



Evaluating surface roughness consistency in UVAM of Inconel 718 via coefficient of variation

Norsilawati Ngah ¹, Mohd Shahir Kasim ^{1*}, Siti Nurul Akmal Yusof ¹, Roslan Awang ¹, Afifah Zakiyyah Juri ², Raja Izamshah Raja Abdullah ³, Muhamad Akmal Mohd Zakaria ⁴

¹ Faculty of Innovative Design and Technology, University Sultan Zainal Abidin (UNISZA), MALAYSIA.

² Centre for Materials Engineering and Smart Manufacturing (MERCU), Department of Mechanical and Manufacturing Engineering, Universiti Kebangsaan Malaysia, MALAYSIA.

³ Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, MALAYSIA.

⁴ Faculty of Mechanical Engineering, Universiti Teknologi MARA, MALAYSIA.

*Corresponding author: shahirkasim@unisza.edu.my

KEYWORDS	ABSTRACT
Ultrasonic Vibration-Assisted Milling (UVAM) End milling; surface roughness Coefficient of variation (CV) Inconel 718 Taguchi method	Machining Inconel 718 presents challenges such as suboptimal surface quality and rapid cutting tool failure due to its abrasiveness and low thermal conductivity. This study looks at how consistent the surface roughness of Inconel 718 is after using ultrasonic vibration-assisted milling (UVAM), measured by the coefficient of variation (CV). Using a Taguchi L8 orthogonal array, the impacts of five machining parameters were carefully examined: ultrasonic frequency (20–27 kHz), breadth of cut (0.5–1.8 mm), depth of cut (0.5–1 mm), feed rate (0.1–0.2 mm/tooth), and cutting speed (100–140 m/min). The findings from the eight experimental runs showed that feed rate and ultrasonic frequency had less of an impact on surface quality than depth of cut, which was highest, followed by cutting speed and width of cut. A cutting speed of 140 m/min, feed rate of 0.1 mm/tooth, depth of cut of 0.5 mm, width of cut of 1.8 mm, and ultrasonic frequency of 20 kHz were determined to be the ideal parameter combination. With an average CV of 20.30%, the recorded surface roughness values varied from 0.23 to 0.58 μm , which is significantly less variability than that usually seen in conventional milling (sometimes surpassing 30%). These results illustrate how UVAM can improve surface quality and consistency.

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1.0 INTRODUCTION

Inconel 718 is well known as difficult to machine material. This a nickel based alloy that is widely used in power generation plants, aircraft engine components, and automotive parts because of excellent of mechanical properties, such as high strength, creep resistance, and thermal stability [1, 2]. Premature tool failure, poor surface finish, rapid wear, and fracture are commonly reported during the removing process of this material, resulting in reduced productivity and increased tooling costs [3]. Researchers have explored alternative methods, including introducing new cutting tool technology with advance coating features, as well as lubrication techniques such as high-pressure coolant, chilled air, nitrogen, CO₂, and minimum quantity lubrication (MQL) to address these issues [4, 5]. Despite these methods demonstrating varying levels of performance, challenges associated with machining Inconel 718 endure. Ultrasonic vibration-assisted milling (UVAM) represents a promising technique [6, 7]. Applications with high frequency vibrations in both the turning and milling processes enable higher rates of material removal that lead to improved surface finish, lowered cutting force, and reduced tool wear [8-11].

Tool wear, chip morphology, and surface quality are all significantly impacted by the tribological is based on manifest of cutting tool-workpiece interaction. The friction at the cutting region during conventional milling especially in Inconel 718 material results in the development of built-up edges (BUE) especially during low speed, which causes uneven material evaluation in chip formation which accelerates tool wear [12]. Interrupted cutting processes like milling accelerates cutting tool fracture as compared to turning process [13]. UVAM on the other hand, modifies this tool workpiece engagement by introducing high-frequency oscillations that create intermittent tool-workpiece contact. This effect significantly reduces friction, lowers tool-chip adhesion, and enhances chip evacuation, thereby enabling a more controlled and efficient cutting process [14]. Studies have shown that UVAM minimizes BUE formation and adhesion-related wear mechanisms, significantly improving tool life and surface quality [15]. Furthermore, the oscillatory micro-motion of cutting tool, promotes periodic chip segmentation, lowering cutting forces and preventing excessive heat accumulation, which is a common issue in conventional machining of nickel-based superalloys [11].

The conventional removing process, the surface roughness values recorded as low as 0.167 μm during the turning process [16], while in milling, roughness typically ranges between 0.2 and 25 μm [17]. Conventional milling using end mills, slightly improved by the surface roughness obtained, is around 0.5 μm , averaging 0.74 μm [18]. By implementing UVAM, the surface roughness values improvise with the Ra of 0.42 - 0.87 μm [8]. The measurement of surface roughness during milling presents another challenge. The standard deviation in data readings is often more scattered during milling as compared to turning processes. It is common for variations in the Ra (average surface roughness) value to reach up to 40% during milling, as reported in previous studies. This variability complicates the assessment of machining performance and underscores the need for more precise measurement techniques and process optimization. To address such inconsistencies, this study uses the coefficient of variation (CV) as a normalized metric to evaluate machining consistency, following practices established in previous tribology and machining research [19, 20].

To address the issue of data variability, a structured experiment design was employed during data acquisition stage. Among the available methods. The Taguchi method stands out as one of the reliable statistical tools for optimizing machining parameters and reducing inconsistency. It's effectively to determine the combination parameter as to achieve low cutting force, low surface

finish, longer tool life especially dealing with challenging material like Inconel 718 and Titanium [8, 21, 22].

Although many studies have focused on optimizing surface roughness in conventional machining, limited research has address process design and optimization in ultrasonic vibration assisted milling (UVAM) of Inconel 718, particularly using TialN coated carbide and the Taguchi method. This study fills that gap by combining experimental design, statistical modelling, and tribology analysis to examine the effects of UVAM on milled surface. The outcomes aim to improve machining effectiveness and provide practical strategies for enhancing the machinability of Inconel 718 in industrial application.

2.0 EXPERIMENT SETUP AND MACHINING PARAMETERS

The milling experiments were conducted on a HAAS VF-1 3-axis CNC –machine under flooded cutting conditions. To enhance the heat dissipation and lubrication, the biocompatible coolant was continuously applied onto the cutting zone. The cutting tool used was a Sumitomo round-shaped insert end mill with a 10 mm diameter and TiAlN-coated layer, specifically recommended for machining Inconel 718. The experimental setup is illustrated in Figure 1 and Figure 2, showing the integration of the tool holder with CNC machine and the cutting environment. Special focus was given to the effect of ultrasonic vibration using Nuth BT40 tool holders operating at frequency of 20 kHz and 27 kHz with a fixed amplitude of 1 μm (Figure 3). The 1 μm amplitude was selected based on the operational stability limits of UVAM system used in this study. Surface roughness (Ra) was measured using a digital surface roughness tester profilometer KR110, while the surface texture analysis was further supported by suing optical microscope. The chemical composition of the Inconel 718 workpiece is provided in Table 1.

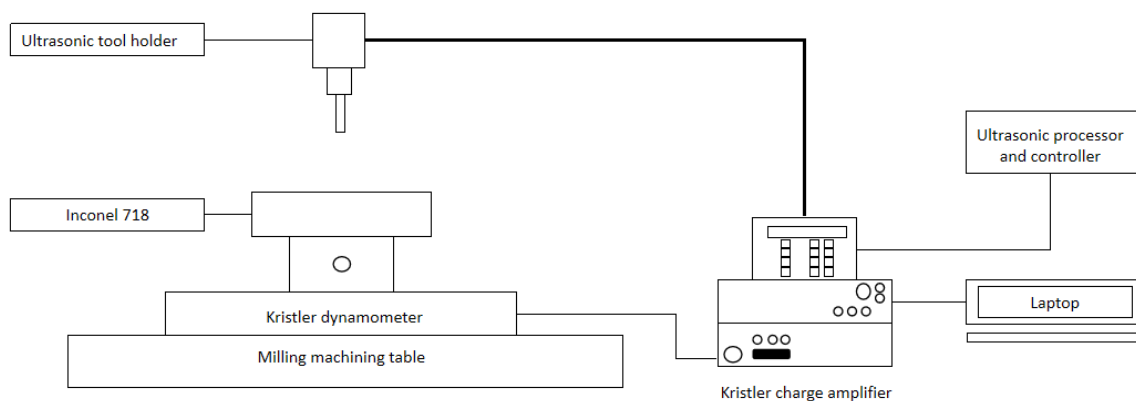


Figure 1: Schematic diagram of the overall experiment setup.

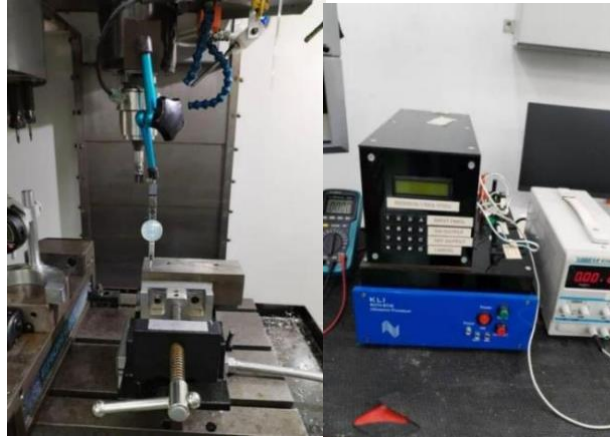


Figure 2: Experimental setup ultrasonic assisted milling.



Figure 3: Ultrasonic tool holder.



Figure 4: Digital surface roughness tester profilometer KR110.

Table 1: Chemical composition of the Inconel 718 in percentage by weight (Hynes, 2009).

Al	B	C	Nb.T a	C o	Cr	Cu	Fe	Mn	Mo	N i	P	S	Si	Ti
0.4 9	0.00 4	0.05 1	5.05	0. 3	18. 3	0.0 4	18. 7	0.2 3	3.0 5	5 3	<0.00 5	<0.00 2	0.0 8	1.0 5

As a structured statistical technique, the Taguchi approach was used to construct the experiment and optimise the surface roughness performance in Inconel 718 ultrasonic vibration-assisted milling (UVAM). Cutting speed (Vc), feed rate (fz), depth of cut (ap), width of cut (ae), and ultrasonic frequency (f) are the five main process parameters that were chosen as control elements based on the directions provided by the tooling manufacturer [23] (Sumitomo Tool Catalogue) and pertinent literature. Level 1 (low) and Level 2 (high) were the two levels assigned to each element in order to capture the range of possible operating circumstances without making the experiment too complicated. An L8 (2⁵) orthogonal array was chosen as a viable option for resource-efficient analysis since it could contain these five parameters while requiring the fewest number of experimental trials (eight total). With the use of signal-to-noise (S/N) ratios, this array makes it possible to assess the primary effects of each component and choose the ideal parameter combination. The levels chosen for each parameter are listed in Table 2, and the matching experimental run matrix based on the Taguchi L8 design is shown in Table 3.

Surface roughness (Ra) was measured at 20 different locations along the machined surface for each experimental condition using the KR110 profilometer. The mean and standard deviation from these 20 readings were used to calculate the coefficient of variation (CV), ensuring statistical reliability and consistency in evaluating surface texture.

Table 2: Cutting levels and parameters for machining.

Variable inputs	Units	Lower level (1)	Upper level (2)
Cutting speed, Vc (A)	m/min	100	140
Feed rate, fz (B)	mm/tooth	0.1	0.2
DOC, ap (C)	mm	0.5	1
WOC, ae (D)	mm	0.5	1.8
UAM Frequency, f (E)	kHz	20	27

Table 3: The Orthogonal Array of experiment from the Taguchi Method.

No of Run	Factor A	Factor B	Factor C	Factor D	Factor E
1	1	1	1	1	1
2	1	1	1	2	2
3	1	2	2	1	1
4	1	2	2	2	2
5	2	1	2	1	2
6	2	1	2	2	1
7	2	2	1	1	2
8	2	2	1	2	1

3.0 RESULTS AND DISCUSSION

3.1 Surface Roughness Measurement and Analysis

The experimental findings on surface roughness (Ra), obtained through the Taguchi method based on L8 orthogonal array are summarized in the Table 4. The Ra values for each run were measured based on five machining parameters corresponding to cutting Speed (A), Feed Rate (B), Depth of Cut (C), Width of Cut (D), and Frequency (E). Based on the data, the lowest surface roughness (Ra) value was recorded in Run 3 (A1B2C2D1E1) and Run 4 (A1B2C2D2E2), with Ra measurement of 0.23 μm and 0.26 μm respectively. This finding indicates that employing larger depth of cut (C2) leads to smoother surface finish. Conversely, the highest Ra value of 0.58 μm was observe in Run 8 (A2B2C1D2E1) which implying that smaller depth of cut (C1) results in a rougher surface.

Table 4: Results of surface roughness during the experiment.

Experimental run	Factors					Designation	Ra
	A	B	C	D	E		
1	1	1	1	1	1	A1B1C1D1E1	0.43
2	1	1	1	2	2	A1B1C1D2E2	0.45
3	1	2	2	1	1	A1B2C2D1E1	0.23
4	1	2	2	2	2	A1B2C2D2E2	0.26
5	2	1	2	1	2	A2B1C2D1E2	0.27
6	2	1	2	2	1	A2B1C2D2E1	0.35
7	2	2	1	1	2	A2B2C1D1E2	0.51
8	2	2	1	2	1	A2B2C1D2E1	0.58

The results show that UVAM significantly reduces surface roughness variability, with an average of 0.23 μm , which is less and more reliable than traditional milling. This outcome aligns with previous UVAM studies on micro milling and turning, which demonstrated similar surface roughness improvements as found by [16], who reported a minimum Ra of 0.167 μm to demonstrate how UVAM improves surface integrity by lowering tool-workpiece friction and enhancing chip evacuation. The other similar result in ultrasonic-assisted micro milling, where Ra values typically ranged from 0.3 and 0.7 μm [13].

The observation on the result contradicts common conventional machining principles, where a smaller depth of cut typically results in a better surface finish. Considering UVAM alters the cutting dynamics, enabling greater depth of cut to result in a smoother surface. It is because of how the cutting tool interacts with the material. In traditional milling, deeper cuts typically increase cutting force, heat generation, and material deformation, which worsens the surface quality. However, in UVAM, high-frequency vibration, particularly at 20 kHz superimposed on the tool's motion, causes intermittent contact between the tool and the workpiece. This pulsed engagement reduces continuous friction and minimizes sticking material on the tool surface. The finding was supported by studies by Feng, Hsu [8] and Xu, Chen [11] which highlight how ultrasonic assistance significantly improves surface quality under deeper cutting conditions. De Bartolomeis, Newman⁶ specifically noted this effect in Inconel 718, attributing it to enhanced chip evacuation by improving material flow on the tool's rake face during UVAM. Moreover, Tu, Lin

[24] found the intermittent contact between the tool and workpiece inherent in UVAM improves coolant access and heat dissipation, even at higher depth of cut. The UVAM also suppresses the BUE formation as compared to conventional milling. Collectively, these findings demonstrated that UVAM reverses the traditional assumption.

3.2 Taguchi Result

Based on Table 5 and the Main Effects Plot for S/N Ratios in Figure , the optimal machining parameters for minimizing surface roughness (Ra) in milling were identified using the "Smaller is Better" criterion. The ideal combination includes cutting speed (Vc) at Level 2, feed rate (fz) at Level 1, depth of cut (ap) at Level 1, width of cut (ae) at Level 2, and frequency at Level 1. The slopes of the graph indicate that depth of cut (ap) has the most significant impact on surface roughness, reflected by the highest Delta value of 5.028. This is followed by cutting speed (Vc) with a Delta of 1.915 and width of cut (ae) with a moderate impact (Delta = 1.208). Frequency has a smaller but noticeable effect, while feed rate (fz) appears to be the least influential, showing minimal variation in Ra. These findings highlight the critical role of controlling the depth of cut to achieve better surface finish, whereas variations in feed rate have negligible impact.

Table 5: Response Table for Signal to Noise Ratios.

Level	Cutting Speed, Vc	Feed Rate, fz	Depth of Cut, ap	Width of Cut, ae	Frequency
1	9.683	8.689	6.212	9.329	8.487
2	7.768	8.762	11.239	8.122	8.964
Delta	1.915	0.072	5.028	1.208	0.478
Rank	2	5	1	3	4

Smaller is better

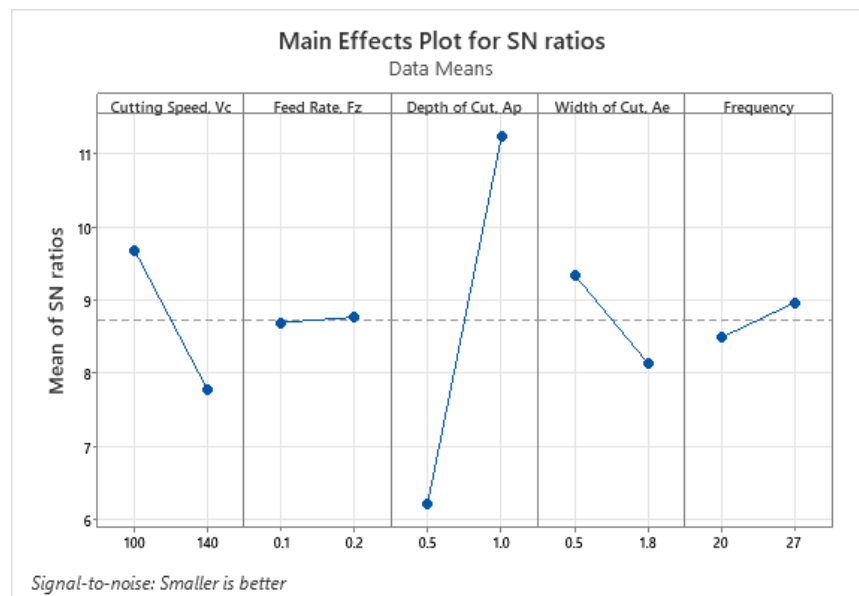


Figure 5: Main Effects Plot for SN ratios.

3.2.1 Analysis of Variance (ANOVA)

The ANOVA results in Table 6 confirm the statistical significance of machining parameters on surface roughness (Ra). All five parameters show P-values below the 0.05 threshold, indicating that their influence is statistically significant at the 95% confidence level. The depth of cut (ap) has the greatest influence on surface roughness (Ra), as evidenced by its exceptionally high F-value of 3698.00 and P-value of 0.000, making it the most significant factor among those examined. Cutting width (ae) and speed (Vc) also play a major role, with high P-values of 0.002 and 0.005 and F-values of 578.00 and 200.00, respectively. Feed rate (fz) and frequency have comparatively lower F-values of 32.00 and 50.00, but they still show significant effects on Ra with their P-values of 0.030 and 0.019. The model is adequate in capturing the effect of the chosen parameters on surface roughness, as evidenced by the small error variance (Adj MS = 0.000025).

Table 6: Variance analysis.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed, Vc	1	0.014450	0.014450	578.00	0.002
Feed Rate, fz	1	0.000800	0.000800	32.00	0.030
Depth of Cut, ap	1	0.092450	0.092450	3698.00	0.000
Width of Cut, ae	1	0.005000	0.005000	200.00	0.005
Frequency	1	0.001250	0.001250	50.00	0.019
Error	2	0.000050	0.000025		
Total	7	0.114000			

A quantitative relationship between surface roughness (Ra) and the machining parameters; cutting speed (Vc), feed rate (fz), depth of cut (ap), width of cut (ae), and frequency is established by the regression equation (Equation 1) Ra. Among these parameters, depth of cut (ap) has the most significant negative coefficient (-0.43), indicating that increasing ap results in a substantial reduction in Ra, leading to an improved surface finish. This finding is consistent with the ANOVA results, which also identified ap as the most dominant factor. Conversely, feed rate (fz) has the highest positive coefficient (+0.20), suggesting that increasing fz leads to a rougher surface. This aligns with machining principles, as higher feed rates typically generate more pronounced tool marks, increasing surface irregularities.

$$Ra = 0.462 + 2.125 \times 10^{-3}Vc + 0.2fz - 0.43ap + 3.846 \times 10^{-2}ae - 3.571 \times 10^{-3}f \quad (1)$$

The effect of cutting speed (Vc) is minor, with a small positive coefficient (+0.0021), indicating that an increase in Vc slightly increases surface roughness. Similarly, width of cut (ae) has a moderate positive influence (+0.038), meaning that a larger ae contributes to a rougher surface. In contrast, frequency has a small negative coefficient (-0.004), implying that higher frequencies slightly reduce Ra, though its overall effect is minimal compared to other parameters. In summary, the regression model confirms that depth of cut (ap) plays a crucial role in improving surface roughness, whereas feed rate (fz) significantly increases Ra. Cutting speed, width of cut, and frequency exhibit smaller effects but should still be considered when optimizing machining parameters to achieve a better surface finish.

The Pareto chart of standardized effects in Figure 6 provides a visual representation of the significance of machining parameters on surface roughness (Ra) at a 95% confidence level ($\alpha =$

0.05). The red reference line at 4.30 indicates the critical value; any factor exceeding this threshold is considered statistically significant. From the chart, depth of cut (a_p) (C) is the most influential factor, showing the largest standardized effect, which aligns with the ANOVA and regression results. This confirms that changes in a_p strongly affect R_a , reinforcing its critical role in determining surface finish. Cutting speed (V_c) (A) ranks second, indicating a considerable impact on R_a , though to a lesser extent than a_p . Other factors, including width of cut (a_e) (D), frequency (E), and feed rate (f_z) (B), exhibit relatively smaller effects, suggesting a lower influence on R_a . Among these, feed rate (f_z) (B) has the least impact, which is consistent with the response table analysis.

These results align with the Taguchi, ANOVA, and regression findings, confirming that depth of cut (a_p) and cutting speed (V_c) are the most influential variables affecting surface roughness, while feed rate (f_z) remains the least influential.

Figure 7 illustrates the variation in surface roughness (R_a) across eight experimental runs under Ultrasonic vibration-assisted milling (UVAM). The bar chart presents the mean R_a values for each run, with error bars representing the standard deviation of the measurement. This visual comparison highlights not only the differences in surface finish quality but also the consistency of results across trials. The degree of variability between run will be further analysed using coefficient of variation (CV), providing deeper insight into the stability and reliability of each parameter setting.

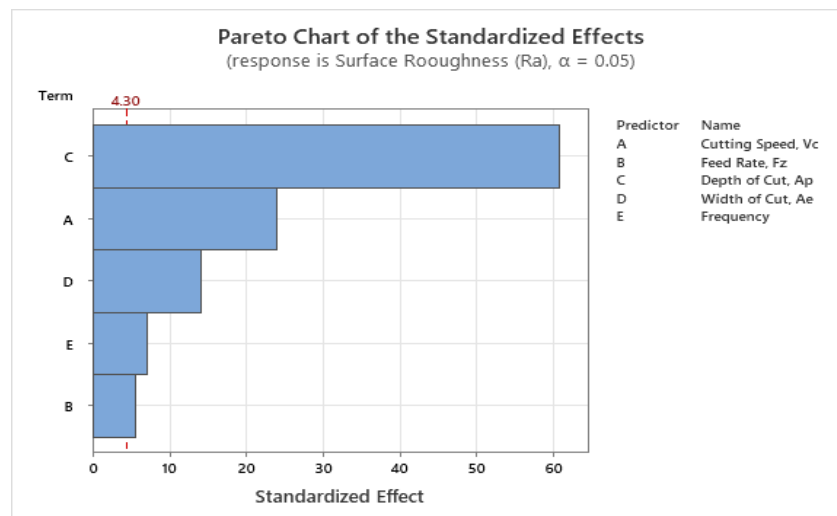


Figure 6: Pareto Chart of the Standardized Effects.

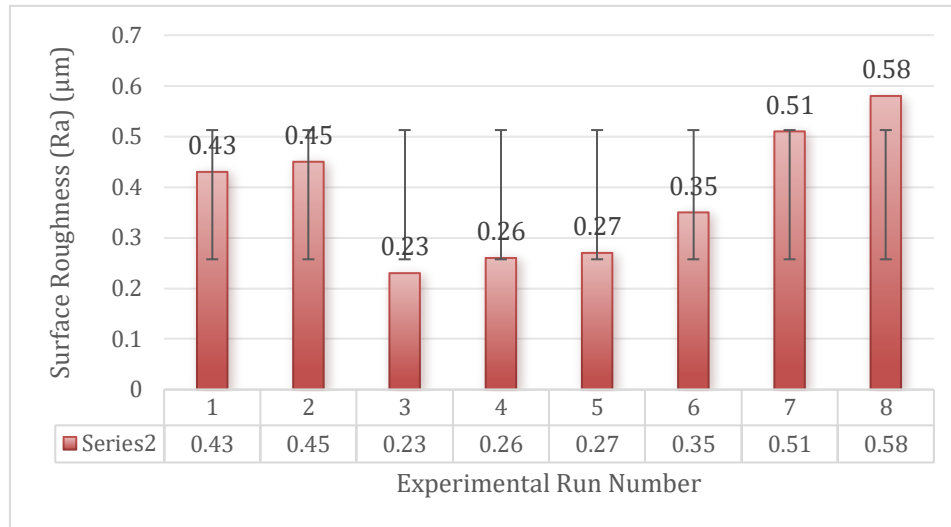


Figure 7: Variation of Surface Roughness (Ra) Variation Across Experimental Runs in UVAM. Run 1 had minimal variability (CV = 7.67%) and a comparatively high average surface roughness (Ra = 0.43 μm). This suggests that, although the machining process was stable, the surface was continuously rougher. In Run 1, the parameters with the lowest cutting speed, feed rate, depth of cut, and width of cut were combined. These cautious settings decreased tool engagement and chip load, but they also minimised dynamic instability and helped to produce reliable results. This might have limited the efficiency of ultrasonic vibration and produced rougher but consistent surface finishes by causing material spreading and inadequate chip evacuation. The significance of maximising cutting depth and width to fully reap the benefits of UVAM is shown by this research.

Table 7 presents the Coefficient of Variation (CV) analysis for eight experimental runs. The CV is calculated using equation 2:

$$CV = \frac{\sigma}{\mu} \times 100 \tag{2}$$

where σ is standard deviation and μ is the mean surface roughness (Ra). In this study, CV value ranged from 7.67% to 38.26%, with an average of 20.30%, indicating moderate variability. This is comparatively lower than 38% average CV reported by ²⁵ under conventional milling conditions. Based on thresholds reported by [25, 26] and [27], a CV below 10% reflects low variability (excellent consistency). 10-30% indicates moderate variability, and above 30% indicates high variability. Run 7, with the highest CV of 38.26%, was identified to have outliers, which were confirmed through interquartile range (IQR) analysis. After removing these outliers, the CV significantly decreases. While IQR highlights the central spread and flags outliers, CV offers a normalized comparison of variability across different experimental conditions.

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Table 7: Statistical analysis of surface roughness (Ra) across experimental runs.

Run No.	Mean (μ)	Standard Deviation (σ)	Surface roughness indicator	Outliers	Coefficient of Variation (CV)	CV Indicator
1	0.43	0.033	Moderate	None	7.67%	Low variability
2	0.45	0.104	Moderate	None	23.11%	Moderate variability
3	0.23	0.063	Excellent	None	27.39%	Moderate variability
4	0.27	0.033	Good	None	12.22%	Moderate variability
5	0.27	0.057	Good	None	21.11%	Moderate variability
6	0.34	0.081	Good	0.56	23.82%	Moderate variability
7	0.46	0.176	Moderate	0.86, 0.96	38.26%	High variability
8	0.58	0.051	Moderate	None	8.79%	Low variability

The standard deviation values across the eight machining runs reveal varying levels of data consistency and variability. Run 1 and Run 4 demonstrate the lowest standard deviation (0.033), aligning with low CV values of 7.67% and 12.22%, respectively. These indicate tightly clustered data around the mean (0.43 and 0.27), reflecting stable and consistent machining performance. In contrast, Run 7 exhibits the highest standard deviation (0.176) and CV (38.26%) that greatly inflated the spread of the data. When these outliers are excluded, the standard deviation and CV are substantially reduced, highlighting the strong value of extreme value. Run 2, 3, 5, and 6 show moderate standard deviations (0.057-0.104) and corresponding CVs (21.11%-27.39%), indicating moderate variability in machining consistency. Notably, despite Run 3 having the lowest mean Ra value (0.23 μm), it still exhibits moderate variability due to a relatively higher CV

(27.39%). Run 8 presents a unique case with a high mean Ra (0.58 μm) but a low standard deviation (0.051) and CV (8.79%), suggesting consistency through rougher surface. Overall, the combination of mean, standard deviation, CV, and outlier detection offers a comprehensive view of machining performance, with standard deviation serving as a key indicator of data reliability and the need for outlier control.

3.3 The Effect of UVAM on Milled Surface

Surface roughness variation in milling is influenced by factors such as the overlap of cycloidal feed marks and the location of stylus measurements along the cutter path. In conventional milling, areas with widely spaced cutter marks exhibit distinct grooves and higher roughness, while regions with overlapping tool paths experience smearing, which reduces Ra. In contrast, UVAM introduces high-frequency vibrations, particularly along the Z-axis, that generate an intermittent cutting motion. This oscillatory movement helps to dislodge built-up material and chips from the cutting edge, reducing continuous smearing along the tool path. As a result, the removed material is deposited more uniformly onto the machined surface, reducing Ra variation. UVAM significantly improves surface consistency by minimizing material adhesion and redistribution, leading to more stable and predictable surface quality.

The results of Run 1, which achieved an average surface roughness (Ra) of 0.43 μm with a low standard deviation of 0.033 μm and a coefficient of variation (CV) of 7.67%, indicate a consistent and moderately smooth surface finish under ultrasonic-vibration-assisted milling (UVAM) conditions. This consistency is visually supported by the surface morphology shown in Figure , where distinct ultrasonic marks are observed on the machined surface of Inconel 718. These marks are a direct result of the high-frequency ultrasonic vibrations (20 kHz) applied during the milling process, which reduce cutting forces and material adhesion, allowing for smoother chip evacuation and improved surface integrity. The fine, periodic micro-textures visible in the magnified region align with the tool's oscillatory motion, highlighting UVAM's capability to create uniform surface features while minimizing surface defects. Combined with the machining parameters; cutting speed of 100 m/min, feed rate of 0.1 mm/rev, depth and width of cut both at 0.5 mm. The process demonstrates high precision and stability.

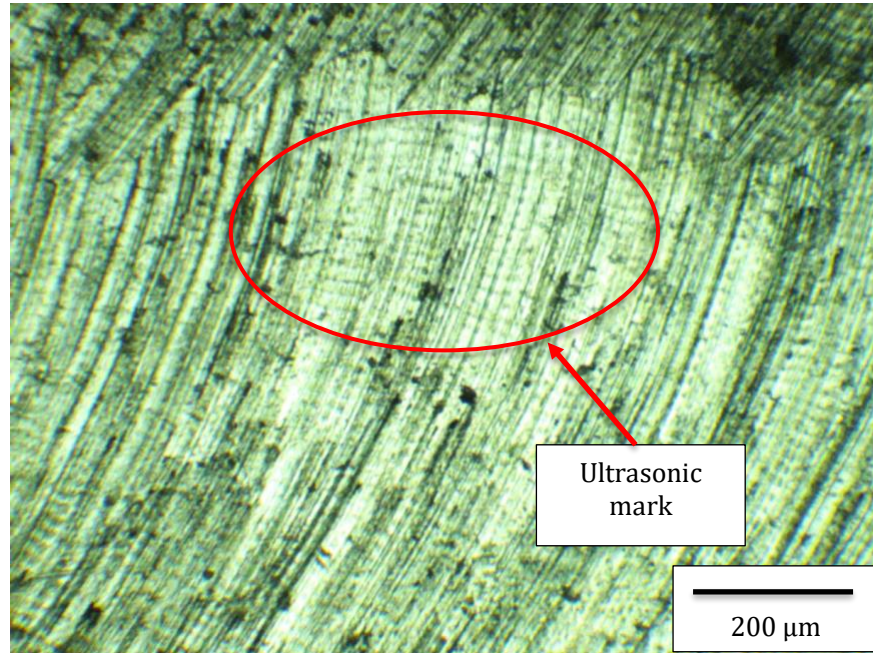


Figure 8: Ultrasonic marks on the machined surface of Inconel 718 (Run 1).

3.4 Effect Notch Wear on Surface Roughness

The schematic and microscopic image in Figure 9 provide a detailed representation of the relationship between tool geometry, cutting parameters, and surface roughness in ball nose end milling. The left schematic illustrates the scallop height (h) formed by the cutting path, which is a direct function of the feed rate (fz) and depth of cut (ap). The right-side magnified image of the cutting edge shows wear characteristics, but it confirms that surface roughness is not directly affected by notch wear.

Notch wear, prominently observed near the depth-of-cut (DoC) line, results in a ribbed surface profile that reflects the grooved shape of the worn cutting edge. However, subsequent passes of the tool effectively removed these surface defects, as the notched region did not extend to the highest cusp height, h (Figure 8). The cusp height in ball-end milling is a crucial factor that directly influences the surface quality of machined components. It is primarily controlled by the feed rate and the width of cut, with the smaller of the two having a dominant effect. This is due to the ball-end cutter's geometric nature, which results in residual material left between successive tool passes forming characteristic cusps on the machined surface. The observed results align with findings from [28] and [29], who also reported similar valuable insights into the mechanisms and predictive models that optimize machining parameters to minimize cusp height and improve surface integrity.

The significance of optimizing feed rate and toolpath overlap to minimize cusp height and improve surface integrity. A reduction in either the feed rate (fz) or depth of cut (ap) leads to smaller scallop heights and hence a smoother surface finish. However, in high-speed milling, variations in feed rate introduce dynamic effects on surface topography, making it challenging to predict roughness using models that assume constant feed conditions.

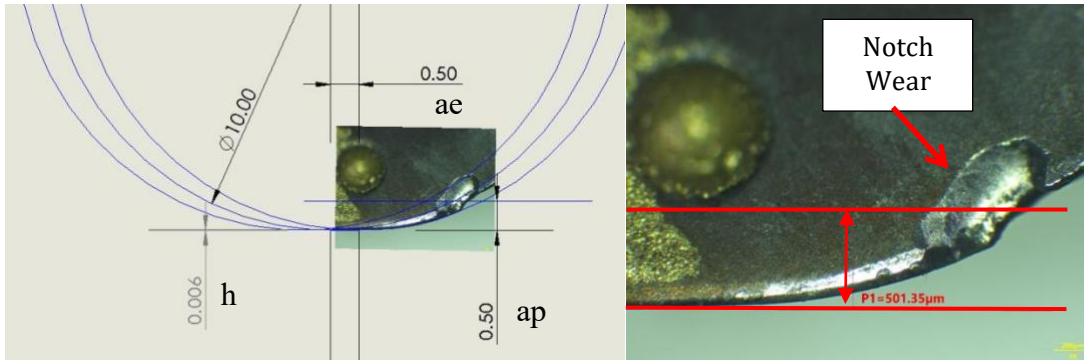


Figure 9: Schematic illustration showing surface roughness unaffected by notch wear in Run No. 7.

The relationship between feed rate and scallop height in ball nose milling, as shown in

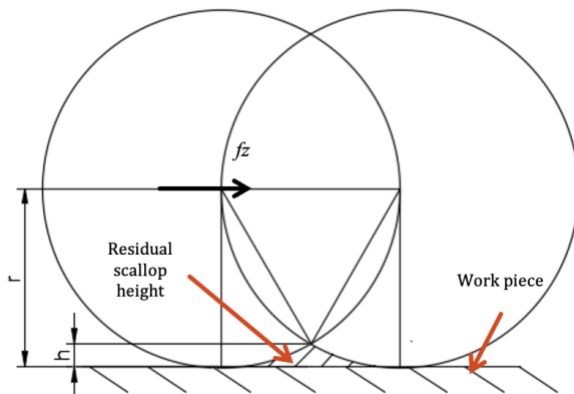


Figure 10, directly influences surface roughness, where a lower feed per tooth (fz) reduces scallop height and improves surface finish. However, as highlighted in Figure 8, real machining conditions, such as high-speed milling dynamics and notch wear, introduce additional factors affecting surface topography. In this experiment, the improvement in roughness with increased depth of cut suggests that factors beyond scallop height, such as stable chip formation and reduced chatter, contributed to the final surface profile. The fact that notch wear did not significantly degrade surface roughness indicates that adaptive cutting conditions played a crucial role in achieving a smoother finish, reinforcing the idea that theoretical predictions must account for practical machining variations.

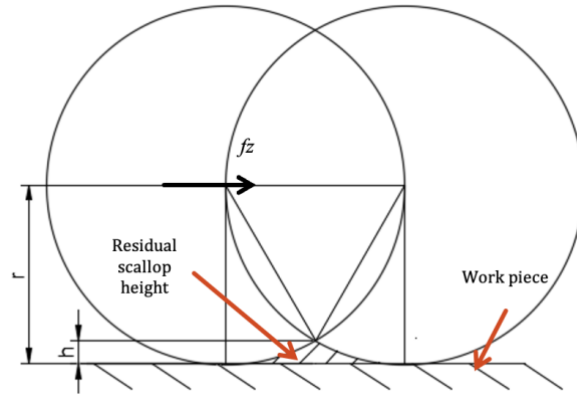


Figure 10: Schematic representation of scallop height formation in ball nose milling.

Conversely, notch wear is a localized form of tool damage that develops along the depth-of-cut line (DoC), impacting both the rake and flank faces. It typically results from chip pressure welding, which elevated cutting force and temperature. Although notch wear can reduce tool life, it does not directly affect the surface roughness. The size of the scallop height is directly influenced by both feed rate and depth of cut; increasing either parameter generally leads to a larger scallop height, which in turn produces a rougher surface finish. The peak-to-valley scallop height can be estimated by the following equation:

$$h = r \left[1 + \cos\left(\frac{\pi}{2}\right) + \cos^{-1} \frac{fz}{2r} \right] \quad (3)$$

where, h = Scallop height (mm), fz = feed rate, and r = radius insert.

A low feed rate combined with a small width of cut (WoC) effectively reduces scallop height, the small ridges or peaks left between successive tool passes during machining. This reduction in cusp height leads to a finer surface finish, as the smaller scallops result in a smoother surface profile. The improved finish occurs because the cutting tool, influenced by both parameters, engages more completely with the material and removes more of the uncut surface. As a result, the formation of residual ridges is minimized, enhancing the overall quality of the machined surface.

3.5 Chip Morphology

The chips in the Figure 4 have a distinctive wavy or undulating shape because Ultrasonic Vibration-Assisted Machining (UVAM) applies ultrasonic vibrations to the cutting tool. These high-frequency vibrations induce periodic tool-workpiece separation, which results in sporadic cutting and gives the chip surface wave-like striations. This waviness reflects the cyclical nature of the cutting action and demonstrates controlled chip segmentation. This lessens the possibility of long, continuous chips forming, which could cause overheating and clogged tools. Additionally, the regular patterns indicate a shorter tool-chip contact time, which helps to produce the finer surface textures of the chips and reduces the presence of the adhesive and thermal effects typically associated with traditional machining. This behaviour aligns with findings from [30], who reported that ultrasonic vibration improves chip breakage.

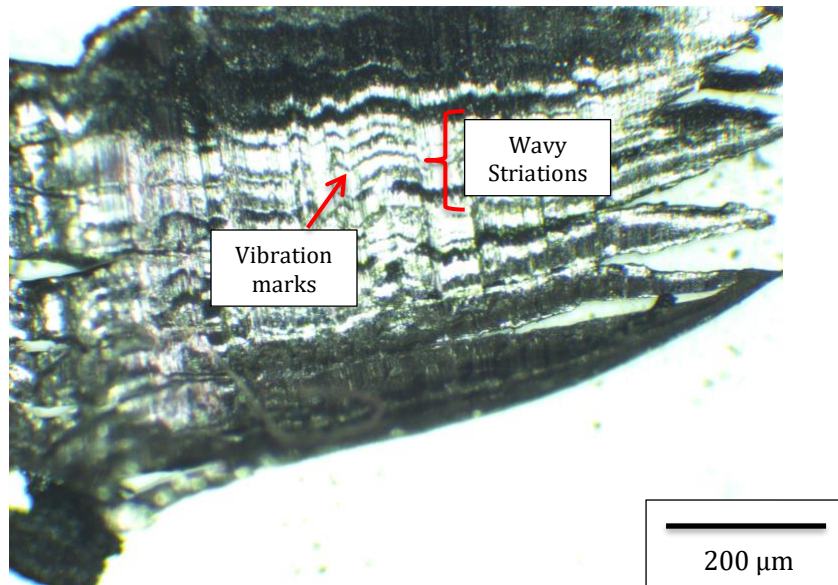


Figure 4: Chip Morphology in Ultrasonic Vibration-Assisted Machining, V_c 140 m/min, f_z 0.2 mm/rev, a_p 0.5 mm, f 27 kHz, a_e 0.5 mm.

CONCLUSIONS

Ultrasonic vibration-assisted milling (UVAM) has shown great promise in increasing Inconel 718's machinability through improved chip formation, decreased tool wear progression, and improved surface integrity. This work validates that UVAM mitigates the negative impacts of notch wear and successfully reduces surface roughness variability, reaching an average R_a of 0.23 μm . By decreasing friction, improving chip evacuation, and postponing wear-induced degradation, which is frequently a limiting factor in traditional milling—the intermittent tool-workpiece contact in UVAM is essential. The results support UVAM's tribological benefits, especially in lowering cutting forces, minimising adhesion-related wear processes, and encouraging regulated chip segmentation. Cutting speed (V_c) and depth of cut (a_p) were found to be the most important parameters using the Taguchi L8 orthogonal array, highlighting the need of maximising these variables to attain optimum machining performance.

In order to further reduce surface roughness fluctuations, future study should examine the long-term impacts of notch wear under UVAM settings as well as the ideal vibration parameters. Further research into improving UVAM's efficacy may also be possible by broadening the study to incorporate various cutting tool materials, coatings, and lubrication techniques. These developments will not only solve present machining issues but also open the door for a broader use of UVAM in sectors like aerospace, energy, and biomedical production that demand very precise components.

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