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Statistical analysis of surface roughness in meso scale ultrasonic vibrations assisted end-milling (UVAEM) of titanium alloy Ti–6Al–4V under dry, flooded, MQL and cryogenic environments

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ABSTRACT

Titanium is a prominent material in major industries for production of high reliability parts and components to be used under extreme conditions. However, despite unique properties, it is characterized as a difficult-to-machine element. Ti–6Al–4V is highly utilized & researched α + β alloy of titanium having various machinability challenges. Nowadays, miniaturized micro and meso scale devices and components are in demand but surface finish issues are being experienced. Thus, the analysis of surface roughness is essential for optimization and minimization of post machining processes. The hazards of cutting fluids have shifted the attention on the way to latest cooling and machining methods to reduce or eradicate them. In current research, Surface Roughness of machined Ti–6Al–4V during meso-scale UVAEM under Dry, Flooded, MQL & Cryogenic conditions is examined at various levels of machining inputs including cutting speed, feed per tooth, depth of cut (DoC), amplitude of ultrasonic vibrations and cooling conditions. The analysis showed that surface roughness is significantly influenced by machining conditions, the cooling medium, and ultrasonic vibrations. The DoC proved to be the leading factor, contributing 48.49 % to surface roughness. Cryogenic cooling remained the best cooling environment to minimize surface roughness. Surface roughness is reduced by 11.76 % under UVAEM in comparison with the Conventional Machining (CM), however, the effect of ultrasonic vibrations amplitude is non-linear and also results in a negative effect when it exceeds a certain threshold. For optimal results with least surface roughness, cryogenic environment along with higher cutting speed, lower feed per tooth, lower DoC and optimum ultrasonic vibrations amplitude should be adopted.

Symbols & Abbreviations

CM	Conventional Machining
UVAEM	Ultrasonic Vibrations Assisted End-Milling
MRR	Material removal rate (cm^3/s)
ANOVA	Analysis of Variance
MQL	Minimum Quantity Lubrication
UVAM	Ultrasonic Vibrations Assisted Machining
LN_2	Liquid Nitrogen

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1. Introduction

Aerospace, biomedical, automotive, marine, nuclear, oil, gas, and chemical industries rely heavily on titanium-based superalloys due to their proven ability to withstand demanding operational conditions [1]. Their demand arises from outstanding properties, including high-temperature resistance, chemical stability, corrosion and heat resistance, toughness, and a superior strength-to-weight ratio [2]. Nevertheless, despite advantages, titanium alloys are categorized as difficult-to-machine, credited to low thermal conductivity, high chemical reactivity, retention of strength at elevated temperatures, and a pronounced tendency toward strain hardening [1,3]. Within the family of titanium alloys, Ti–6Al–4V (α+β alloy) represents the primary grade applied in industry, representing about 50 % of titanium consumption and attracting extensive research due to its machining challenges [1].

The expanding interest in downsized meso-scale components and devices, typically sized between 100 μm and 10 mm, is driving significant advancements in the medical, aeronautical, aerospace, automobile and telecommunication industries. Consequently, focus has been transitioned from traditional macro-machining processes to those at the micro and meso levels. [4]. Ti–6Al–4V finds broad application as a manufacturing material for such components and devices. Hence, machining processes are being designed to shape small and accurately detailed Ti–6Al–4V parts through micro and meso scale end-milling. Due to small size, difficulties are experienced in the quality control of these components especially in terms of their surface roughness as post process enhancement of surface finish results in variations in tolerances and dimensions [5]. The key differences between meso- and macro-scale milling processes arise from several factors such as "the ratio between feed per tooth and radius of cutting edge", commonly referred as size effect, the greater sensitivity of meso-milling to tool runout and the smaller minimum chip thickness typically associated with meso-scale operations [6].

The machinability of a material is generally evaluated through machining outputs such as cutting forces, tool wear, surface roughness, burr formation, chip morphology etc, all interrelated [7]. These outputs are influenced by input parameters like cutting speed, DoC, feed per tooth, and cooling conditions. Precise measurement of these effects and subsequent optimization are critical to enhancing machinability. To address the limitations of conventional techniques, researchers have proposed a range of advanced and hybrid machining methods, such as Ultrasonic Vibrations Assisted Machining (UVAM), LAM, EDM and EBM. Additional approaches include pre-heating of the workpiece and the use of alternative environments like Minimum Quantity Lubrication (MQL), cryogenic cooling, and other specialized conditions.

After machining, the factors contributing to a workpiece's surface integrity include surface texture, metallurgical properties and topography that significantly impact the component's service life, reliability, performance and its compliance with safety requirements [8]. Fatigue life, fracture resistance, reliability, wear, corrosion resistance, quality and performance of a part depends on its surface integrity and dimensional accuracies [9]. A poor surface finish is an indicator of a non-homogeneous workpiece, unstable machining process, hostile machining conditions and extreme tool wear [10]. Surface topography can be classified further into waviness, form error and surface roughness [11]. At present, the surface roughness is mainly being focused in modern industry to assess the quality of machined components and production costs as it mainly influences appearance, reliability and functionality of the product [12]. When milling titanium alloys, the material's challenging properties and high tool wear rates make surface roughness a significant marker of the operational properties of machined components [13]. The surface integrity of milled components is prone to rapid deterioration which changes the surface roughness due to poor machinability, complex machine tool linear motions and cyclic chip loading in end-milling [14].

Extensive research on Ti–6Al–4V indicated that machining inputs like cutting speed, DoC, feed per tooth, and cooling conditions are vital in determining surface quality and roughness. Yusuf et al. [15] concluded that speed, end mill type, feed rate, and DoC are the main factors influencing surface roughness in titanium end-milling. Similarly, Rahmati et al. [16] reported that spindle speed, feed and DoC adversely impact surface finish if not properly controlled. Samsudeensadham et al. [17] emphasized cutting speed as the most significant factor, noting its strong influence on both temperature and roughness. Sun et al. [18] examined rise in roughness of Ti–6Al–4V with higher feed rate and radial DoC, however, it falls with cutting speed increase. Polishetty et al. [19] conveyed a similar trend, attributing reduced roughness to thermal softening in the cutting region at higher speeds. Wang et al. [20] analyzed that roughness initially rises at low cutting speeds but decreases with further increase because of the interplay of strain hardening & thermal softening, also pointing out that small radial DoC and feed rate can lower surface roughness. Other studies support these findings. Kuram et al. [21] observed roughness reduces with cutting speed but rises with feed rate and DoC during Ti–6Al–4V micro-milling. Kilickap et al. [22] attained the lowest roughness at elevated cutting speeds, low feed rates, and shallow depths of cut when milling Ti–6242S. Özel et al. [23] confirmed the strong influence of cutting speed in multi-objective optimization. Bandapalli et al. [24] explored that both forces and roughness increase with DoC and feed rate in Grade-2 titanium. Numerous studies have consistently emphasized the pivotal influence of feed rate. Ali et al. [25], Ginting et al. [26], Hughes et al. [27], Ginta et al. [28], Ramesh et al. [29], Thepsonthi and Ozel [30] all reported that feed rate is a primary contributor to increased roughness. In contrast, DoC has also been recognized as highly significant. Lebaal et al. [31], Patwari et al. [32], Liu et al. [33] and Hayajneh et al. [34] all verified its strong effect, with many ranking DoC as the most influential parameter. Taken together, these experimental and modeling-based studies demonstrate that machining inputs, especially speed, feed and DoC, exert major impacts on surface roughness in titanium alloys machining, particularly Ti–6Al–4V.

Cutting fluids are employed to reduce cutting-zone temperatures, decrease machining forces and improve finish when working with difficult-to-machine alloys like titanium and nickel [35,36], but health and environmental hazards have accelerated the shift towards dry machining, MQL, cryogenic and hybrid systems [37,38].

Several researchers have confirmed the significant impact of cooling environments on machining outputs. Yang et al. [39] stressed the strong effect of cooling conditions in milling Ti–6Al–4V. Huang et al. [40] and Shokrani et al. [41] underlined the need for fluids to reduce cutting-zone temperatures, particularly in machining superalloys with poor thermal conductivity. Liu et al. [42] demonstrated improved surface quality under cooled conditions, while Ishii et al. [43] observed wider temperature ranges in wet machining relative to dry machining. Nonetheless, because of health concerns, dry machining has received growing attention. Arif et al. [44] pointed out that at elevated cutting speeds, dry machining led to surface damage, and allowable speed limits were significantly lower compared with other materials. Ginting et al. [45], however, demonstrated that by using optimized cutting parameters, dry machining can still be viable. Samsudeensadham et al. [46] found feed rate to be the highest influencer for temperature and roughness in Ti–6Al–4V dry cutting, while Safari et al. [47] indicated that although higher speeds enhanced surface finish, they also raised cutting forces and made results strongly dependent on tool condition.

To overcome these limitations, alternative approaches including MQL and cryogenic cooling have been explored. MQL introduces atomized lubricant into machining zone to reduce heat and friction [48]. Wang et al. [49] and Shi et al. [50] reported significant improvements in surface finish, tool life & cutting forces under MQL equated to dry and flooded conditions. Rahim and Sasahara [51] observed severe thermal cracking in dry cutting, which MQL successfully mitigated. Cai et al.

[52] showed that increasing oil supply in MQL further reduced cutting forces and roughness. Researchers like Krishnaraj et al. [53], Boswell et al. [54], Davim et al. [55] and Pervaiz et al. [56] have consistently emphasized MQL's environmental sustainability and performance advantages over conventional cooling. Advanced adaptations such as nanofluid MQL were also shown to improve cutting forces, burr formation, and roughness as demonstrated by Kim et al. [57] and Hassanpour et al. [58] in their research.

Cryogenic cooling, using agents such as LN_2, CO_2, or other gases, has also gained attention for titanium alloys machining at elevated cutting speeds [59]. Shokrani et al. [60] demonstrated enhanced tool life and surface characteristics with LN_2 cooling in comparison to dry or wet conditions. Josyula et al. [61] noted notable reductions in roughness and enhanced surface integrity under cryogenic conditions. Similar benefits were reported by Khanna et al. [62], Rotella et al. [63] and Bordin et al. [64]. Collectively, these studies confirm cryogenic cooling as a highly effective means for reducing tool wear, lowering cutting forces, and enhancing surface integrity in Ti–6Al–4V machining.

UVAM applies high-frequency (≥20 kHz), low-amplitude (1–40 μm) vibrations to the cutting tool or workpiece, producing pulsed cutting action that reduces resistance [65]. It has shown strong potential for machining difficult alloys such as titanium and nickel [66,67]. Studies consistently report reduced surface roughness under UVAM compared with CM. Su et al. [68] found a 37.5 % reduction in Ti–6Al–4V, while Shen et al. [69] and Kumabe et al. [70] showed improvements in aluminum and hard materials. Ramazan et al. [71] demonstrated that UVAM + MQL of Ti–6Al–4V significantly reduced cutting forces & roughness. Zhang et al. [72] highlighted the strong influence of vibrations and cutting speed on roughness and surface texture. Su [73] and Ming [74] confirmed reductions in cutting forces & roughness in Ti–6Al–4V. Hybrid approaches provide further benefits. Ni et al. [75] reported that UVAM + MQL improved surface quality and tool wear beyond UVAM or CM alone. Gajarani [76] showed Cryo-MQL gave superior performance to cryogenic or dry machining. Adil Rauf et al. [77] found that UVAM + MQL and UVAM + Cryo produced significant improvements in Ti–6Al–4V, reducing forces & tool wear.

Research on end-milling of Ti–6Al–4V at meso-scale remains limited, particularly regarding the influence of machining parameters at this intermediate scale, which has received far less attention compared to macro and micro-scale levels. Moreover, no single study has comprehensively investigated the combined effects of Ultrasonic Vibrations Assisted End-Milling (UVAEM) with different cooling environments on surface roughness at meso-scale. The aim of this work is to address this gap by examining the impact of Machining Parameters (cutting speed, feed per tooth, DoC), Ultrasonic Vibrations and Cooling Strategies (Dry, Flooded, MQL, Cryogenic) on surface roughness during meso-scale UVAEM of Ti–6Al–4V. This research is primarily motivated by the need to determine machining parameters and conditions that result in improving Ti–6Al–4V machinability in industrial setups, while simultaneously minimizing reliance on post-processing to obtain high-quality surface finishes.

2. Research material, tool and experimentation

2.1. Composition & properties of alloy

This research utilized Ti–6Al–4V (titanium alloy) having α + β crystal structure, as the experimental material with HCP structured α-phase in the range of 60–90 % and BCC structured β-phase in the range of 10–40 % at room temperature. Experiments were performed on 65 mm × 50 mm x 7.5 mm rectangular workpieces at four different cooling conditions (Dry, Flooded, MQL & Cryogenic) as depicted in Fig. 1(a). Flattening of all workpiece surfaces was ensured before the experiments. Table 1 displays the material's composition in addition to its properties.

2.2. Cutting tools

Tungsten carbide (Uncoated, by Changzhou North Carbide Tools) meso-scale flat end-mills were utilized for experiments, as in Fig. 1. Tools specifications in Table 2.

2.3. Experimental setup and equipment calibration

3-axis CNC milling center (YDPM-1060, 8000 rpm maximum speed) equipped with Acrow Machinery manufactured ultrasonic tool holder, operating at 21 kHz with amplitude range of 0–10 μm is used for experiments. Workpieces were clamped in a 2-inch precision vise to ensure rigidity. MQL was applied at its minimum flow rate of 120 ml/h (2 ml/min), confirmed through direct measurement, while cryogenic machining used liquid nitrogen (LN_2). Cooling environment details are provided in Table 3. Surface roughness was calculated with an optical microscope (Olympus DSX-1000) with DSX software (v1.1.5), after cleaning samples with 99.5 % ethanol. Each test was carried out with a new tool, pre-set using a tool pre-setter to maintain uniform DoC. The overall experimental setup is indicated in Fig. 2.

Table 1
Properties of Ti–6Al–4V.

UTS	E (Elasticity Modulus)	G (Shear Modulus)	σy (Yield strength)	Hardness	Melting Point
952 MPa	113 GPa	45 GPa	837 MPa	Vickers: 35 Brinell: 335 Rockwell C: 364	1665 °C
Density	**Thermal Conductivity**	**Specific Heat Capacity**	**Co-efficient of Thermal Expansion**	**Chemical Composition (% of Elements)**	
4.37 g/cc	6.72 W/mK	0.5269 J/g°C	9.6 C^{-1}(μm (mC) $^{-1}$)	Ti: 88.5 %; Al: 6.20 %; V: 3.93 %; Fe: 0.27 %; O: 0.22 %; H: 0.0120 %; N: 0.05 %; C: 0.12 %	

Fig. 1. (a) cutting tool (b) workpiece (Ti–6Al–4V).

Table 2
Tools specifications.

Material	WC (Tungsten Carbide)
Diameter	3 mm
Coating	Uncoated
Rake Angle	60°
No. of flutes	04
Length	75 mm
Edge Radius	3 μm

Table 3
Cooling environments parameters.

Parameter	Dry Condition	Flooded Cooling	Minimum Quantity Lubrication (MQL)	Cryogenic Cooling
Flow Rate	No cutting fluid	6 lit/min	120 ml/hr (2 ml/min)	4 lit/min
Oil/Cooling Medium Type	No cutting fluid	Macron 32 by Shell	Macron 32 by Shell	Liquid Nitrogen (LN_2)
Flow Pressure	No cutting fluid	30 psi	60 psi	20 psi

2.4. Design of experiments (DOE)

Taguchi L16 orthogonal array, with five factors at four levels, was applied to study the relative influence of machining parameters, cooling methods, and ultrasonic vibration amplitude on surface roughness in meso-scale UVAEM of Ti–6Al–4V. Each input parameter was assigned four levels, as summarized in Table 4, with values determined from the tool catalogue, ISO standards [78] and research studies [79,80]. Surface roughness was considered as the response variable. The Taguchi L16 array is indicated in Table 5.

3. UVAEM experiments

End-milling of 65 mm length was conducted on separate workpieces under the cooling conditions as per DoE, as illustrated in Fig. 3 [112]. Ultrasonic tool holder imparted ultrasonic vibrations, with amplitudes assigned according to the L16 orthogonal array. To minimize experimental error and obtain reliable averages, each test was repeated twice under identical conditions. Each slot was machined using new tool to avoid tool wear influence. In total, 32 x experiments were carried out. Confirmatory experiments were later conducted to verify the ANOVA predictions regarding the best & worst machining conditions for surface roughness.

4. Results and analysis

4.1. Surface roughness in UVAEM of Ti–6Al–4V

Surface roughness was calculated using optical microscope (Olympus DSX-1000) with DSX software, as shown in Fig. 2. The effects of input parameters on surface roughness were assessed using ANOVA with a lower-the-better criterion to determine contribution ratios. The analysis was performed at a 95 % confidence level, with factors considered significant when $P < 0.05$. Surface roughness across the four cooling environments is illustrated in Figs. 4–7. These figures clearly

Table 4
Independent variables/input parameters levels.

Inputs	Units	Levels	Values of Input Parameters			
Vc	m/min	4	15	30	45	60
fz	mm/tooth	4	0.01	0.02	0.03	0.04
ap	mm	4	0.1	0.2	0.3	0.4
Cutting Conditions	–	4	Dry	Flooded	MQL	Cryogenic
au	μm	4	0	3	6	9

Fig. 2. Experiments setup - measurement & analysis of surface roughness.

Table 5
DoE - Taguchi L16 orthogonal array.

Exp No.	Vc (m/min)	Fz (mm/t)	ap (mm)	Cooling Conditions	au (μm)
1	15	0.01	0.1	Dry	0
2	15	0.02	0.2	Flooded	3
3	15	0.03	0.3	MQL	6
4	15	0.04	0.4	Cryogenic	9
5	30	0.01	0.2	MQL	9
6	30	0.02	0.1	Cryogenic	6
7	30	0.03	0.4	Dry	3
8	30	0.04	0.3	Flooded	0
9	45	0.01	0.3	Cryogenic	3
10	45	0.02	0.4	MQL	0
11	45	0.03	0.1	Flooded	9
12	45	0.04	0.2	Dry	6
13	60	0.01	0.4	Flooded	6
14	60	0.02	0.3	Dry	9
15	60	0.03	0.2	Cryogenic	0
16	60	0.04	0.1	MQL	3

depict the variation in surface roughness and pattern of surface finish under different environments and different combinations of input parameters.

Table 6 depicts the ANOVA results along with the contribution ratios of input parameters while Fig. 8 indicates the main effect plots. ANOVA results depicted that DoC had the highest effect amongst the parameters, contributing 48.49 % to surface roughness variation. Feed per tooth ranked second with 31.85 %, followed by cooling conditions and cutting speed with 7.16 % and 6.61 % influence respectively. Ultrasonic vibrations amplitude contributed the least at 4.09 %. The error remained within 1.80 %, demonstrating the reliability and consistency of both initial and repeated trials, conducted under identical conditions.

4.1.1. *Effects of cutting speed*

Fig. 8 illustrates influence of cutting speed on surface roughness. When the speed raised from 15 to 60 m/min, roughness decreased. This effect is explained by higher temperatures at the tool–workpiece interface, causing thermal softening of Ti–6Al–4V. As alloy softens, machining requires less force, producing a better surface finish. Similar reductions in surface roughness with rising cutting speed, explained by thermal softening, have been reported in previous studies [81–83] and are consistent with the results of Sun et al. [18], Polishetty et al. [19], Zoya et al. [84], Kuram et al. [21] and Kilickap et al. [22]. However, ANOVA results in Table 6 displayed that contribution of cutting speed was only 6.61 %, highlighting its relatively minor role in influencing surface roughness during Ti–6Al–4V machining.

4.1.2. *Effects of feed per tooth*

Surface roughness was observed to increase steadily as feed per tooth increased, with nearly constant slope of this trend as shown in Fig. 8. This is due to the expansion of the shear plane area at higher feed rates, which enlarges the undeformed chip thickness. As a result, both the material removal rate (MRR) and the normal force on the tool rake face increase, producing greater roughness. This rising trend has been noted by several researchers [19,24], and is in line with findings of Ali et al. [25], Ginting et al. [26], Hughes et al. [27] and Thepsonthi et al. [30]. The contribution ratio of feed per tooth in Table 6 was found to be 31.85 %, ranking it as the second most influential parameter affecting surface roughness during Ti–6Al–4V machining.

4.1.3. *Effects of DoC*

DoC emerged as the greatest influencer, showing a clear upward

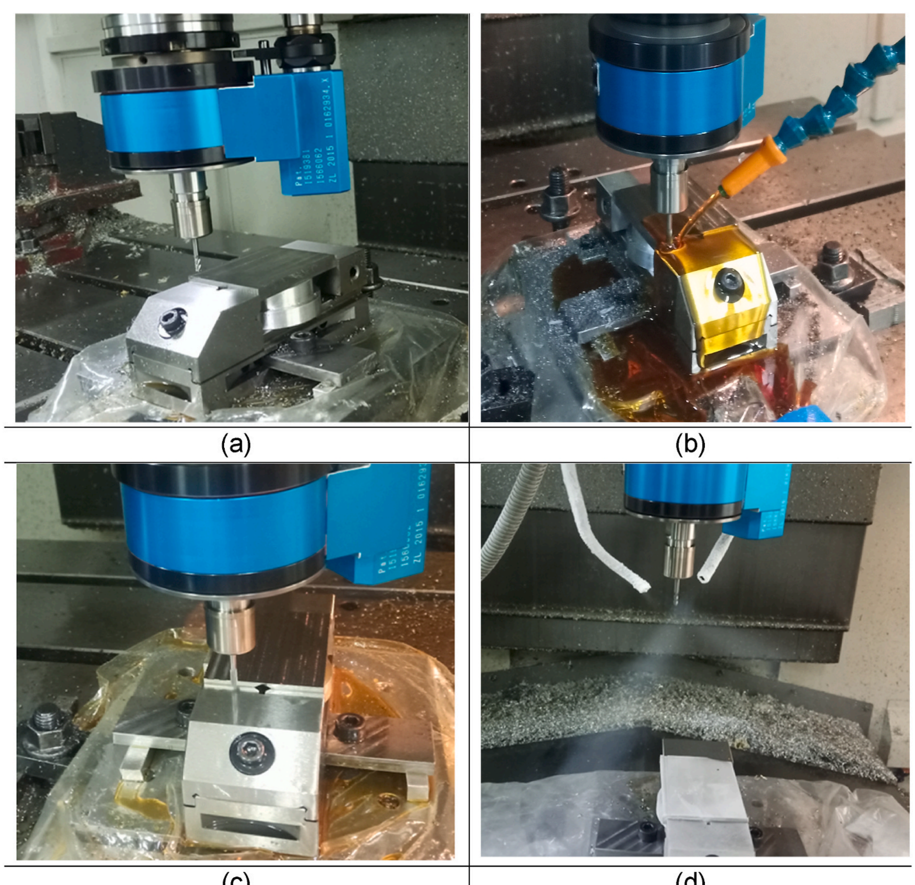

Fig. 3. Experiments under different Cooling Conditions (a) Dry (b) Flooded (c) MQL & (d) Cryogenic [112].

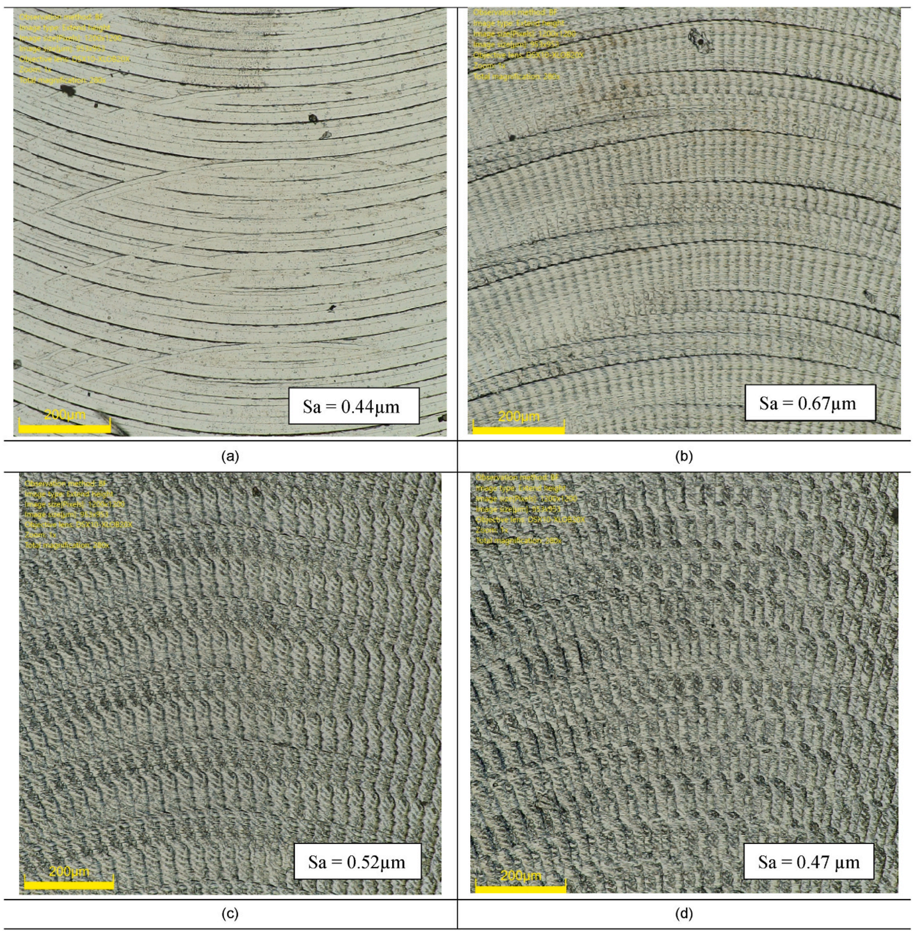

Fig. 4. Surface roughness - dry machining - experiments no. 1, 7, 12 & 14 (a,b,c,d).

trend as depth is increased as shown in Fig. 8. This effect is primarily linked to the expansion of the shear plane vis-a-vis tool–chip contact area, which raises the material removal rate (MRR) and creates greater resistance during cutting [9,20]. Furthermore, higher depths of cut increase the uncut chip thickness and elevate friction within primary & secondary deformation zones, leading to higher cutting forces. Similar findings have been reported in prior studies and are consistent with findings of Mersni et al. [85], Patwari et al. [32], Liu et al. [33] and Hayajneh et al. [34]. The contribution ratio of DoC in Table 6 was 48.49 %, making it the most leading factor for optimizing roughness in Ti–6Al–4V.

4.1.4. Effects of cooling environment

The maximum surface roughness was observed under dry machining, while cryogenic cooling produced the lowest as shown in Fig. 8. The poor performance of dry machining is mainly linked to high cutting-zone temperatures, which may approach 600 °C and rise up to 1400 °C at elevated cutting speeds, as a result of low thermal conductivity of alloy. Shaw et al. [86] explained this by pointing to the low product of thermal conductivity and specific heat, which results in heat concentration during titanium machining. Without cutting fluid, there is no lubrication, cooling, or proper chip evacuation, leading to greater mechanical and thermal tool loads, which accelerate wear, raise cutting forces, and worsen surface roughness [87]. At such high temperatures, Ti–6Al–4V is also chemically reactive towards tools material and undergoes strain hardening, further degrading the surface finish. These findings are consistent with Liu et al. [42], Arif et al. [44], Samsudeensadham et al. [46] and Safari et al. [88].

Flood cooling reduces roughness compared to dry machining due to improved heat dissipation, as noted by Yang et al. [39], Huang et al. [40], Shokrani et al. [41] and Ishii et al. [43]. MQL also reduced roughness relative to dry and flood machining, as atomized lubricant droplets penetrated cutting zone, forming a film that decreased friction and temperature, lowered tool wear, and reduced forces [89]. The ease of droplet evaporation further enhanced cooling efficiency, improving machining outcomes [90]. These results align with the work of Wang et al. [49], Shi et al. [50], Cai et al. [52], Boswell et al. [54], Gariani et al. [91], Kim et al. [57] and Hassanpour et al. [58].

The most favorable outcomes were obtained under cryogenic cooling, where liquid nitrogen (LN_2) reduced cutting temperatures and penetrated the machining zone under high pressure, creating a cooling layer that enhanced tool life and surface integrity [92]. These results agree with the observations of Shokrani et al. [60], Chen [93], Khanna et al. [62] and Masood et al. [94]. Quantitatively, as per Table 6, cryogenic cooling lowered surface roughness by 13.46 % in comparison with dry machining, 8.16 % relative to flood cooling, and 1.53 % against MQL. This indicates that both cryogenic cooling and MQL play an important role in improving surface finish, though the overall contribution of cooling environments was only 7.16 %, signifying a relatively modest effect on surface roughness in Ti–6Al–4V machining.

These effects of UVAM combined with MQL and Cryogenic cooling have also been studied by many researchers in recent years. Blasl et al.

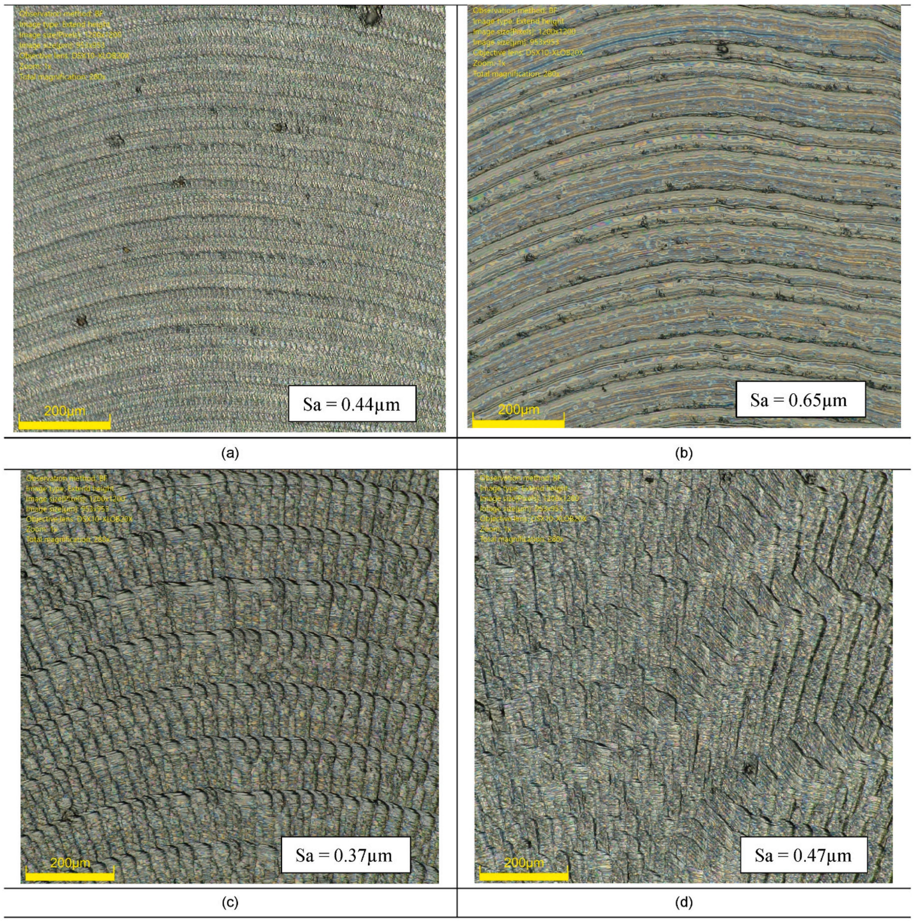

Fig. 5. Surface roughness - Flood cooling - experiments no. 2, 8, 11 & 13 (a,b,c,d).

[95] studied ultrasonic machining under Cryogenic + MQL combined effect and found reduced cutting zone temperature and a positive effect on surface roughness in Ti–6Al–4V machining. Airao et al. [96] observed that the Ra is maximum in dry conditions compared to wet, MQL and LCO_2. The UAT (ultrasonic assisted turning) showed a significant reduction in Ra mainly under wet and LCO_2 conditions, indicating similar findings as concluded in this study.

4.1.5. *Effects of ultrasonic vibrations Amplitude*

To allow a comparison with conventional machining (CM), an ultrasonic vibration amplitude of 0 μm was included, representing the absence of vibration assistance. Fig. 8 shows that surface roughness decreased as amplitude rose from 3 μm to 6 μm. At the CM setting of 0 μm, the highest roughness was observed. The reduction in roughness with amplitude is attributed to the intermittent cutting action in UVAEM, where the tool alternately engages and disengages with the workpiece, thus lowering temperature at the tool tip, decreasing cutting forces, and reducing tool wear [97,98]. This mechanism also changes the surface texture from continuous tool marks to a hammering-like pattern, enhancing the surface finish.

The drop in roughness was sharp between 0 μm and 6 μm, but beyond this amplitude the trend reversed. At 9 μm, roughness began to rise due to stronger hammering effects that created deeper dents on the work surface as indicated in Fig. 9. This phenomenon was particularly evident at lower cutting speeds when amplitudes exceeded 6 μm. These findings indicate that the impact of ultrasonic vibration amplitude on surface finish is non-linear: improvements are limited to an optimum range, after which surface finish deteriorates. At 6 μm, where the lowest roughness was recorded, values were 11.76 % lower compared with the CM setting of 0 μm. However, contribution ratio as per Table 6 was only 4.09 %, showing that vibration amplitude has a relatively small influence on surface roughness in Ti–6Al–4V machining.

5. Cutting forces, Tool Wear & Burr at Minimum & Maximum Surface Roughness

After the analysis of results and identification of minimum & maximum Surface Roughness achieved, other machining outputs like Cutting Forces, Tool Wear & Burr (both height & width during up & down milling) were measured and analyzed at these conditions in order to further investigate the reasons behind the behaviour of Surface Roughness & to further verify our results through establishing a connection between Surface Roughness & other machining outputs. Within the current DOE, Table 7 lists the conditions that produced the minimum and maximum surface roughness values.

5.1. *Cutting forces vs surface roughness*

Cutting forces were recorded with a force dynamometer in same experiments, following the procedure outlined in earlier work by Adil Rauf et al. [77]. The link between cutting forces and surface roughness was then examined through comparison and analysis of their values, as illustrated in Fig. 10.

The results in Fig. 10 indicate that cutting forces were considerably higher under the conditions that produced maximum surface roughness compared to those yielding minimum roughness. However, the variation in cutting force values does not follow a strictly linear relationship with surface roughness variation. This is explained by the observation that cutting forces first rise with cutting speed (Vc) until thermal softening occurs, after which they begin to decline, as also reported in earlier

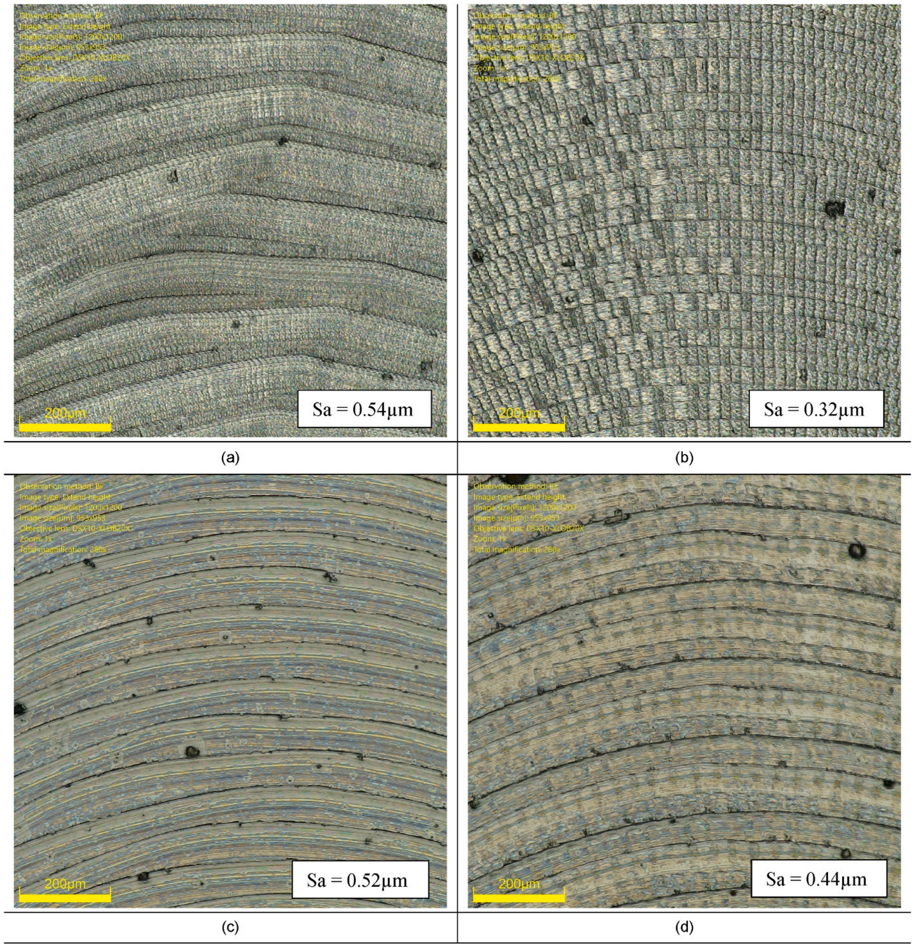

Fig. 6. Surface roughness - MQL - experiments no. 3, 5, 10 & 16 (a,b,c,d).

studies by the authors [77]. In contrast, surface roughness typically decreases as speed rises. Moreover, the contribution of machining inputs towards cutting forces & surface roughness is not identical, highlighting the complexity of their relationship. Overall, the analysis suggests that higher cutting forces tend to produce greater surface roughness, whereas lower forces are associated with smoother surfaces.

5.2. Tool wear vs surface roughness

Tool wear was also measured during experiments at which minimum & maximum values of surface roughness were achieved through analysis of tools under microscope as published in previous research work by authors Adil Rauf et al. [77]. Fig. 11 shows the evaluation of tool wear vis-a-vis surface roughness.

The findings in Fig. 11 indicate that tool wear was considerably greater under conditions that produced maximum surface roughness than under those yielding minimum roughness. However, their correlation is not entirely linear. This is because tool wear generally rises with cutting speed (Vc), as previously reported by the authors [77], while surface roughness tends to decline when cutting speeds are higher. Moreover, the influence of other parameters on tool wear and surface roughness is different, indicating that their effects are not consistent. Overall, the analysis suggests a positive correlation: higher tool wear is usually linked with greater surface roughness, whereas lower tool wear corresponds to smoother surfaces.

As long as the tool operates within its effective tool life, as per relevant standards, the effect of tool wear on surface quality remains consistent and within acceptable level. Only once the useful tool life is expended, does the surface roughness deteriorate considerably [99].

5.3. Burr formation vs surface roughness

Burr height & Burr Width during both Up & Down milling have also been determined and analyzed during the experiments at which minimum & maximum values of Surface Roughness were achieved through analysis of workpiece under DSX-1000 Optical Microscope. The values of both burr & surface roughness have been compared and analyzed as portrayed in Fig. 12.

Results in Fig. 12 specify that burr values were higher under conditions that produced maximum surface roughness compared to those associated with minimum surface roughness. However, this difference between burr values was again not linear compared to the variation in surface roughness. This may be due to multiple factors, such as cooling conditions, ultrasonic vibrations, and machining inputs, which influence both burr and surface roughness differently. However, the overall analysis indicates that the machining conditions that produce excessive burr also result in excessive surface roughness.

6. Confirmatory experiments for best & worst machining conditions

After analyzing the outcomes, confirmatory experiments were undertaken to validate the machining conditions predicted as best and worst for surface roughness, as identified through the Taguchi L16 orthogonal array and ANOVA during Ti–6Al–4V machining. A total of two confirmatory trials were performed, as summarized in Table 8. The outcomes confirmed that the predicted parameters indeed represent the optimized conditions for achieving both the lowest and highest surface roughness values. This verification strengthens the dependability of the

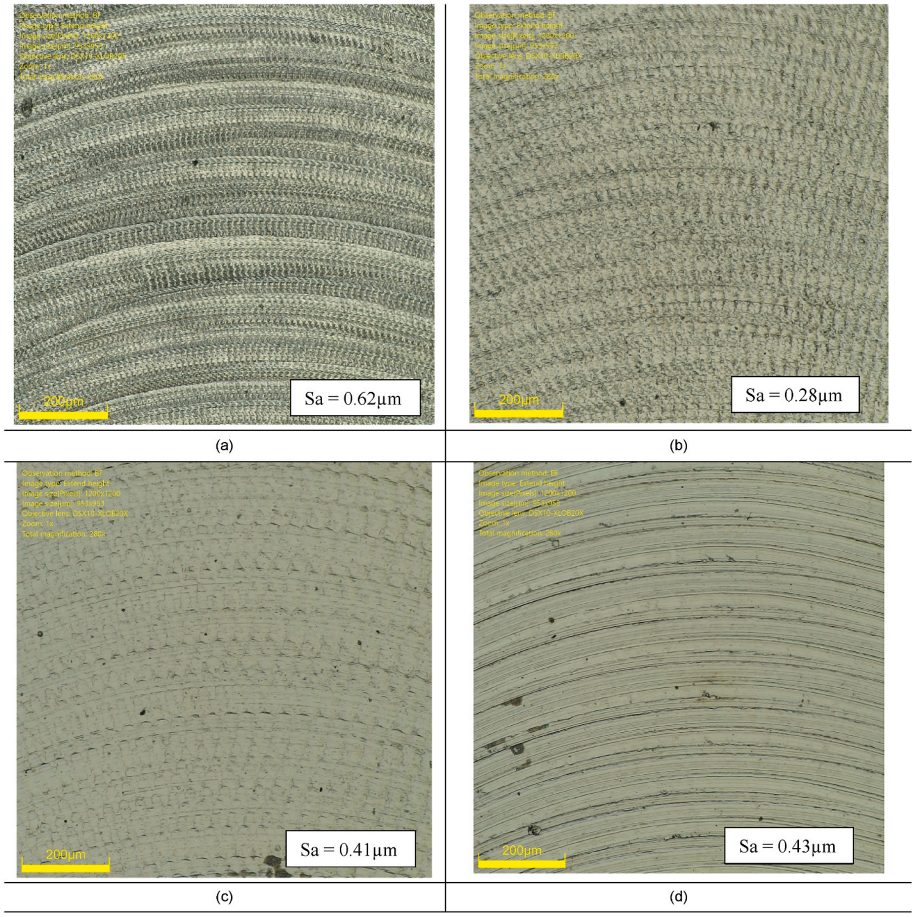

Fig. 7. Surface roughness - cryogenic cooling - experiments no. 4, 6, 9 & 15 (a,b,c,d).

Table 6
ANOVA results for Surface Roughness.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	3	0.027969	6.61 %	0.027969	0.009323	19.59	0.000
Feed per tooth	3	0.134822	31.85 %	0.134822	0.044941	94.42	0.000
DoC	3	0.205252	48.49 %	0.205252	0.068417	143.75	0.000
Cooling Conditions	3	0.030306	7.16 %	0.030306	0.010102	21.22	0.000
Amplitude of Vibration	3	0.017321	4.09 %	0.017321	0.005774	12.13	0.000
Error	16	0.007615	1.80 %	0.007615	0.000476		
Total	31	0.423284	100.00 %				

experimental framework and statistical evaluation adopted in this study.

7. Conclusions

Surface roughness was investigated in UVAEM of Ti–6Al–4V and the main conclusions are.

- Surface roughness is significantly affected by machining inputs.
- Higher cutting speeds reduce surface roughness; however, its overall effect remained relatively limited (6.61 % contribution).
- Larger feed per tooth and DoC led to an increase in surface roughness.
- Feed per tooth significantly contributed 31.85 % towards surface roughness.
- DoC remained the most influential parameter, contributing 48.49 %, becoming the most critical factor to be optimized for improved surface quality.
- Cryogenic cooling proved most effective, lowering surface roughness by 13.46 % compared with dry machining, 8.16 % compared with flooded cooling and 1.53 % compared with MQL.
- Ultrasonic vibrations amplitude contributed 4.09 %, with a non-linear effect on surface finish, as it deteriorates once the optimum level is surpassed.
- The lowest roughness was obtained at an ultrasonic amplitude of 6 µm, corresponding to an 11.76 % reduction compared with the conventional (0 µm) condition.
- For best results, cryogenic cooling combined with higher cutting speed, low feed per tooth, shallow DoC and optimum ultrasonic vibrations amplitude is recommended for Ti–6Al–4V machining.
- Cutting forces, tool wear, and burr formation were consistently greater under conditions producing maximum surface roughness and lower under those yielding minimum surface roughness.

In this research, the focus was directed toward advancing the goals of sustainable manufacturing and green production while simultaneously

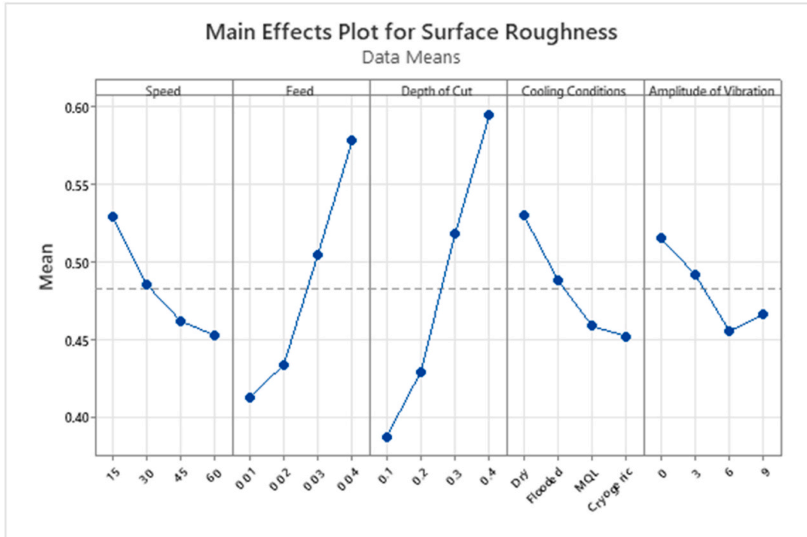

Fig. 8. Main effect plots.

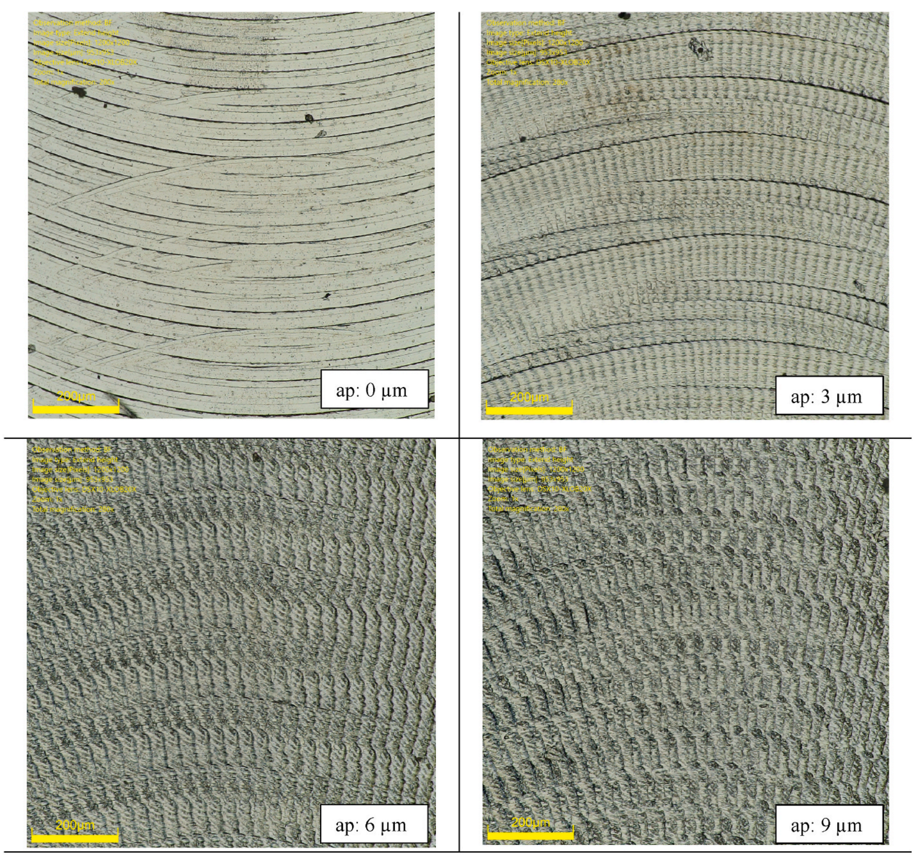

Fig. 9. – 'Hammering Effect' by Ultrasonic Vibrations at different Amplitudes.

Table 7
Machining parameters - minimum & maximum surface roughness.

Minimum Value	Vc: 30 m/min; fz: 0.02 mm/tooth; ap: 0.1 mm; Cooling Condition: Cryogenic; au: 6 µm
Maximum Value	Vc: 30 m/min; fz: 0.03 mm/tooth; ap: 0.4 mm; Cooling Condition: Dry Machining; au: 3 µm

improving the machinability of Ti–6Al–4V. Surface roughness was evaluated under UVAEM in combination with various cooling strategies to propose an environmentally friendly machining approach for industrial applications. Surface roughness was also correlated with cutting forces, tool wear, and burrs to provide an integrated assessment of machining performance. Furthermore, ongoing evaluation of additional outputs, including burr and chip morphology, is expected to provide deeper insights that can contribute to further productivity enhancement and sustainable titanium machining practices.

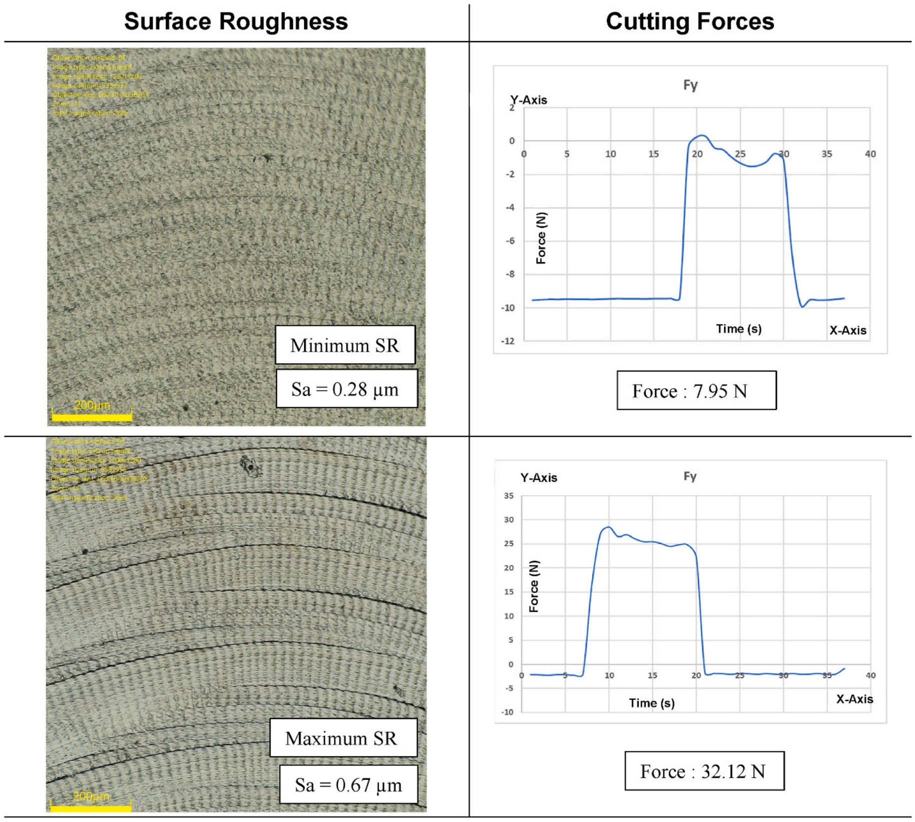

Fig. 10. Cutting forces against minimum & maximum surface roughness [77].

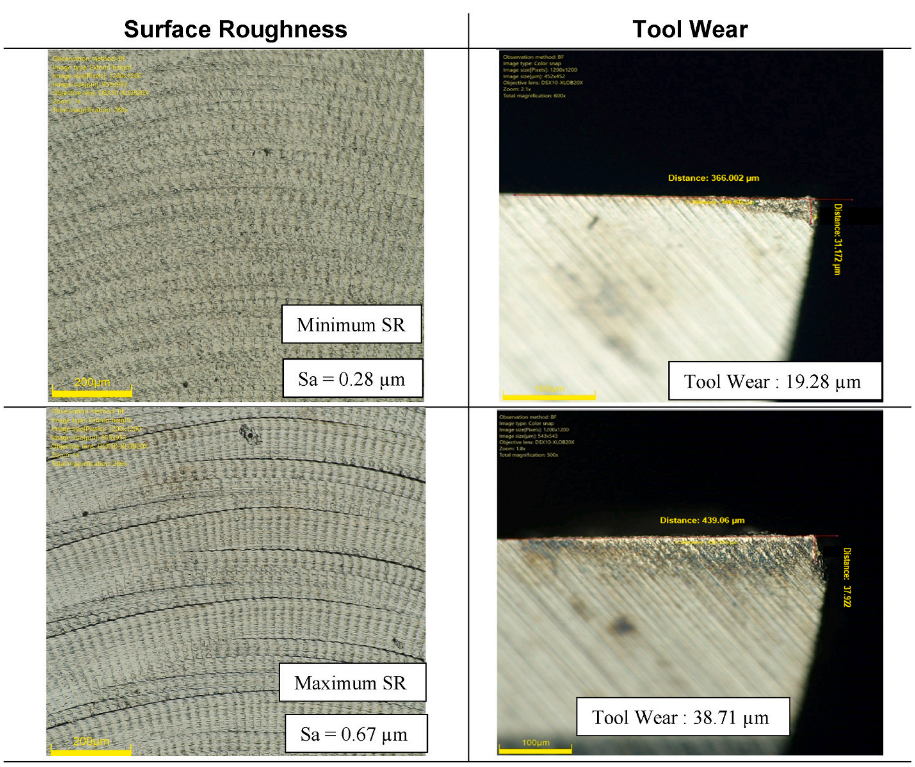

Fig. 11. Tool wear against minimum & maximum surface roughness [77].

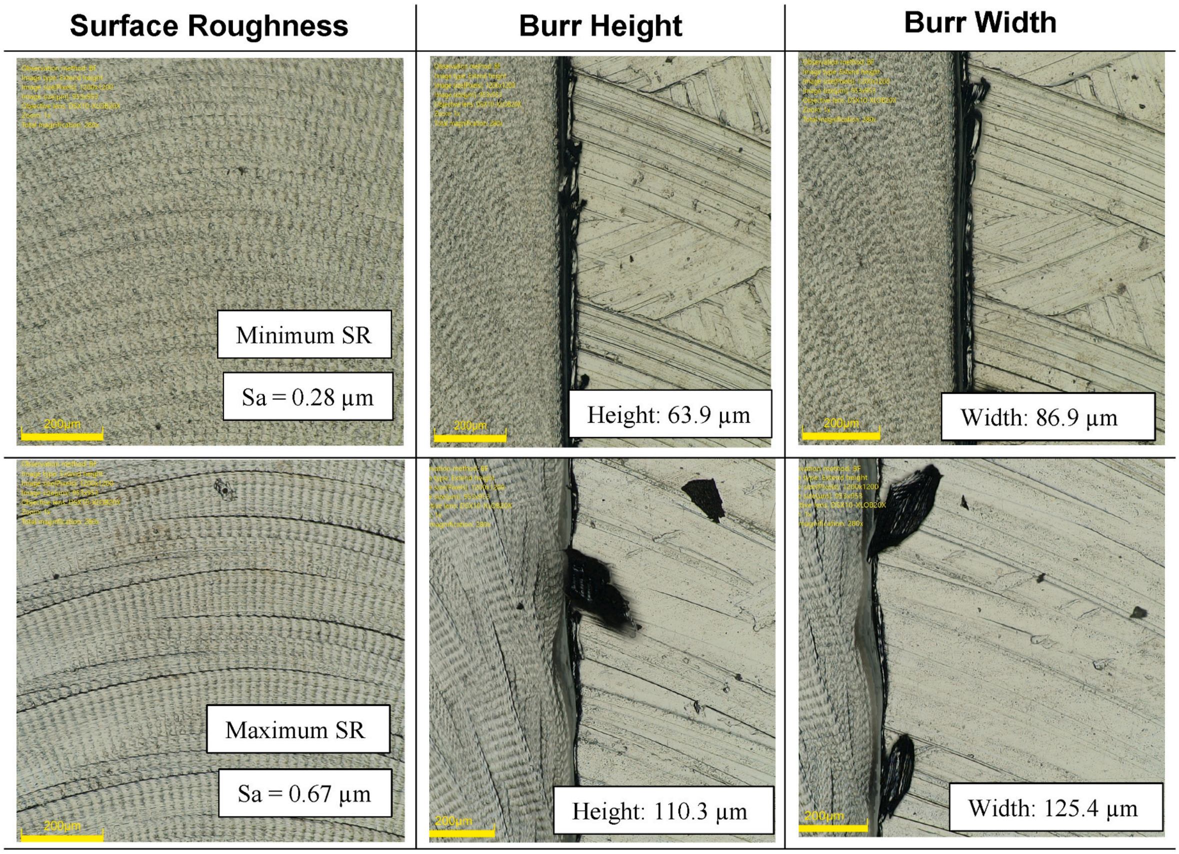

Fig. 12. Burr height & burr width against minimum & maximum surface roughness.

Table 8
Optimal machining parameters and corresponding surface roughness.

Machining Conditions	Parameters	Results
Best	Vc = 60 m/min; fz = 0.01 mm/tooth; ap = 0.1 mm; Cooling = Cryogenic; au = 6 µm	Sa = 0.24 µm
Worst	Vc = 15 mm/min; fz = 0.04 mm/tooth; Ap = 0.4 mm; Cooling = Dry; au = 0 µm (CM)	Sa = 0.72 µm

Consent to participate

There was no human participant involved during the conduct of this research.

Availability of data and material

Data of research is being used for further extended research and can be made available on request.

Ethics approval

We confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere.

Consent for publication

All authors consented to submit the outcome of this research for publication in the journal.

Authors' contributions

Adil Rauf: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing - original draft. Shahid Ikramullah Butt: Conceptualization, DOE, Formal analysis, Visualization, Resources, Supervision, Validation, Writing - original draft. Syed Husain Imran Jaffery: Project administration, Resources, Supervision, Validation, Formal analysis, Visualization, Writing - original draft. Muhammad Ali Khan: Conceptualization, DOE, Visualization, Formal analysis, Resources, Supervision, Validation, Writing - original draft. Ashfaq Khan: Data curation, Formal analysis, Investigation, Project administration, Resources. Danyal Zahid: Conceptualization, DOE, Visualization, Formal analysis, Resources, Writing - original draft. Mushtaq Khan: Data curation, Formal analysis, Investigation, Resources, Supervision, Project administration, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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