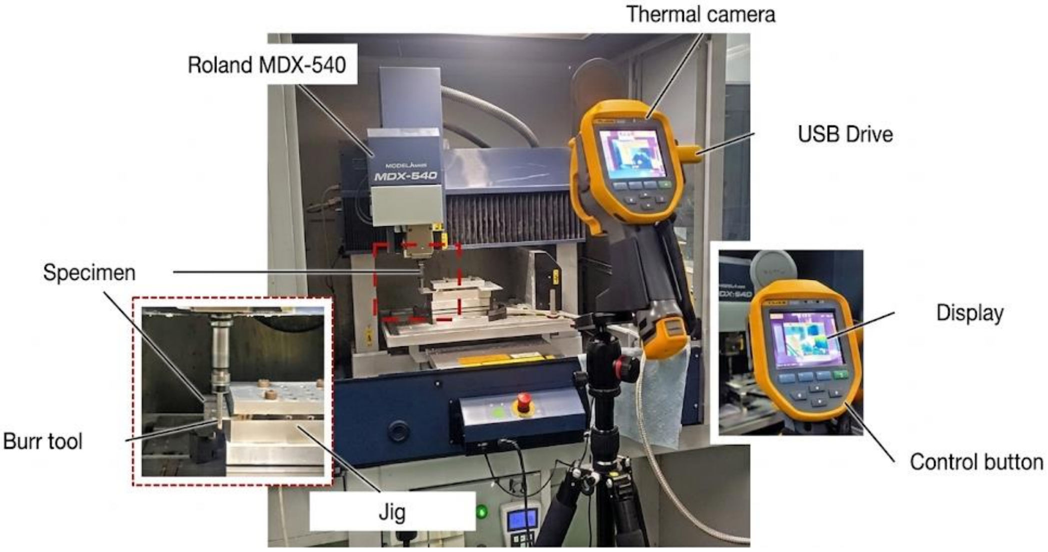


Figure 7. Actual setup of the Fluke Ti400 thermal imager during the trimming experiments.

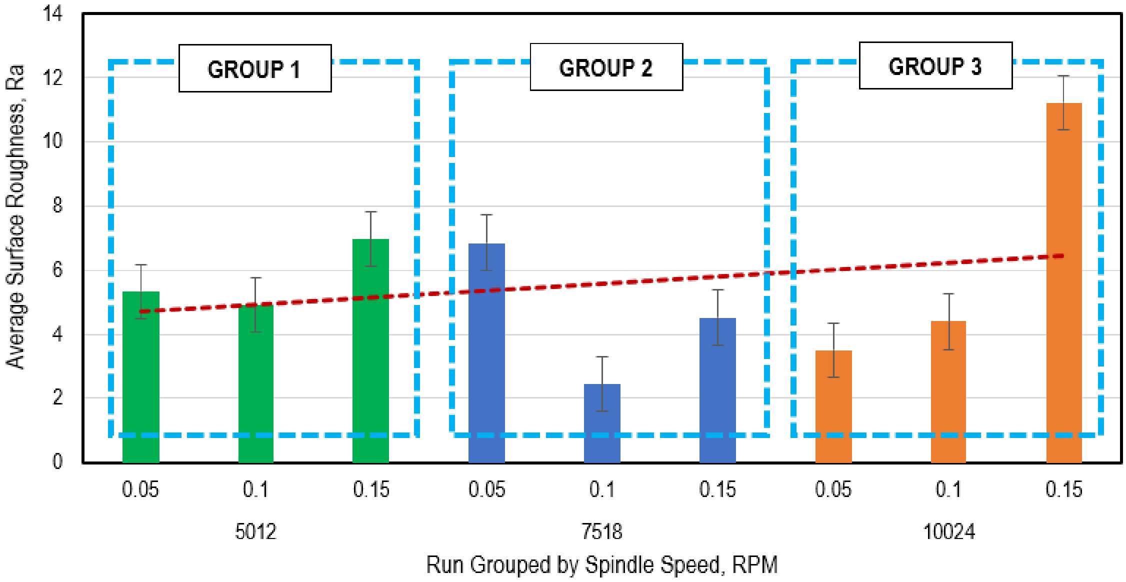


Figure 8. Surface roughness results grouped by spindle speed and arranged by feed per tooth

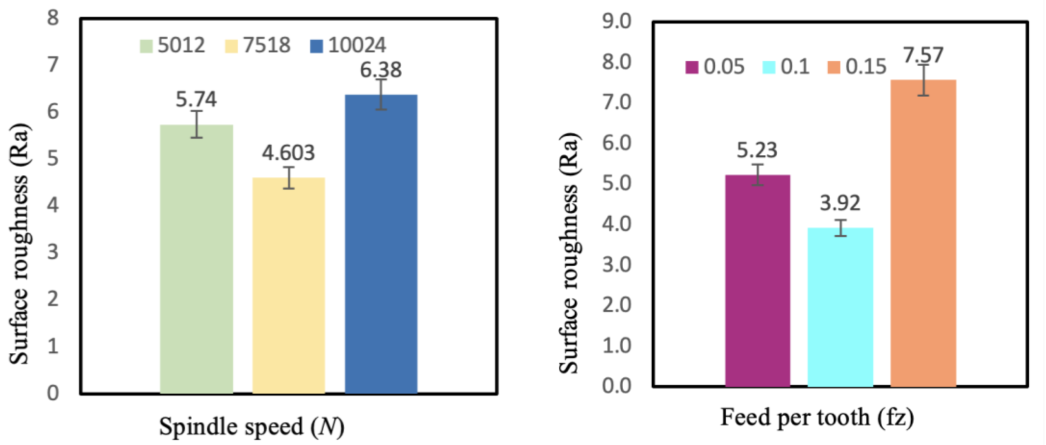
3. Results and Discussion

3.1 Surface Conditions

The machining results for the hybrid fibre-reinforced polymer samples indicate that both spindle speed (rpm) and feed per tooth (*fz*) clearly influence the surface roughness produced during trimming. The variation in *Ra* is strongly governed by the combined mechanical and thermal effects generated during chip formation and tool engagement. At higher spindle speeds, frictional heat softens the polymer matrix, while excessive feed per tooth increases the cutting load and fibre breakage. The analysis in Figure 8 found that at a spindle speed of 7518 rpm and a feed per tooth of 0.1 mm, the lowest surface roughness was 2.44 µm, indicating the best surface quality in this parameter range. This optimum corresponds to a resonance-free condition in which the tool-workpiece contact is sufficient for clean shearing without excessive matrix smearing or fibre pull-out. In contrast, the highest roughness, 11.23 µm, occurred at 10024 rpm with a feed per tooth of 0.15 mm, indicating the roughest surface.

Figure 9 shows that increasing spindle speed from 5012 rpm to 10024 rpm consistently increases surface roughness, with an average of 4.603 µm at 7518 rpm, better than 5.74 µm at 5012 rpm and 6.38 µm at 10024 rpm. When the spindle speed was further increased to 10024 rpm, the surface roughness rose to Ra = 6.38 µm, likely due to the onset of tool vibration and microchipping. This trend is consistent with Wang et al. (2016) [18], who reported that, during high-speed dry milling of CFRP, surface roughness increases once the spindle speed exceeds the tool–holder system's damping capacity. A similar trend was observed for feed per tooth. A higher feed per tooth of 0.15 mm produced a higher average roughness (Ra ≈ 7.57 µm), whereas reducing the feed per tooth to 0.10 mm lowered the average roughness to Ra ≈ 3.92 µm. Overall, these results indicate that smaller feed per tooth values promote a smoother trimmed surface. At 0.15

mm/tooth, the uncut chip thickness exceeded the matrix deformation limit, leading to tearing in the interlaminar regions. Conversely, moderate feed (0.10 mm/tooth) allowed sufficient chip evacuation, improving texture uniformity. This result is in line with a previous study by Ozkan et al. [15], which showed that increasing the feed rate increases surface roughness. A study by Sundi et al. [25] also found that high spindle speeds tend to produce coarser surface roughness. A study by Jenarthanan et al. [26] also confirmed that increasing feed per tooth significantly increases surface roughness. These findings reinforce the notion that higher spindle speeds, combined with larger feed per tooth values, tend to increase surface roughness during the milling of hybrid fibre-reinforced polymers. This observation is consistent with the findings of Ghafarizadeh, Chatelain, and Lebrun [27], who reported an increase in surface roughness with higher feed rates. These findings are also consistent with the work of Sundi et al. [19], who reported that using lower spindle speeds and feed rates generally leads to better surface quality. Figure 10 presents the surface topography images comparing the lowest and highest surface roughness conditions.



(a) (b)

Figure 9. (a) Average surface roughness against spindle speed, and (b) Average Surface roughness against feed per tooth

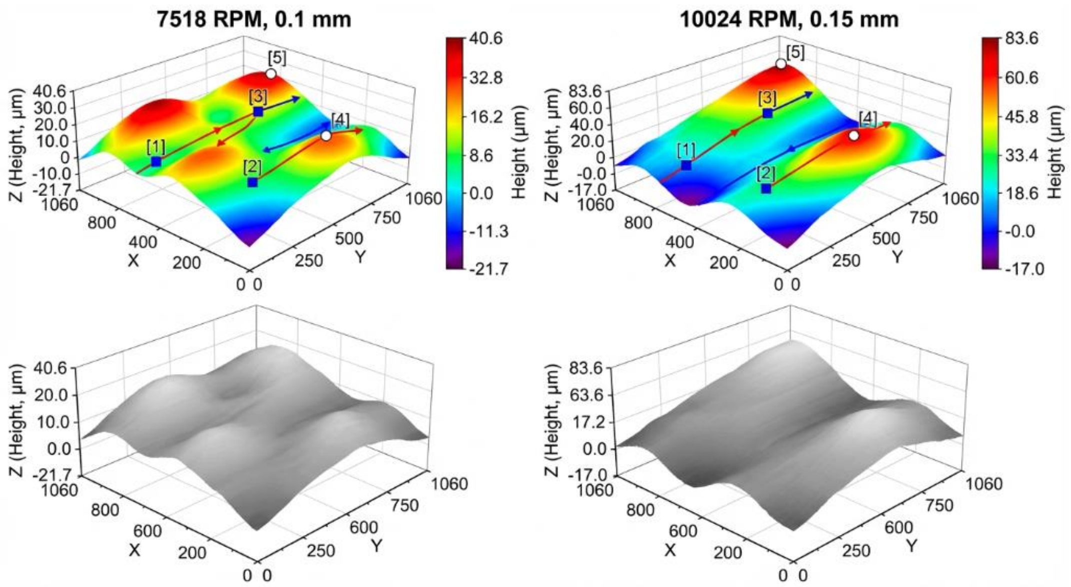


Figure 10. The left image shows the minimum average surface roughness, while the right image shows the maximum average surface roughness

3.2 Cutting Temperature

Cutting temperature during trimming was monitored with a Fluke Ti400 thermal imager. The results clearly show that spindle speed and feed per tooth (*fz*) strongly influence the thermal response during machining. Figure 11 summarises the temperatures recorded by the Ti400 across all experimental runs. As shown in Figure 12(a), the maximum cutting temperature increased steadily with spindle speed. At 5012 rpm, 7518 rpm, and 10024 rpm, the recorded peak temperatures were 110.2 °C, 114.5 °C, and 126.4 °C, respectively. The highest value (126.4 °C) occurred at 10024 rpm with a 0.05 mm/tooth chip load, suggesting prolonged rubbing and frictional heating due to the low chip load. At this level, the temperature may approach the epoxy matrix glass transition temperature, potentially causing localised softening and increasing the risk of micro-delamination.

In contrast, Figure 12(b) shows an inverse trend for feed per tooth. The highest maximum temperature (126.4 °C) occurred at the lowest feed per tooth (0.05 mm/tooth), whereas lower temperatures were observed at 0.10 mm/tooth

(114.5°C) and 0.15 mm/tooth (112.9 °C). This suggests that lower feed per tooth promotes heat build-up. By contrast, higher feed reduces temperature because the tool spends less time in contact with the material and removes more material per revolution. Overall, the results show a direct relationship between spindle speed and cutting temperature, but an inverse relationship between feed per tooth and temperature. This trend aligns with the findings of El-Hofy et al. [28], who reported that higher feed rates reduce thermal accumulation during CFRP slotting by reducing the tool–workpiece engagement time. Wang et al. [29] also support this finding, showing that cutting temperature increases with cutting speed during high-speed machining in dry conditions. Furthermore, the embedded aluminium layer within the HFRP panel enhanced lateral heat conduction, redistributing thermal energy and preventing excessive matrix burning. This effect of metallic interlayer coupling has recently been quantified by Berkowitz et al. [30], who reported a 12–15% reduction in peak interface temperature during hybrid laminate trimming.

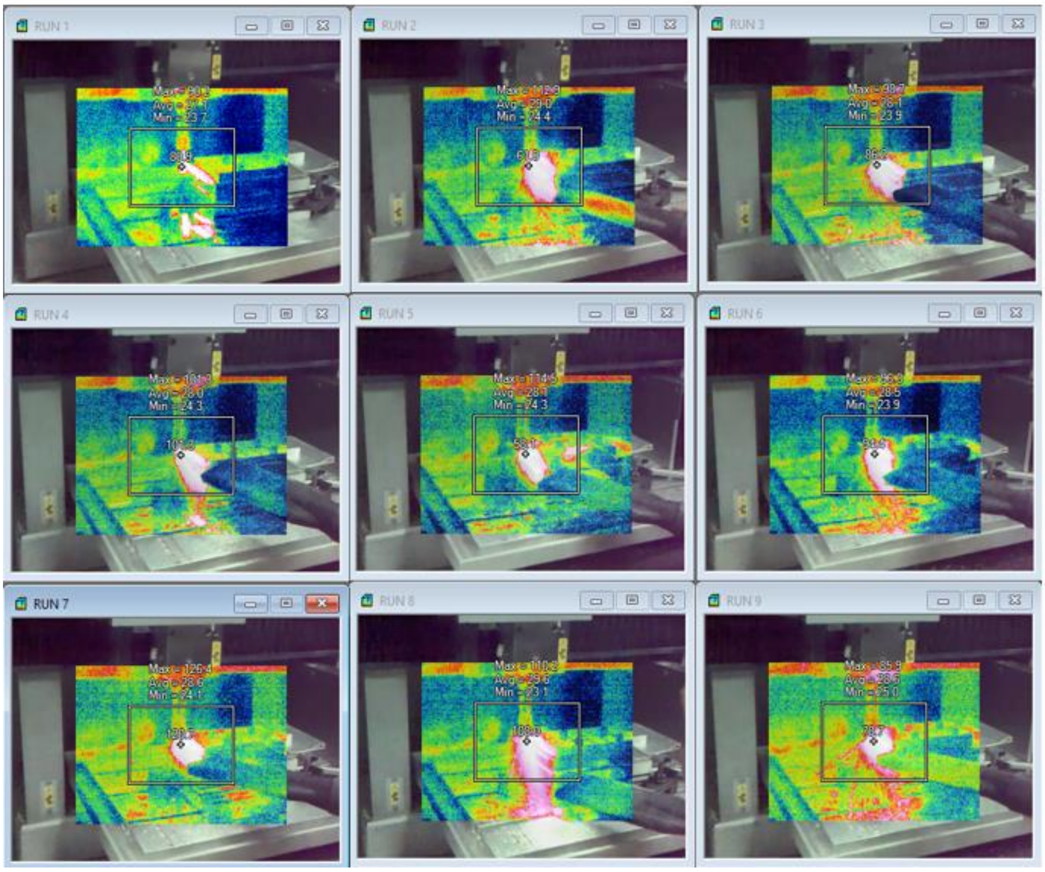
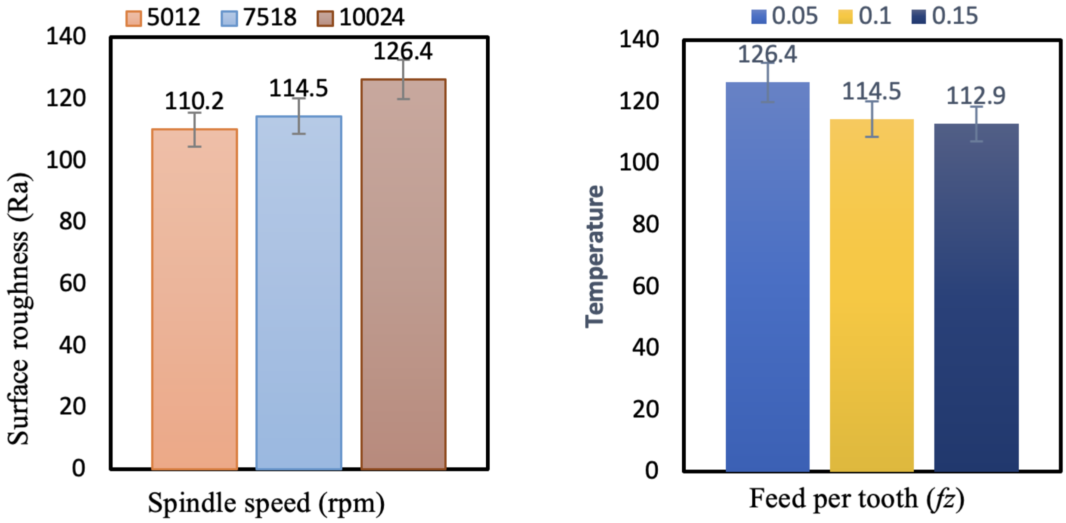


Figure 11. Machining temperature recorded by the Fluke Ti400 thermal imager during the trimming operation for all runs



(a) (b)

Figure 12. Average surface roughness by (a) spindle speed and (b) feed per tooth

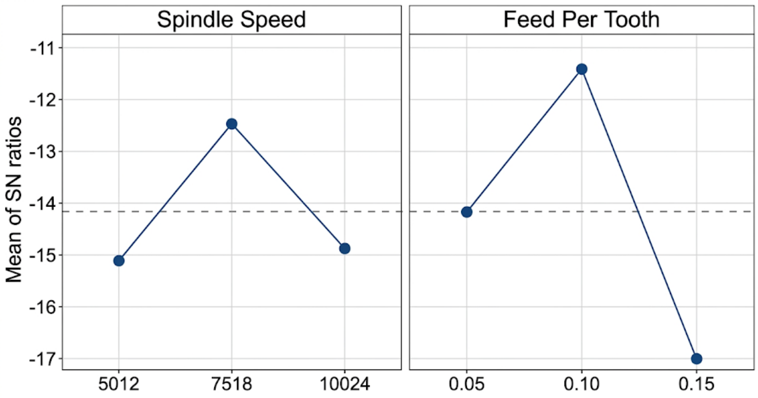


Figure 13. Mean of SN ratio for the smaller the better characteristics of surface roughness

3.3 Analysis of Variance

3.3.1 Surface roughness

Based on the ANOVA analysis, feed per tooth was the cutting parameter that most significantly affected surface roughness, followed by spindle speed. An increase in feed per tooth led to a substantial increase in surface roughness, whereas spindle speed had a more modest effect. This indicates that feed per tooth is more influential than spindle speed in achieving smoother surface integrity. The best combination of cutting parameters to achieve optimal surface roughness was a spindle speed of 7518 rpm and a feed per tooth of 0.1 mm. Figure 13 shows that the SN ratio for the "smaller-the-better" feature clearly illustrates the influence of feed per tooth and spindle speed on surface roughness. Furthermore, residual analysis indicates that the tabulated data are within an acceptable range, with most data concentrated near the centre of the diameter line. Although there are minor non-uniformities, the residuals are generally normally distributed. For HFRP machining, surface integrity is a critical quality indicator, since the trimmed edge directly affects dimensional accuracy and bonding performance in aerospace structures. Therefore, surface roughness was prioritised as the main response when determining the overall optimum machining condition. Although this parameter combination (7518 rpm and 0.10 mm/tooth) does not correspond to the lowest cutting temperature, it offers an acceptable thermal level (approximately 115 °C), which remains well below the thermal degradation threshold of the polymer matrix. Hence, this setting ensures a balance between minimal surface damage and controlled heat generation.

3.3.2 temperature

ANOVA analysis of cutting temperature showed that spindle speed had a significant effect on temperature rise, whereas feed per tooth reduced cutting temperature. Temperature increased consistently with spindle speed but decreased as feed per tooth increased. The optimal combination of cutting parameters to control cutting temperature, as indicated by the SN ratio for the "smaller-the-better" characteristic, was a spindle speed of 5012 RPM and a feed per tooth of 0.15 mm, producing the lowest maximum temperature of 110.2 °C, as shown in Figure 14. The residuals showed a normal distribution, with most values concentrated around the centre line, although the tabulation was irregular. However, this parameter setting also produced a relatively higher surface roughness (Ra = 5.74 µm), highlighting a clear trade-off between lowering temperature and maintaining surface quality. For aerospace trimming, a smoother and more uniform edge finish is typically prioritised over achieving the lowest possible cutting temperature, as long as the temperature remains within a safe range that does not risk matrix degradation. Therefore, while the temperature-optimum condition (5012 RPM, 0.15 mm/tooth) successfully minimises heat generation, the most practical overall setting for HFRP trimming is 7518 RPM and 0.10 mm/tooth. This combination delivers a better surface finish while maintaining a controlled cutting temperature, reducing the risk of thermal damage.

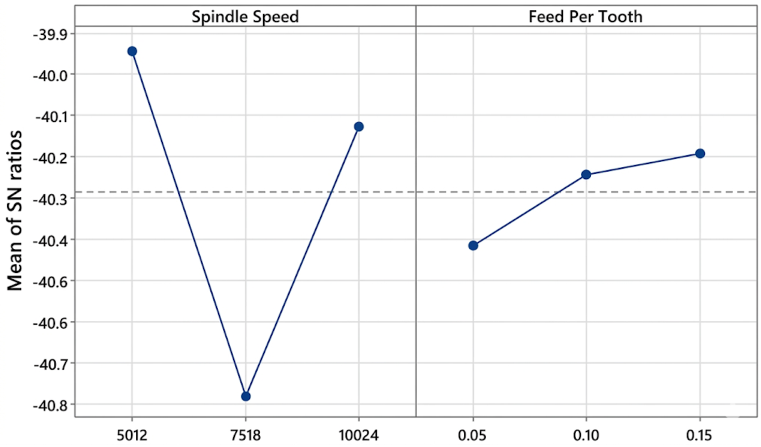


Figure 14. Mean signal-to-noise ratio for cutting temperature using the “smaller-the-better” criterion

3.5 Optimization

The optimisation identified two parameter combinations, one minimising surface roughness and another minimising cutting temperature. However, for aerospace-grade HFRP components, surface roughness was prioritised because it directly affects bonding performance, dimensional accuracy, and the quality of subsequent post-processing. Under the selected condition of 7518 RPM and 0.10 mm/tooth, the cutting temperature remains at approximately 115 °C, which is within a stable thermal range and well below the polymer matrix glass transition temperature ($Tg \approx 160$ °C). This indicates that the trimming process is thermally safe and unlikely to cause matrix degradation or interlayer delamination. Therefore, 7518 RPM / 0.10 mm/tooth is considered the most practical machining setting, as it provides a strong balance between mechanical performance and thermal control—delivering a consistent surface finish while maintaining reliable process stability for aerospace trimming. In general, operating at moderate spindle speeds and feed rates is important for managing the interaction between heat generation and cutting mechanics in HFRP machining. These conditions help limit excessive heat build-up while reducing machining-induced defects, leading to improved stability and surface integrity [31-32]. Figure 15 illustrates the dual-objective optimisation logic adopted for HFRP trimming.

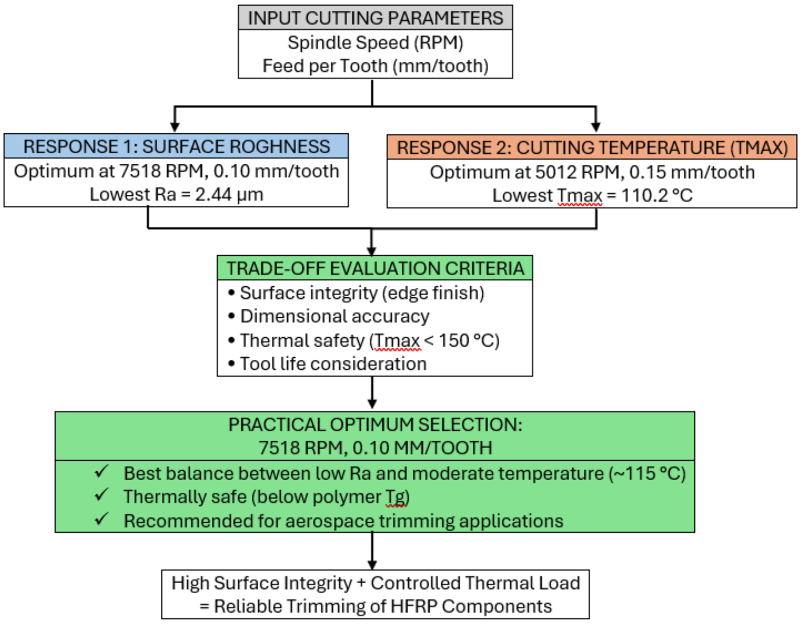


Figure 15. Schematic representation showing how surface roughness and cutting temperature were jointly considered to determine the optimal HFRP trimming condition

4. Conclusions

This study conducted a detailed evaluation of cutting parameters for trimming Hybrid Fibre Reinforced Polymer, with particular attention to surface roughness and cutting temperature. Based on the findings, the following conclusions can be drawn:

i) Influence of Cutting Parameters: Two distinct optimal parameter combinations were identified: 7518 RPM and 0.10 mm/tooth for the lowest surface roughness, and 5012 RPM and 0.15 mm/tooth for the lowest cutting temperature. However, for HFRP aerospace applications, surface integrity is prioritised because it directly affects dimensional accuracy, bonding reliability, and aerodynamic performance.
ii) Optimum Parameters: The most practical machining condition was identified as 7518 RPM and 0.10 mm/tooth. This setting produced the smoothest surface ($Ra = 2.44$ µm) while keeping the cutting temperature at a moderate level (≈ 115 °C), remaining safely below the threshold associated with polymer matrix degradation.
iii) Impact on Surface Quality: These results confirm that prioritising surface finish offers the best balance between mechanical performance and thermal control. In other words, high-quality trimming can be achieved without excessive heat build-up. The findings can therefore serve as a useful guide for selecting and optimising HFRP machining parameters in aerospace manufacturing.
iv) ANOVA analysis of surface roughness confirmed that feed per tooth is the factor that most influences machining results, with spindle speed a close second.

In summary, achieving high cutting quality generally requires a lower feed per tooth. This setting helps maintain surface integrity and can also reduce tool wear, thereby extending tool life. As a result, it offers a practical option for industrial applications where both high quality and cost-effectiveness are important.

Acknowledgements

The authors thank the Ministry of Education for funding and Universiti Teknikal Malaysia Melaka (UTeM) for funding and for providing the laboratory facilities that enabled this work.

Funding
The authors appreciate the financial support from the Ministry of Education (MOE) and Universiti Teknikal Malaysia Melaka (UTeM). Industrial Matching Grant, INDUSTRI(URMG)/EISSB/FTKMP/2023/I00078 and INDUSTRI(URMG)/MAWEA/2024/FTKIP/I00096 were utilised to fund the project.

Declaration of Competing Interest
The author declares no conflicts of interest.

CRediT Authorship Contribution Statement
Syed Mohd Fadly Syed Hassan (Conceptualisation; Methodology; Investigation; Data curation; Formal analysis; Writing - original draft)
Syahrul Azwan Sundi (Supervision; Validation; Formal analysis; Writing - review & editing; Project administration)
Mohd Hakim Mohd Ramaly (Investigation; Resources; Data curation)
Izzat Afandi Abdul Hakim (Formal analysis; Visualisation; Writing - review & editing)
Mazran Ahmad (Validation; Writing - review & editing)
Raja Izamshah (Resources; Supervision; Funding acquisition)
Intan Sharhida Othman (Methodology; Formal analysis; Writing - review & editing)
Raymond Loh (Resources; Technical support)

Availability of Data and Materials
The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors stated that generative AI was not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

References

[1] H. Xiao, T. Liu, T. Li, Y. Duan, "Design of damage-resistant hybrid lay-up structures for fiber-reinforced composites based on interface properties," *Composite Structures*, vol. 319, p. 117210, 2023.
[2] C.L. Tan, A.I. Azmi, N. Muhammad, "Delamination and surface roughness analyses in drilling hybrid carbon/glass composite," *Materials and Manufacturing Processes*, vol. 31, no. 10, pp. 1366–1376, 2016.
[3] I. O. Oladele, T.F. Omotosho, and A. A. Adediran, "Polymer-based composites: An indispensable material for present and future applications," *International Journal of Polymer Science*, vol. 2020, no. 1, p. 8834518, 2020.
[4] A. Raheem, K.M. Subbaya, "A review on hybrid composites used for marine propellers," *Material Science Research India*, vol. 18, no. 1, pp. 1–6, 2021.
[5] M. Hashish, "Trimming of CFRP Aircraft Components," in *Proceedings of the 2013 WJTA-IMCA Conference and Expo*, Houston, TX, USA, Sep. 2013.
[6] M.A. Karataş and H. Gökkaya, "A review on machinability of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composite materials," *China Ordnance Society*, vol. 14, no. 4, pp. 318-326, 2018.
[7] M. Slamani, J.F. Chatelain, "A review on the machining of polymer composites reinforced with carbon (CFRP), glass (GFRP), and natural fibers (NFRP)," *Discover Mechanical Engineering*, vol. 2, no. 1, p. 4, 2023.
[8] S. Kesarwani, R.K. Verma, "Investigation on interface temperature and parametric optimization during machining of reduced graphene oxide nanoflakes dispersed polymer-based carbon fiber reinforced (rGO/CF) nanocomposites," *Silicon*, vol. 14, no. 17, pp. 11181–11198, 2022.
[9] W. Xu, L. Zhang, "A new approach to characterising the surface integrity of fibre-reinforced polymer composites during cutting," *Composites Part A: Applied Science and Manufacturing*, vol. 103, pp. 272–282, 2017.
[10] U. Farooq, M.S. Ahmad, S.A. Rakha, N. Ali, A.A. Khurram, T. Subhani, "Interfacial mechanical performance of composite honeycomb sandwich panels for aerospace applications," *Arabian Journal for Science and Engineering*, vol. 42, no. 5, pp. 1775–1782, 2017.
[11] A.G. David, V.S. Ramalingam, A.P. Chandran, A. Ramachandra, A. Selvam, "Statistical modelling and assessment of surface roughness in drilling of hybrid fiber composite," *Multidisciplinary Science Journal*, vol. 6, no. 3, p. 2024019, 2024.
[12] A. Caggiano, V. Lopresto, R. Teti, "Improved tool geometry to enhance surface quality and integrity in trimming of cfrp composite materials," in *Procedia CIRP*, Elsevier B.V., 2017, pp. 187–192.
[13] F. Wang, G. Bi, X. Wang, X. Zhao, "Influences of milling strategies and process parameters on the cavity defect generated during milling of carbon fiber reinforced polymer," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 235, no. 4, pp. 723–733, 2021.
[14] S.A. Sundi, R. Izamshah, M.S. Kasim, M.F. Jaafar, M. H. Hassan, "Milling/trimming of carbon fiber reinforced polymers (CFRP): Recent advances in tool geometrical design," *Machining and Machinability of Fiber Reinforced Polymer Composites*, pp.101-128, 2021.
[15] D. Ozkan, M.S. Gok, H. Gokkaya, A.C. Karaoglanli, "Effects of machining parameters on delamination failure in milling of multi-directional CFRP laminate with uncoated carbide cutting tools," *Emerging Materials Research*, vol. 8, no. 4, pp. 673–685, 2019.

[16] S. Gara, S. M'hamed, O. Tsoumarev, "Temperature measurement and machining damage in slotting of multidirectional CFRP laminate," *Machining Science and Technology*, vol. 22, no. 2, pp. 320–337, 2018.

[17] U. A. Khashaba and A. A. El-Keran, "Drilling analysis of thin woven glass-fiber reinforced epoxy composites," *Journal of Materials Processing Technology*, vol. 249, pp. 415–425, 2017.

[18] H. Wang, J. Sun, J. Li, L. Lu, N. Li, "Evaluation of cutting force and cutting temperature in milling carbon fiber-reinforced polymer composites," *International Journal of Advanced Manufacturing Technology*, vol. 82, no. 9–12, pp. 1517–1525, 2016.

[19] S.A. Sundi, R. Izamshah, M.S. Kasim, "Effect of machining parameters on surface roughness in edge trimming of carbon fiber reinforced plastics (CFRP)," *Tribology Online*, vol. 15, no. 2, pp. 53–59, 2020.

[20] S.A. Sundi, R. Izamshah, M.S. Kasim, M.K.A. Abdullah, "Effect of machining parameters on surface quality during edge trimming of multi-directional CFRP material: Taguchi method," in *IOP Conference Series: Materials Science and Engineering*, vol. 469, no. 1, p. 012095, 2019.

[21] G. Zhu, Y. Zhang, X. Niu, C. Duan, Z. Wang, X. Zhao, "Novel multiscale modeling strategy for hybrid fiber reinforced composites," *International Journal of Mechanical Sciences*, vol. 287, p. 109997, 2025.

[22] J. Xiao, G. Wang, H. Su, P. Huang, "Study on cutting force and induced thermal damage of carbon fiber reinforced polymer composites using microscopic simulation modeling," *Polymer Composites*, vol. 43, no. 3, pp. 1626–1636, 2022.

[23] N. Li, J. Y. Sheikh-Ahmad, A. El-Sinawi, V. Krishnaraj, "Multi-objective optimization of the trimming operation of CFRPs using sensor-fused neural networks and TOPSIS," *Measurements*, vol. 132, pp. 252–262, 2019.

[24] F. Hafeez, D.J. Devan, J. Sheikh-Ahmad, F. Almaskari, "Wear mechanism and quantification of polycrystalline diamond milling cutter in high-speed trimming of carbon fiber reinforced epoxy," *International Journal of Refractory Metals and Hard Materials,* vol. 106, p. 105863, 2022.

[25] S.A. Sundi, R. Izamshah, M.S. Kasim, M.F. Jaafar, M.H. Hassan, "Surface roughness and cutting forces during edge trimming of multi-directional carbon fiber reinforced polymer (CFRP)," in *Lecture Notes in Mechanical Engineering*, Springer Science and Business Media Deutschland GmbH, 2020, pp. 409–415.

[26] M.P. Jenarthanan, V.S.S. Gujjalapudi, V. Venkataraman, "Multi-objective optimization in end-milling of glass fiber reinforced polymer composites using desirability functional analysis and grey relational analysis," *Multidiscipline Modeling in Materials and Structures*, vol. 13, no. 3, pp. 391–408, 2017.

[27] S. Ghafarizadeh, J F. Chatelain, G. Lebrun, "Effect of cutting tool lead angle on machining forces and surface finish of CFRP laminates," *Science and Engineering of Composite Materials*, vol. 23, no. 5, pp. 543–550, 2016.

[28] M.H. El-Hofy, S.L. Soo, D.K. Aspinwall, W.M. Sim, D. Pearson, R. M'Saoubi et al., "Tool temperature in slotting of CFRP composites," in *Procedia Manufacturing*, pp. 371–381, 2017.

[29] H. Wang, J. Sun, J. Li, L. Lu, N. Li, "Evaluation of cutting force and cutting temperature in milling carbon fiber-reinforced polymer composites," *International Journal of Advanced Manufacturing Technology*, vol. 82, no. 9, pp. 1517–1525, 2016.

[30] K. Berkowitz, D.E. Sommer, B.T. Werner, K.N. Long, A.J. Skulborstad, "Comparison of interlaminar damage modeling strategies for hybrid composite/aluminum laminates subjected to low-velocity impact," *Composite Structures,* vol. 372, p. 119534, 2025.

[31] I.I. M. Priya, K. Palanikumar, N. Senthilkumar, P.S. Prabha, "Investigation of delamination and surface roughness in end milling of glass fibre reinforced polymer composites using fuzzy model and grey wolf optimizer," *International Journal on Interactive Design and Manufacturing*, vol. 18, no. 2, pp. 749–769, 2024.

[32] M. P. Jenarthanan, A. L. Prakash, R. Jeyapaul, "Experimental investigation and analysis of factors influencing delamination and surface roughness of hybrid GFRP laminates using Taguchi technique," *Pigment and Resin Technology*, vol. 45, no. 6, pp. 463–475, 2016.