Journal of Engineering and Technological Sciences

Research Paper

Influence of Machining Parameters on Surface Roughness in Trochoidal Milling of Ti-6Al-4V via Response Surface Methodology

Nur Aina Farhanah Aziz[1], Norfauzi Tamin[1*], Kahirol Mohd Salleh[1], Hairizal Osman[2], & Tun Danish Tun Mohamed Kamarul[3]

[1]Faculty of Technical and Vocational Education, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat 86400, Johor, Malaysia
[2]Faculty of Industrial and Manufacturing Technology and Engineering, Universiti Teknikal Malaysia Melaka, Air Keroh, Melaka 75400, Malaysia.
[3]Resonac Pte Ltd, 2 Pioneer Cres, Singapore 628553, Singapore

*Corresponding author: norfauzi@uthm.edu.my

Abstract

Machining of Ti-6Al-4V titanium alloy poses significant challenges, mainly due to its low thermal conductivity and tendency to form a built-up edge (BUE), which can lead to high surface roughness (*Ra*) and rapid tool wear. In this context, the trochoidal milling strategy emerges as a promising solution, as it can reduce thermal and mechanical loads by using a spiral-shaped tool path with intermittent contact between the tool and Ti-6Al-4V. Therefore, this research aims to evaluate the effectiveness and optimise the machining parameters, specifically, cutting speed (v_c) and feed rate (v_f), when using the trochoidal strategy for machining Ti-6Al-4V, with the primary objective of minimising *Ra*. The methodology used is Response Surface Methodology (RSM) with a Central Composite Design (CCD) to model the nonlinear relationships among v_c, v_f, and *Ra*. The experiment was conducted using a 3-axis CNC machining centre with carbide cutting tools. Based on the optimisation results, the optimal parameter combination to minimise *Ra* is 155 m/min for v_c and 124 mm/min for v_f. Experimental validation tests of the predicted optimal parameters yielded an *Ra* value of 0.118 µm, with an error of 2.47% relative to the RSM-predicted value, confirming the model's applicability. In conclusion, this research confirms that targeted parameter optimisation using RSM is highly effective in improving the surface quality of Ti-6Al-4V, further proving the potential of the trochoidal strategy as an efficient method for critical applications in the aerospace and biomedical sectors where surface integrity is a prerequisite.

Keywords: *CNC milling; parameters; surface roughness; Ti-6Al—4V; trochoidal.*

Introduction

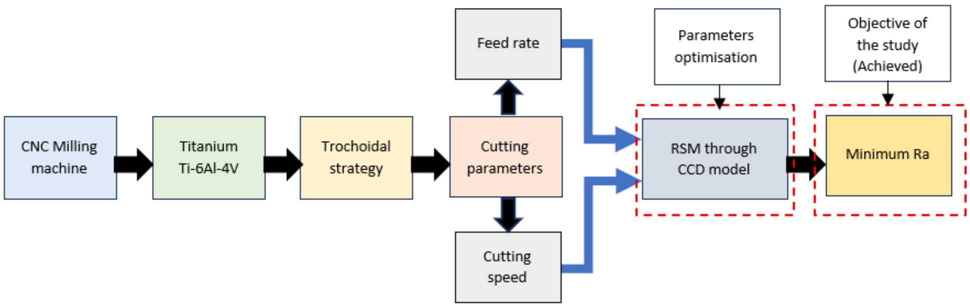
Titanium Ti-6Al-4V (also known as Grade 5) is the most used titanium alloy, characterised by high strength, low weight, and excellent corrosion resistance. This alloy contains approximately 6% aluminium (*Al*) and 4% vanadium (*V*), providing an ideal balance of properties and making it suitable for critical applications in the aerospace industry (engine components and aircraft structures) and in medicine (biocompatible implants) (Wu, 2022). It can be heat-treated to increase its strength and maintain its mechanical properties even at high temperatures (Jin et al., 2023). To achieve product quality in machining Ti-6Al-4V, the use of computer numerical control (*CNC*) is critical for precise control of cutting parameters such as *vc*, v_f, and axial depth of cut (*ap*).

Manufacturing Ti-6Al-4V via CNC milling presents significant challenges due to the material's unique properties, particularly regarding *Ra*. Compared to conventional milling, CNC milling is essential because it enables more precise and consistent control of cutting parameters, thereby reducing vibration and heat buildup and minimising Ra in this difficult-to-machine titanium alloy (Patil et al., 2024; Asalekar & Rama Sastry, 2024). Ti-6Al-4V is known for its high strength, light weight, and excellent corrosion resistance, making it essential in aerospace and medical applications. However, its low thermal conductivity and high hardness make it difficult to machine. These characteristics cause intense heat generation in the cutting tool, which cannot be efficiently dissipated through the chips or the workpiece, thereby increasing the tool wear rate and, consequently, the *Ra* of Ti-6Al-4V (Cagan & Buldum, 2023). Therefore, the

ISSN: 2337-5779
DOI: 10.5614/j.eng.technol.sci.2026.58.5.3

machining process requires optimised cutting strategies, such as low *vc*, high v_f, and effective high-pressure cooling, to aggressively manage the cutting zone temperature, ensure workpiece integrity, and extend tool life. It is also necessary to effectively manage the high temperatures in the cutting zone, which can exceed 550°C due to the material's low thermal conductivity (Hoyne et al., 2015; Ueda et al., 2020). Other than conventional cutting methods (linear cutting), trochoidal strategies can help significantly reduce the thermal and mechanical loads on the cutting tool when machining Ti-6Al-4V (Deng et al., 2020). This is achieved by using an arc-shaped cutting path that maintains a consistently slight radial contact angle, allowing for longer cooling times and better heat dissipation, thereby increasing the material removal rate. Furthermore, trochoidal machining tends to produce lower *Ra* because it reduces vibration during machining (Józwik, 2019; Lin et al., 2020). Ultimately, this improved final surface quality is critical for aerospace and biomedical components, where surface integrity directly affects fatigue performance and product reliability.

In this paper, the aim is to determine an optimal set of machining parameters (v_c and v_f) to achieve the minimum *Ra* using a trochoidal strategy during the machining of Ti-6Al-4V alloy. This involves implementing a detailed experimental design using the Response Surface Method (RSM), in which the interactive effects of v_c and v_f on surface quality parameters are statistically analysed. This optimisation aims to reduce thermal and mechanical stresses, a significant challenge in titanium machining, while also achieving superior surface integrity, essential for critical applications in the aerospace and biomedical sectors.



Pipelines of the study.

This research differs from most previous research, in which researchers used simpler statistical methods, such as complete factorial Design of Experiments (*DOE*) or Taguchi methods (Mgherony et al., 2020; Li et al., 2021). This method can be improved by using RSM to model the nonlinear relationship between the input and output parameters to obtain the minimum *Ra*. This paper uses RSM, which enables researchers to model and optimise the combined effects of multiple variables (*vc* and v_f) in greater detail. It is very effective at finding the exact optimal point rather than simply identifying the most critical parameters. Some researchers prioritise parameter optimisation for material removal rate (*MRR*) or tool wear in conventional cutting (linear cutting), without considering the effects on surface quality (Amaro et al., 2018). Additionally, other studies have focused on optimising machining processes for simpler materials such as mild steel or aluminium (Deng et al., 2020; Javidikia et al., 2021).

While this study focuses on Ti-6Al-4V, it directly addresses the Ra problem in critical engineering applications (e.g., aerospace and medical), where this alloy is commonly used. This approach is critical because the trochoidal strategy, which better manages heat, shifts the focus from preventing tool failure to improving final surface quality. Future research recommendations would focus on dynamic measurements of cutting temperature. Given that conventional instability may result from inefficient thermal management at high vc, research should focus on temperature measurements at the cutting zone of Ti-6Al-4V for both methods. This needs to be investigated to confirm the hypothesis that trochoidal milling, with its alternating engagement/release cycles, results in lower average cutting zone temperatures or more favourable thermal cycling that extends tool life. Further studies focus on tool life and failure modes. While the Ra data indicate process stability, in-depth studies of tool life and failure modes (e.g., flank wear versus crater or chip wear) under high vc parameters are important. This will confirm whether the trochoidal Ra stability directly translates into reduced operating costs and downtime.

Materials and Methods

Ti-6Al-4V (Grade 5) titanium alloy, available as a 200 mm x 200 mm x 50 mm block, is a frequently used choice for machining studies. This alloy, which has an excellent strength-to-weight ratio, corrosion resistance, and high-temperature resistance, is often used in critical applications such as aerospace and medical ones. However, its intrinsic properties, especially low thermal conductivity and tendency to work harden, make it very difficult to machine. Table 1 shows the mechanical properties of the Ti-6Al-4V used in this study.

DOI: 10.5614/j.eng.technol.sci.2026.58.5.3

Table 1 Ti-6Al-4V physical properties

Hardness (HRC)	Melting point (°C)	Yield strength (MPa)	Tension strength (MPa)	Elongation at break (%)
41	1649	483	550	15

The CNC vertical milling machine was used in this study to evaluate the machinability of materials, such as titanium, under various cutting parameters. This high-precision machine allows researchers to consistently and precisely control key variables such as *vc* and v_f. With the CNC machine, researchers can conduct controlled experiments to study the effects of varying *vc* and v_f on surface quality using the trochoid. Figure 2 shows the movement of the trochoid in CATIA V5 software. Machining was performed using a 10 mm diameter tool with an axial depth (ap) of 5 mm and a cutting width (ae) of 13 mm, with a 15% (1.5 mm) stepover of the tool diameter per trochoid cycle. To optimise the surface quality measured as average *Ra*, a comprehensive experimental design was established. This study focused on the effects of varying *vc* and v_f as the main parameters, while holding ap constant. Based on the initial suggestion from the cutting tool packaging box, this parameter range was expanded to include several levels of *vc* and v_f (as detailed in Table 2) to effectively evaluate the full influence of each parameter on *Ra*.

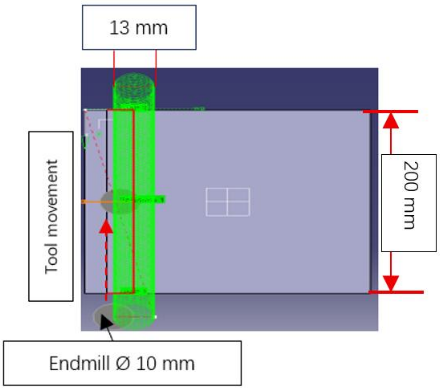


Figure 2

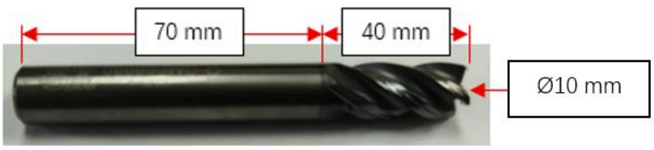
CNC Milling machine (Hwacheon model), and (b) Trochoidal method.

Table 2 Parameter ranges

Cutting speed (m/min)	Feed rate (mm/min)	Radial depth of cut (mm)	Radial depth of cut (mm)	Stepover (%)
140-160	100-160	5	13	15

The 10 mm diameter cutting tool shown in Figure 3 is a solid-carbide end mill (four flutes) ideal for trochoidal machining of difficult-to-machine materials such as Ti-6Al-4V. Table 3 shows the end mill specifications used. The multi-flute design increases v_f, and the solid carbide provides the hardness and wear resistance needed to withstand the high temperatures and cyclic cutting forces encountered in trochoidal machining. The trochoidal cutting strategy uses this tool with a small *ae* but a considerable *ap*, allowing for efficient chip removal and reduced thermal load on each tool tooth.

Figure 3



Carbide endmill.

Table 3 Specification of the four-flute cutting tool used

Parameter	Value (angle)
Helix angle	35°
Radial rake angle	10°
Axial rake angle	10°
clearance angle	8°

The *vc* and v_f values presented in Table 4 were generated using RSM (Design-Expert 13 software). The simulation adhered to the parameter range specified in Table 2 and incorporated a constant *ap* and the experimentally derived *Ra*. The statistical methodology employed in this study is RSM, which facilitates modelling and analysis of interactions between independent (explanatory) variables and dependent (response) variables. This study employed the Central Composite Design (CCD) method using a face-centred option. This experimental setup involved two factors (*vc* and v_f), was based on a second-degree polynomial model, and included three centre points to boost model accuracy. This resulted in 13 runs for the machining tests. To determine the statistical significance of the RSM model and assess the influence of each machining parameter, an analysis of variance (ANOVA) was performed.

Table 4 Cutting parameters and *Ra* average results

Run	v_c (m/min)	v_f mm/min	*ap* mm	*Ra* 1 µm	*Ra* 2 µm	*Ra* 3 µm	Average *Ra* µm
1	140	200	2.0	0.15	0.14	0.18	0.16
2	150	150	2.0	0.11	0.11	0.12	0.11
3	145	200	2.0	0.16	0.17	0.17	0.17
4	140	150	2.0	0.15	0.16	0.15	0.15
5	150	200	2.0	0.2	0.21	0.2	0.20
6	145	100	2.0	0.12	0.13	0.11	0.12
7	140	100	2.0	0.14	0.14	0.11	0.13
8	150	100	2.0	0.11	0.13	0.12	0.12
9	160	100	2.0	0.13	0.15	0.12	0.13
10	150	150	2.0	0.12	0.11	0.13	0.12
11	160	160	2.0	0.15	0.18	0.12	0.15
12	150	150	2.0	0.12	0.11	0.11	0.11
13	160	200	2.0	0.19	0.18	0.19	0.19

Lowest

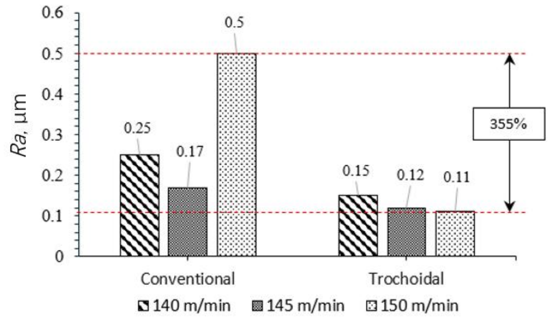
Result

In the first phase, a comparison was conducted between conventional and trochoidal machining methods. The comparison aimed to evaluate the effectiveness of each technique based on the minimum *Ra* value achieved with the specified v_c and v_f parameters. The next phase involves conducting a trochoidal strategy. These parameters (focus to trochoidal) are generated via RSM using a CCD with defined ranges. This method is essential for optimising the process and finding the best parameter combination. The results from these experiments are then analysed statistically.

Conventional Versus Trochoidal Strategy

Figure 4 shows a clear comparison of surface quality (Ra) between the conventional (linear) and trochoidal machining strategies for Ti-6Al-4V, with vc and vf varied. Overall, trochoidal machining is far superior, producing consistently low Ra values (0.11-0.15 µm) and demonstrating high stability as vc increases, even reaching the lowest Ra (0.11 µm) at the highest vc (150 m/min). In contrast, the conventional method shows significant instability: although it achieves an Ra as low as 0.17 µm at 145 m/min, increasing vc to 150 m/min results in a dramatic degradation of surface quality to 0.50 µm. The difference between the worst Ra of Conventional (0.50 µm) and the best Ra of Trochoidal (0.11 µm) is a 355% improvement in surface quality, confirming that Trochoidal machining is a more robust and high-performance strategy for managing the challenges of machining Ti-6Al-4V at higher vc.

Figure 4

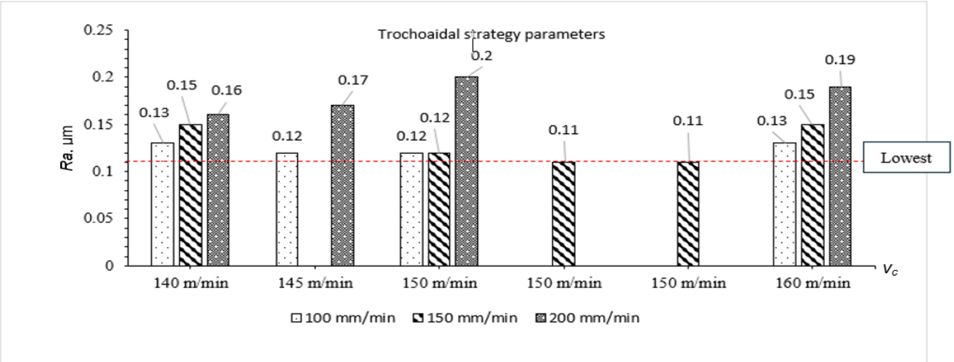


Comparison between conventional and trochoidal strategies.

DOI: 10.5614/j.eng.technol.sci.2026.58.5.3

Trochoidal Optimisation

Figure 5 shows the effect of the combination of v_c and v_f on *Ra* achieved using the trochoidal machining strategy. In general, the surface quality remains in an excellent range (0.11 µm—0.20 µm), demonstrating the inherent stability of the trochoidal method. However, two main trends stand out: First, *Ra* tends to increase with v_f for most v_c values, especially at 200 mm/min (e.g., at v_c = 150 m/min, *Ra* increases to 0.20 µm). Second, the most optimal surface quality (*Ra* ≈ 0.11 µm) is achieved at v_c 150 m/min with 150 mm/min v_f and also at 150 m/min v_c with 100 mm/min v_f (although 100 mm/min and 200 mm/min data are missing for some runs), suggesting that the combination of higher v_c and moderate v_f is the sweet spot for minimising *Ra* in trochoidal machining of Ti-6Al-4V. The study indicates that there is a complex interaction among cutting parameters that must be balanced to avoid vibration or increased chip load, which could affect quality. Therefore, for optimum efficiency and *Ra* quality, further research should focus on a v_c range of around 150 m/min while maintaining v_f at 150 mm/min.



Comparison of cutting parameters on *Ra* result.

ANOVA Results for Responses

Verification in Table 5 indicates that the model's residuals contain only pure error, thereby confirming the acceptability of removing these terms. Analysis of Variance (ANOVA) showed that the overall regression model was statistically significant (p-value = 0.0012 < 0.05), confirming that the independent variables considered had a significant effect on the response. The significance of this model was supported by the high F-value of 14.2. Both individual terms in the model, B-v_f (p-value 0.0009) and B^2 (p-value 0.0275), were significant, indicating that both linear and quadratic effects of the factors were important in explaining the response. In terms of fit quality, the model performed well, as the lack-of-fit test was not significant (p-value = 0.0925 > 0.05), indicating that the model is well-suited to predicting and explaining the relationship between variables within the experimental range. Furthermore, the coefficient of determination (R^2) of 0.7396 indicates that approximately 73.96% of the variation in the data is explained by the model. In contrast, the Adeq Precision value of 6.8668, which exceeds 4, indicates that the model has a sufficient signal-to-noise ratio and can be used for optimisation.

Table 5 ANOVA for the *Ra* - Quadratic Model.

Source	Sum of squares	df	Mean square	F-value	P-value	Contribution
Model	0.0079	2	0.0039	14.2	0.0012	significant
B- Vf	0.006	1	0.006	21.76	0.0009	
B^2	0.0018	1	0.0018	6.64	0.0275	
Residual	0.0028	10	0.0003			
Lack of Fit	0.0027	8	0.0003	10.18	0.0925	Not significant
Pure Error	0.0001	2	0			
Cor total	0.0107	12				
R^2						0.7396
Adjusted R^2						0.6876
Predicted R^2						0.5710
Adeq. precision						6.8668

Independent variable really affects the output

The model is good enough to explain the relationship between variables (p>0.05)

Regression Mathematical Model

This regression model predicts *Ra* as a function of machining factors. Eq. (1) represents the general quadratic mathematical model, where β is a coefficient to be determined by data analysis. Eq. (2) is the empirical expression obtained from the analysis, using the coded factor B (a unit-independent scale). In Eq. (2), all coefficients are positive, indicating a positive linear and quadratic relationship in the domain of the coded variable.

$$Ra = \beta 0 + \beta 1\mathrm{B} + \beta_{11}\mathrm{B}^2 \quad (1)$$

$$Ra = 0.1280 + 0.0275 * \mathrm{B} + 0.0245 * \mathrm{B}^2 \quad (2)$$

Eq. (3) is the most important operating model because it uses the real factor v_f, making it useful for practical applications. The negative coefficient of -2.390000 in the linear term v_f indicates that, initially, increasing the value of v_f will reduce *Ra*. However, the presence of a significant coefficient of +9.8000 in the quadratic term v_f^2 indicates that the relationship is strongly curved upwards. This combination of a strong negative linear term and a strong positive quadratic term indicates that there is a minimum-optimum point for *Ra*. When the value of v_f passes this optimum point, the quadratic effect will dominate, causing *Ra* to increase rapidly again, providing a clear guide for machining operations.

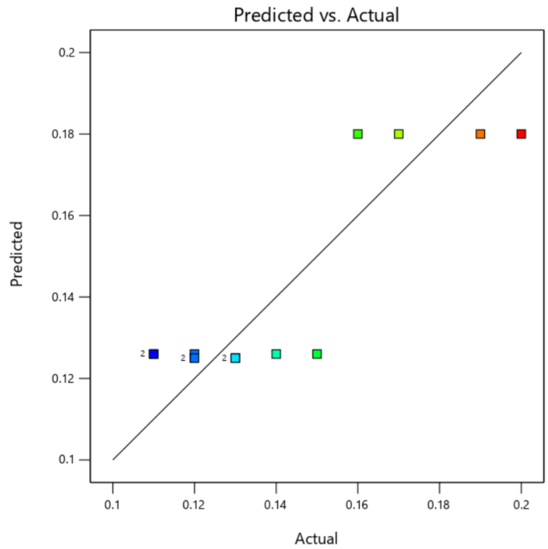
$$Ra = 0.266000 - 2.390000\, v_f + 9.8000\, v_f^2 \quad (3)$$

The equation in terms of actual factors can be used to predict the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor, because the coefficients are scaled to the units of each factor, and the intercept is not at the centre of the design space.

Predicted vs Actual

Figure 6 shows a plot of predicted versus actual values to assess the quality of the regression model. Most of the data points on the left fall reasonably close to the line; there is significant scatter and error on the right. These points lie well above or below the line, indicating that the model tends to predict these values with greater error. This scatter indicates a moderate-to-poor model fit at higher values, suggesting the model may not adequately capture the full variation in the response or that the data have high error variance. Technically, this shows that the model's R^2 value is low (73.96%). The data also show that the model is better at predicting low Ra than high surface roughness.

Figure 6

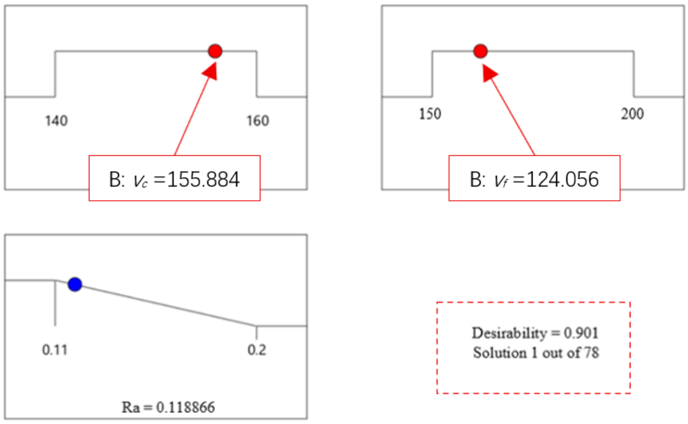


Predicted versus actual experiment.

Confirmation

In this analysis, the optimisation goal was set to “in range", with the target to minimise the output response, as shown in Figure 7. The desirability function follows the “smaller-is-better” rule. From Figure 8, the best cutting parameters were *vc* = 155.884 m/min and v_f = 124.056 mm/min, yielding a *Ra* of 0.1186 µm and a desirability of 90.1%. These conditions were then tested in an actual machining process to confirm the results.

DOI: 10.5614/j.eng.technol.sci.2026.58.5.3



Optimal process parameters using RSM.

Figure 7

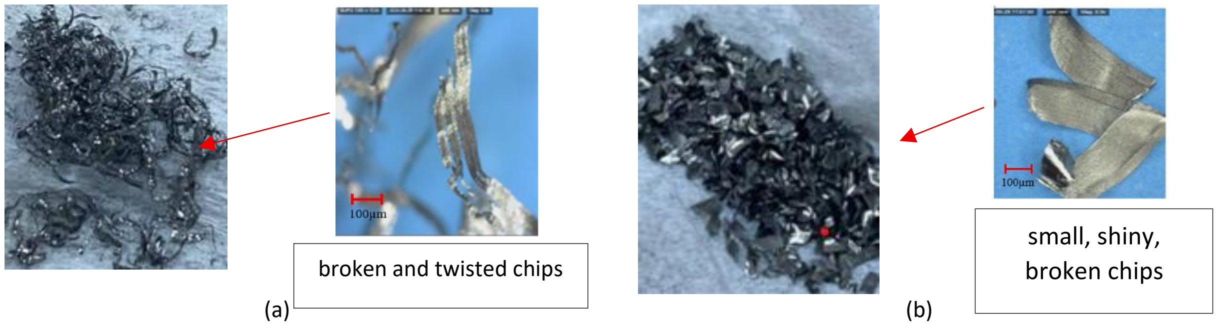
The *Ra* model validation was rerun using the proposed *vc* and v_f with the optimal process parameters, and the average *Ra* value across three runs is reported in Table 6. The predicted and experimental values were compared, and the percentage error was calculated at 2.47%, indicating an error of less than 10%. The validation results showed that the measured *Ra* value was within the optimal confidence range (>97%) at *vc* = 155 m/min and v_f = 124 mm/min, confirming the model's accuracy. The actual machining parameters to produce the minimum *Ra* differ from the validation parameters suggested by RSM because the RSM model is only a mathematical approximation of a complex physical machining system, which is always subject to experimental errors and random variations that the regression equations do not fully account for. RSM is a statistical and mathematical technique that approximates physical phenomena that are challenging to capture accurately through first-principles modelling (Pathapalli et al., 2021; Suhaimey et al., 2025). Although initial machining experiments found the absolute lowest *Ra* (0.11 µm at *vc* = 150 m/min and v_f = 150 mm/min), RSM has recommended statistically optimised settings (*vc* = 155 m/min and v_f = 124 mm/min) which, when validated, produce a very close Ra (0.12 µm). This small difference of 0.01 µm demonstrates the RSM model's effectiveness as a predictor. More importantly, the RSM prediction successfully confirmed that reducing v_f to a lower value (124 mm/min) was the main determining factor for achieving optimal surface quality, consistent with the finding that v_f was the dominant factor. Therefore, the RSM model provided a more stable and reproducible operating point to achieve low *Ra* within the tested experimental range.

Table 6 Parameter confirmation.

Machining parameter		Actual value, *Ra*	Experimental value			Mean	% Error
v_c	v_f		1	2	3		
155	124	0.118	0.121	0.119	0.123	0.121	2.47

Effect on Chip Formation

Figure 8(a) shows the chip formation at vc = 150 m/min and vf = 200 mm/min, which produces the highest Ra (0.2 µm). Figure 9(b) shows 150 m/min at 150 mm/min vf, producing the minimum Ra (0.11 µm) and displaying a collection of small, broken, segmented chip fragments, a direct result of the serrated roll formation process. The lower vf results in a rapid temperature increase in the shear zone, and because of the low thermal conductivity of titanium alloys, this thermal stress cannot be relieved. As a result, although the original chip segments may have been thinner than in Figure 8(b), the roll has completely broken apart and is no longer connected. This morphology is ideal for chip management, as it avoids long scrolls that can cause warping or damage to the machine. However, it inherently leads to instability in cutting force and high peak temperatures in the cutting zone, increasing the risk of accelerated Ra (Bui et al., 2023; Kraynev et al., 2023).



Chip formation at (a) 200 mm/min v_f and (b) 150 mm/min v_f..

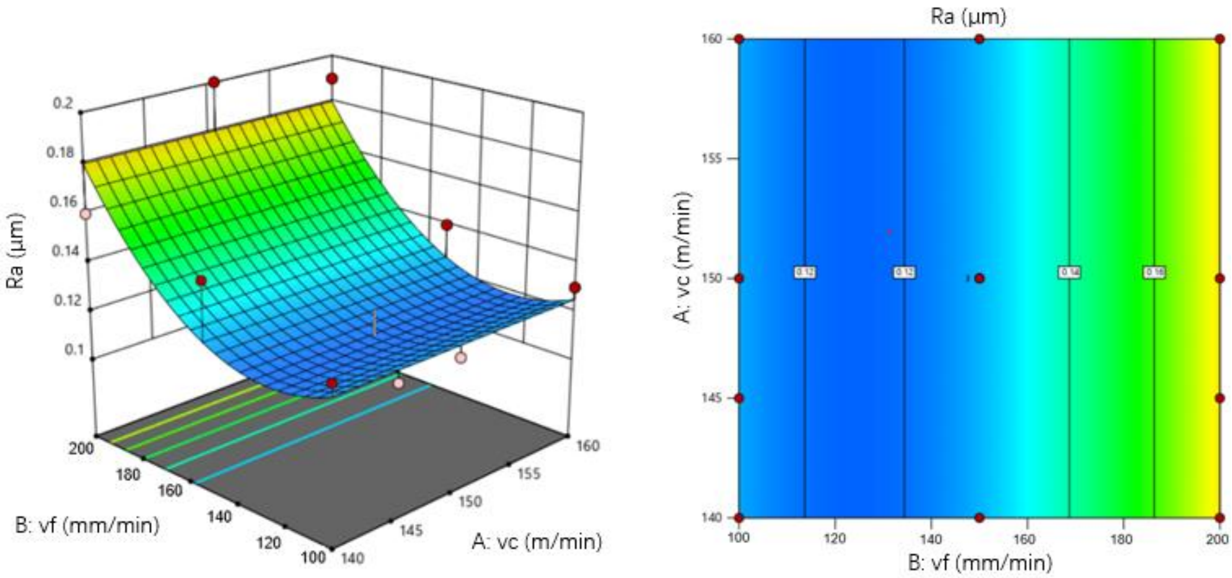
Figure 8

Discussion

Trochoidal machining has proven to be a very robust strategy compared to conventional (linear cutting). The arc-shaped tool path pattern used in trochoidal machining, with a variable tool contact angle and shorter cutting engagement duration, effectively reduces thermal and mechanical loads on the cutting edge. Trochoidal machining uses a smooth, circular-arc tool path, enabling high material removal rates with consistent cutting forces, in which continuous movement and frequent changes of direction effectively suppress chatter (Altintas et al., 2020; Grim et al., 2021). Overall, the results show that *Ra* does not depend on a single parameter but results from the interaction between *vc* and v_f. The effectiveness of trochoidal machining depends on the interaction of various parameters, which can enhance or reduce the stability gain (Korpysa et al., 2024). The interaction between *vc* and v_f governs the effectiveness of trochoidal machining, as these parameters directly influence instantaneous chip thickness, variation in cutting force, and thermal load during the process's intermittent engagement. Their combined effect not only determines the achievable stability gain through force modulation and vibration suppression but also significantly affects the resulting *Ra*, since unstable cutting conditions or excessive v_f can amplify surface irregularities despite the inherent stability advantages of the trochoidal toolpath. When both parameters are increased simultaneously, there is a tendency for surface quality to deteriorate, indicating increased cutting energy and higher vibration. However, there is an optimal operating zone in which moderate *vc* and v_f yield the lowest *Ra*. This suggests that the trochoidal strategy requires a balance of cutting loads so that its main advantages involving heat load removal, smooth tool trajectory, and friction reduction can be fully exploited. If the parameters are too high or too low, these advantages are lost, and the surface quality's repeatability is compromised.

Figure 9(a) shows a 3D response surface plot of the apparent relationship between two key cutting factors, namely, v_f and *vc*, against *Ra*. In general, *Ra* values increase when either *vc* or v_f is increased, indicating that both factors negatively affect surface quality. Increasing *vc* tends to increase tool temperature and wear, while increasing v_f directly leaves coarser feed marks (Faiz et al., 2019; Paengchit & Saikaew, 2018; Rashidi et al., 2025). In particular, the highest *Ra* values, approaching 0.2 µm, are achieved at parameter combinations where both v_f and *vc* are at their highest values. This suggests that, to minimise *Ra*, more aggressive (higher) cutting settings should be avoided. Aggressive feed and depth accelerate material removal but create instability, leading to tool marks, chatter, and excessive heat, which, in turn, increase *Ra* (Osman et al., 2018; Bakar et al., 2018; Khelfaoui et al., 2023). Figure 9(b) shows a contour plot with the axes reversed compared to the previous figure. This plot clearly shows that vf is the dominant factor affecting *Ra*. This is evidenced by the colour contours moving almost vertically, indicating that *Ra* will remain low or high, depending mainly on v_f rather than *vc*. Contour and response surface plots are graphical tools derived from quadratic regression models that illustrate how combinations of two or more input variables affect the response variable (Kumar & Reji, 2023; Datri et al., 2023). The contour and response surface plots derived from the quadratic regression model depict the combined effects of *vc* and v_f on the predicted *Ra*, revealing a predominantly increasing trend in *Ra* with increasing v_f. In contrast, *vc* exhibits a comparatively moderate influence within the investigated range. The nearly vertical contour lines indicate that *Ra* is more sensitive to variations in v_f than to variations in *vc*, demonstrating that higher v_f significantly degrades surface quality. In contrast, adjustments in *vc* produce smaller incremental changes in the output *Ra* under the studied conditions.

DOI: 10.5614/j.eng.technol.sci.2026.58.5.3



(a) (b)

Figure 9 3D surface model of (a) response surface plot and (b) contour plot.

Analysis of the chips shows a long, thin, and irregularly twisted shape, characteristic of a ribbon chip with cracks or tears in the area that produces the maximum *Ra* (as shown in Figure 8(a)). The formation of shiny colours on the chips indicates the occurrence of very high cutting temperatures during the machining process, causing oxidation of the chip surface because the heat generated cannot be efficiently dissipated to the environment or workpiece, thus creating coloured oxide layers (tempering colours) that give a rainbow-like lustre effect on the chip surface. The elongated, curved chip structure indicates semi-continuous chip cutting, which commonly occurs when high v_f or *vc* is used on ductile materials such as stainless steel or nickel alloys. This morphology arises from the localisation of partial shear and strain hardening in the main deformation zone, leading to curled chips without complete segmentation (Grguras et al., 2019; Šramhauser et al., 2024). This feature also suggests a lack of control over chip formation, which can lead to twisted chips that disrupt the cutting process or damage the workpiece surface (Olt et al., 2016; Nie et al., 2022).

Conclusion

This study systematically investigated the effectiveness of the trochoidal milling strategy for machining Ti-6Al-4V, with a primary focus on Ra and process efficiency. The findings demonstrate that trochoidal milling significantly outperforms conventional machining methods by achieving lower, more stable Ra values and increasing efficiency by up to 355%. This improvement is largely attributed to the intermittent strategy's tool engagement, which reduces mechanical and thermal stresses, thereby enhancing surface quality and minimising the BUE formation. To refine the process, RSM optimisation using a Central Composite Design (CCD) identified vf as the dominant factor affecting Ra. The resulting optimal parameters yielded a remarkable Ra of 0.118 µm, with an experimental error of only 2.47%. The statistical significance and high R^2 value of the developed RSM model ensure reliable predictions for optimal cutting parameters. Ultimately, trochoidal milling offers a cost-effective and efficient solution for machining difficult-to-cut alloys, including Inconel-based superalloys. Given that superior surface quality directly enhances fatigue life and wear resistance, this method is highly recommended for critical aerospace and biomedical applications.

Future studies could focus on evaluating the performance of trochoidal milling using cutting tools made of alumina-based ceramics with optimised sintering temperatures to study the synergistic effects of the microstructural properties of the ceramics on the surface roughness quality of Ti-6Al-4V alloys. The thermal stability of alumina-based ceramics makes them a potential candidate for high-speed machining of titanium alloys. However, performance is largely determined by the tool microstructure, with optimised sintering temperatures increasing grain boundary strength (Jalaluddin et al., 2024), thereby directly affecting the surface integrity and roughness of Ti-6Al-4V workpieces.

Acknowledgments

The authors would like to thank the grant Tier 1 Q919, Universiti Tun Hussein Onn Malaysia, for the research facilities provided during the project.

Compliance with ethics guidelines

The authors declare they have no conflict of interest or financial conflicts to disclose.

This article contains no studies with human or animal subjects performed by the authors.

References

Altintas, Y., Stepan, G., Budak, E., Schmitz, T., & Kilic, Z. M. (2020). Chatter Stability of machining operations. *Journal of Manufacturing Science and Engineering, 142*(11), 110801. ASME International. https://doi.org/10.1115/1.4047391

Amaro, P., Ferreira, P., & Simões, F. (2018). Tool wear analysis during duplex stainless steel trochoidal milling. AI*P Conference Proceedings, 1960*, 070001. https://doi.org/10.1063/1.5034897

Asalekar, A. J., & Rama Sastry, D. V. A. (2024). Enhancing high-speed CNC milling performance of Ti6Al4V alloy through the application of ZnO-Ag hybrid nanofluids. *Engineering Research Express. 6*(2), 025532. https://doi.org/10.1088/2631-8695/ad476d

Bakar, H. A., Naim, F., Faiz, M., Tamin, N. F., Umar, A., Adam, A. A., Raja, I., and Shahir, K. (2018). Fabrication and machining performance of powder compacted alumina-based cutting tool. *MATEC Web of Conferences, 150*, 04009. https://doi.org/10.1051/matecconf/201815004009

Bui, L.V., Mac, T.B., & Nguyen, D.-T. (2023). Surface roughness investigation through interplay of cutting speed and thermal-assisted machining in high-speed machining of SKD11 steel. *Journal of Machine Engineering, 23*(4), 33–42. https://doi.org/10.36897/jme/170980

Cagan, S. C., & Buldum, B. B. (2023). A green machining study to investigate the effect of nano-cutting fluid environments on the machinability of Ti6Al4V titanium alloy. Proceedings of the Institution of Mechanical Engineers, Part J: *Journal of Engineering Tribology, 237* (9), 1841–1853. https://doi.org/10.1177/13506501231188358

Datri, S. A., Nataraj, K. S., & Lakshmana, R. A. (2023). Response surface methodology statistical tool for the optimization of responses. *Global Journal of Addiction & Rehabilitation Medicine, 7*(1), 555705. https://doi.org/10.19080/gjarm.2023.07.555705.

Deng, Q., Chen, Z. C., Chang, Z., Shen, R., & Zhou, Y. (2020). A model for investigating the temperature of trochoidal machining. *Journal of Industrial and Production Engineering, 37*(4), 194–203. https://doi.org/10.1080/21681015.2020.1769749

Faiz, M. M., Hairizal, M., Hadzley, A. B., Naim, M. F., Norfauzi, T., Umar, U. A.A., Aziz, A. A., & Noorazizi, S. (2019). Effect of hydraulic pressure on hardness, density, tool wear and surface roughness in the fabrication of alumina-based cutting tool. *Journal of Advanced Manufacturing Technology, 13*(1), 23–37, 2019.

Grguras, D., Kern, M., & Pusavec, F. (2019). Cutting performance of solid ceramic and carbide end milling tools in machining of nickel-based alloy Inconel 718 and stainless steel 316L. *Advances in Production Engineering & Management, 14*(1), 27–38. https://doi.org/10.14743/apem2019.1.309

Grimm, T. J., Kharat, N. A., Potthoff, N., Mears, L., & Wiederkehr, P. (2021). Stability performance of a stochastic toolpath in machining. Volume 2A: Advanced Manufacturing. American Society of Mechanical Engineers, IMECE2021-69264, V02AT02A035. https://doi.org/10.1115/imece2021-69264

Hoyne, A. C., Nath, C., & Kapoor, S. G. (2015). Cutting temperature measurement during titanium machining with an atomization-based cutting fluid spray system. *Journal of Manufacturing Science and Engineering, 137*(2), 024502. https://doi.org/10.1115/1.4028898

Jalaluddin, M.L., Azlan, U.A.A. Rashid, M.W.A., Tamin, N. (2024). Effect of sintering temperatures on the physical, structural properties and microstructure of mullite-based ceramics. *Aims Materials Science*, *11*(2), 243–255. 10.3934/matersci.2024014.

Javidikia, M., Sadeghifar, M., Songmene, V., & Jahazi, M. (2021). 3D FE modeling and experimental analysis of residual stresses and machining characteristics induced by dry, MQL, and wet turning of AA6061-T6. *Machining Science and Technology, 25* (6), 957–983. https://doi.org/10.1080/10910344.2021.1971709.

Jin, B., Wang, Q., Zhao, L., Pan, A., Ding, X., Gao, W., Song, Y., & Zhang, X. (2023). A review of additive manufacturing techniques and post-processing for high-temperature titanium alloys. *Metals, 13*(8), 1327. https://doi.org/10.3390/met13081327

Józwik, J. (2019). Analysis of the effect of trochoidal milling on the surface roughness of aluminium alloys after milling. *Manufacturing Technology, 19*(5), 772–779. https://doi.org/10.21062/ujep/370.2019/a/1213-2489/mt/19/5/772

Khelfaoui, F., Athmane Yallese, M., Boucherit, S., Boumaaza, H., & Ouelaa, N. (2023). Minimizing tool wear, cutting temperature, and surface roughness in the intermittent turning of AISI D3 steel using the DF and GRA method. *Tribology in Industry, 45*(1), 89–101. https://doi.org/10.24874/ti.1395.10.22.01

DOI: 10.5614/j.eng.technol.sci.2026.58.5.3

Korpysa, J., Zagórski, I., Weremczuk, A., & Habrat, W. (2024). Process stability analysis during trochoidal milling of AZ91D magnesium alloy using different toolholder types. *Applied Sciences, 14*(9), 3616. https://doi.org/10.3390/app14093616

Kraynev, D. V., Tikhonova, Zh. S., Islamov, A. M., & Bondarev, A. A. (2023). Evaluation of the influence of the instability of the cutting process on the roughness parameters of the treated surface. *Izvestia Volgograd State Technical University, 8*(279), 21–24. https://doi.org/10.35211/1990-5297-2023-8-279-21-24

Kumar, R., & Reji, M. (2023). Response surface methodology (RSM): An overview to analyze multivariate data. Indian *Journal of Microbiology Research, 9*(4), 241–248. https://doi.org/10.18231/j.ijmr.2022.042

Li, Z., He, D., Xu, K., Xie, F., & Tang, K. (2021). Kinematics-based five-axis trochoidal milling process planning for deep and curved three-dimensional slots. *Journal of Manufacturing Science and Engineering, 144*(2), 021005. https://doi.org/10.1115/1.4051707.

Lin, Y. C., Wu, K. D., Shih, W. C., Hsu, P. K., & Hung, J. P. (2020). Prediction of surface roughness based on cutting parameters and machining vibration in end milling using regression method and artificial neural network. *Applied Sciences, 10*(11), 3941. https://doi.org/10.3390/app10113941

Mgherony, A. W., Mikó, B., & Drégelyi-Kiss, Á. (2020). Design of experiment in investigation regarding milling machinery. *Cutting & Tools in Technological System, 92*, 68–84. https://doi.org/10.20998/2078-7405.2020.92.09

Olt, J., Liyvapuu, A., Madissoo, M., & Maksarov, V. (2016). Dynamic simulation of chip formation in the process of cutting. *International Journal of Materials and Product Technology, 53*(1), 1-14. https://doi.org/10.1504/ijmpt.2016.076363

Osman, M. H., Tamin, N. F., Ahmad, M. N., Ab. Rahman, M. H., Wahid, M. K., Maidin, N. A., Abu Bakar, M. H., & Azahar, A. A. (2018). Effect of cutting parameters on surface roughness in dry drilling of AISI D2 tool steel by using the Taguchi method. *Journal of Advance Manufacturing Technology, 12*(1), 535–546.

Paengchit, P., & Saikaew, C. (2018). Effects of cutting speed and feed rate on surface roughness in hard turning of AISI 4140 with mixed ceramic cutting tool. *Key Engineering Materials, 779*, 153–158. https://doi.org/10.4028/www.scientific.net/kem.779.153

Pathapalli, V. R., Reddigari, M. R., Anna, E. K., Srinivasa Rao, P., & Ramana Reddy, D. V. (2021). Modeling of the machining parameters in turning of Al-5052/TiC/SiC composites: a statistical modeling approach using grey relational analysis (GRA) and response surface methodology (RSM). *Multidiscipline Modeling in Materials and Structures, 17*(5), 990–1006. Emerald. https://doi.org/10.1108/mmms-01-2021-0017

Patil, A., Sunnapwar, Prof. V. K., Bhole, Prof. K. S., Ingle, S., & Singh, D. (2024). Machinability of Ti6Al4V Alloy: tackling challenges in milling operations. *Qeios, 6*(7), 1-16. https://doi.org/10.32388/5o46nj.3

Rashidi, I. F., Tamin, N., Rani, R., Azlan, U. A., Wahab, N., Ismail, A., & Darmawan, A. S. (2025). Low machining parameters produce high cutting performance when machining AISI 1045 at dry cutting conditions using a CNC lathe machine. *Journal of Engineering and Technological Sciences, 57*(5), 590–598. https://doi: 10.5614/j.eng.technol.sci.2025.57.5.2.

Šramhauser, K., Kraus, P., Špalek, F., Černý, P., Ufitikirezi, J. de D. M., Zoubek, T., Strob, M., Kononets, Y., Kříž, P., & Vochozka, V. (2024). Intercomparison of indexable cutting inserts' wear progress and chip formation during machining hardened steel AISI 4337 and austenitic stainless steel AISI 316 L. *Materials, 17*(22), 5418. https://doi.org/10.3390/ma17225418

Tamin, N. F., Azlan, U. A. A., Hadzley, M., Remle, N. S., & Osman, M. H. (2017). Study on surface integrity of AISI 1045 carbon steel when machined by carbide cutting tool, *MATEC Web Conference, 01075*(97), 2–6. doi: 10.1051/matecconf/20179701075

Ueda, T., Suzuki, K., & Shamoto, E. (2020). Fundamental study on cutting temperature in high speed cutting of difficult-to-cut materials. Proceedings of the Machining Innovations Conference (MIC). SSRN Electronic Journal. Elsevier BV, 086-092. https://doi.org/10.2139/ssrn.3724109

Wu, Y. (2022). Application of aluminum alloy in aircraft. *Journal of Physics: Conference Series, 2228*(1), 012024. https://doi.org/10.1088/1742-6596/2228/1/012024

Manuscript Received: 17 November 2025
1st Manuscript Revision Received: 5 March 2026
2nd Manuscript Revision Received: 12 March 2026
Accepted Manuscript: 4 May 2026