

Pulsating minimum quantity lubrication assisted high speed turning on bio-medical Ti-6Al-4V ELI Alloy: An experimental investigation

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Abstract. Machining of bio-medical Ti-6Al-4V ELI grade is categorized in difficult to cut metal alloys due to its lower thermal conductivity and highly reactive in nature at elevated temperature. However, to improve the machinability of this alloy, controlling the temperature during cutting action is a challenging task. On this context, current work introduced a novel cooling strategy named as pulsating minimum quantity lubrication technique to investigate the surface roughness, surface texture (surface topology, surface profile, amplitude distribution curve, Bearing area curve, and Power spectrum), tool-work temperature, and flank wear in high-speed CNC turning of Ti-6Al-4V ELI Alloy. Feed is the leading influencing term towards surface roughness, pulse time contributing the highest impact towards tool-work temperature while flank wear is largely influenced by cutting speed. Abrasion, notch wear, adhesion and diffusion mode of wear is found.

Keywords: Turning / pulsating MQL / Ti-6Al-4V ELI / surface texture / flank wear

1 Introduction

Titanium alloys possess superior combinations of attributes, including greater strength, lesser modulus of elasticity, and superb bio-compatibility characteristics which make it suitable to utilize in dental implants, orthopedic prosthetic devices, and fixtures. Titanium alloys are categorized as α , β , and $(\alpha + \beta)$ type alloys, based on their alloying element phase and quantity [1,2]. Ti6Al4V ELI alloy is an $(\alpha + \beta)$ type alloy and it is the upgraded form of Ti6Al4V alloy consisting of an extra-low amount of interstitial impurities. This ELI grade alloy has lower contents of carbon, oxygen, nitrogen, hydrogen, and iron which exhibit larger strength to weight ratio with depth hardening-ability and larger resistance against corrosion. It is popularly utilized for bio-medical applications such as medical instruments and orthopedic implants. Also, it is one of the potential grades for the turbine, aerospace, and marine parts making industries [2–5].

Practically, machining of titanium alloys is said to be difficult because of its lower thermal conductivity (15.6–19 W/m.K), lower elastic modulus ($90 \times 10^3 - 120 \times 10^3$ MPa), and greater work hardening characteristics [5].

Lower thermal conductivity of Ti-alloy promotes the larger amount of cutting heat transferred into workpiece and tool which exhibited severe metrological alterations (thermal softening, thermal cracking, surface burns etc.) in the finished workpiece. Also, thermal load on tool-tip increases which accelerates the tooling wear thus tool life reduces. Further, the lower elastic modulus of Ti-alloy exhibited the unfavorable spring back phenomena which encourage the chattering of the workpiece thus retarding the quality of finish [5–7]. However, controlling the heat generation during the cutting of Ti-alloys is essential. Thus, many researchers have utilized different combinations of tool geometry, tool materials, cutting parameters and cutting environments to control the cutting heat.

Considering the cooling strategy survey utilized in turning of Ti-6Al-4V Extra Low interstitial (ELI) grade alloy (Fig. 1), the majority of turning works were accomplished under dry circumstances [7–18]. Some works have also reported the utilization of wet [17,18] and flood cooling concept [3,4,17,19–21]. Very few literatures reported the use of minimum quantity lubrication concept in turning of this alloy [17,19,22]. Application of costly nanofluid + minimum quantity lubrication concept in turning of this alloy was accomplished by Rahman et al. [22] in 2019. Also, only single turning work was found on each solid lubricant [17] and high-pressure coolant [23].

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Some relevant findings in turning of Ti-6Al-4V ELI alloys were reported as: According to Sulaiman et al. [4] and Mishra et al. [21], finishing quality of work-surface is largely influenced through feed compared to speed and depth of cut but all terms were significant. Pradhan et al. [7] found the leading trend of surface roughness with leading cutting speed. Ibrahim et al. [14–16] and Rahman et al. [22] noticed reducing trend of surface roughness with leading cutting speed. Kechagias et al. [8] and Sargade et al. [11] found the term feed is most dominant towards surface roughness. Shah et al. [9] found that the nose radius and depth of cut were the leading significant terms while Dillibabu et al. [18] stated that the nose radius and feed were the leading relevant terms for surface roughness. In titanium metal machining with carbide inserts (coated and uncoated), the wear mechanism such as plastic deformation, abrasion, adhesion, diffusion, and chipping worked for the occurrence of tooling wear [3,4,17,22]. In machining of ELI grade of titanium alloy, cutting temperature was traced to be proportional with speed [7,9]. Also, magnitude of cutting temperature is depending on turning time and it was increasing with turning time [13]. According to Ibrahim et al. [13], microstructure of machined part is purely depending on temperature generation. Lower speed

(55 m/min) turning attributed the lower temperature generation, however no variations in microstructure was noticed, while higher speed (95 m/min) exhibited a larger temperature (about 900 °C) which significantly change the surface microstructure. Słodki et al. [23] presented a detailed study on chips form and their length in finish turning of Ti-6Al-4V ELI alloy.

Majority of turning research works on Ti-6Al-4V ELI alloy was accomplished in dry and flood cooling circumstances. Very little works reported the minimum quantity lubrication assisted turning. However, this gap motivates us to use an advanced cooling concept as pulsating minimum quantity lubrication to explore machining analysis of difficult to cut Ti-6Al-4V ELI alloy. Also, very little works included the analysis of tool-work temperature for, particularly machining of this alloy. Further, surface texture analysis using the surface profile, amplitude distribution curve, Bearing area curve, and power spectrum is not yet done for any titanium alloys machining. However, considering these knowledge gaps, the prime objectives of the current work as follows:

- Development of pulsating minimum quantity lubrication system for cooling purpose.
- L_{16} design of experiment based high speed turning of bio-medical Ti-6Al-4V ELI alloys.
- Measurement and analysis of surface roughness, flank wear and tool-work temperature.
- Surface texture analysis using the surface profile, amplitude distribution curve, Bearing area curve, and power spectrum.

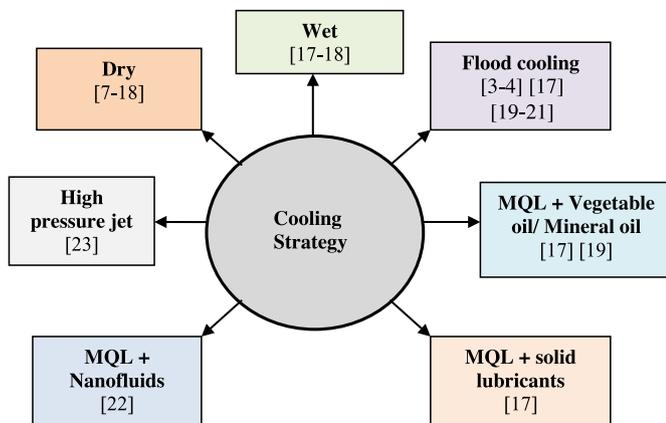


Fig. 1. Cooling strategies utilized in turning of Ti-6Al-4V ELI alloy.

2 Implementation schemes and design

2.1 Details of test-workpiece, insert and machine tool

The workpiece is chosen as Ti-6Al-4V ELI ($\alpha + \beta$) titanium alloy (Grade 23) because of its wide applicability in various engineering and medicine field. The machining length and initial diameter is kept fixed as 105 mm and 35 mm respectively. The hardness of the test-workpiece is measured as 36 HRC and its micro-structure is shown in **Figure 2a**. WIDIA made multi-layered (TiN/TiCN/ Al_2O_3 /ZrCN) CVD coated carbide insert of ISO geometry

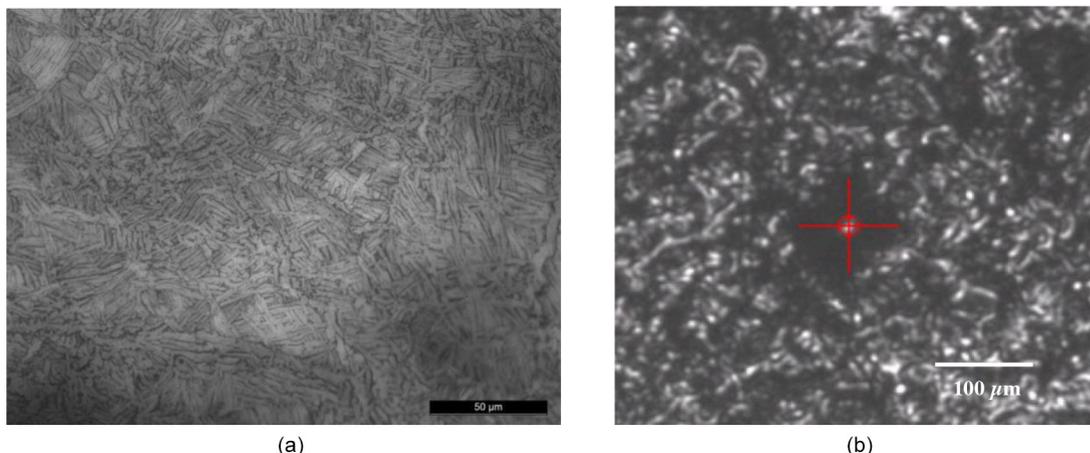


Fig. 2. (a) Micro-structure of test-workpiece (b) micro hardness test of insert.

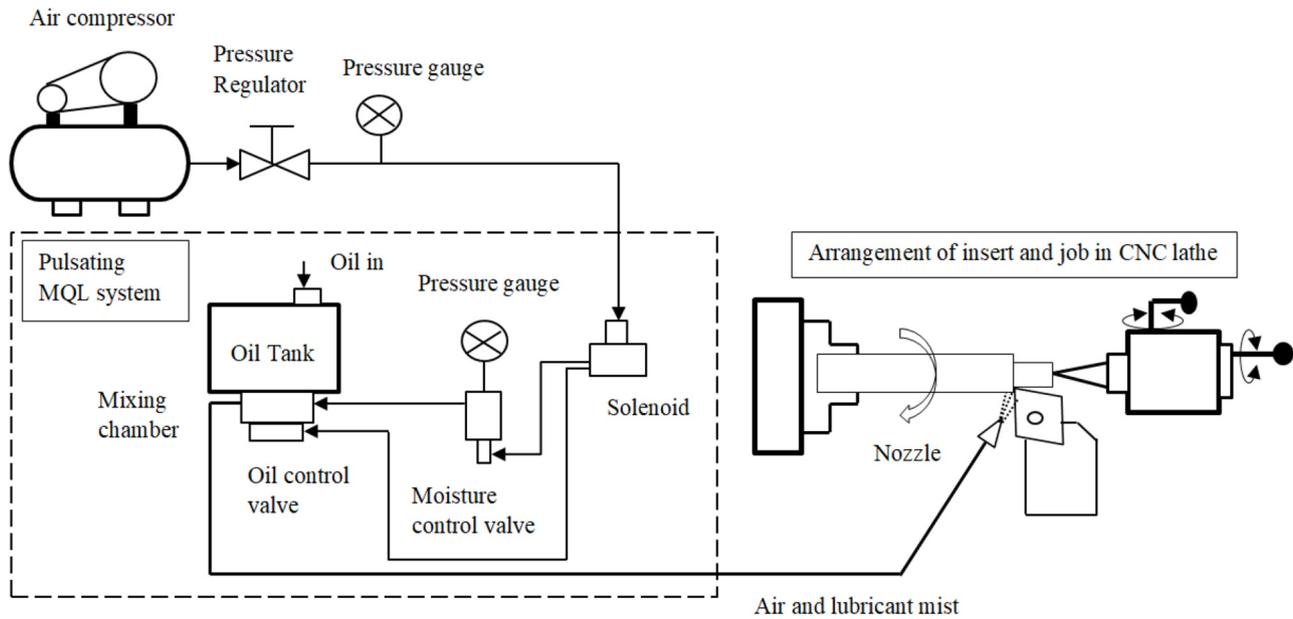


Fig. 3. Schematic view for pulsating minimum quantity lubrication system in CNC turning.

(CNMG120404 FF) with grade WM15CT are utilized for turning experiments. This insert grade was recommended for high degree of wear resistance and good resistance to depth-of-cut notching for long tool life in finishing to medium turning applications. The geometry of insert is as follows: Included angle 80° , approach angle 95° , inclination angle -6° , clearance angle 5° , back rake angle -6° , and nose radius 0.4 mm. The Vickers micro-hardness test of insert is carried using Zwick/Roell, ZHV 30 instrument at 1 Kgf load (Fig. 2b) and the average micro hardness is noted as 2365 HV which ensured that the insert has better wear resistance competency [24]. CNC lathe (Model – DX 200 4A) manufactured by Jyoti CNC Automation Ltd, India is utilized for the turning test. The overhang length of tool holder for entire test was kept fixed as 50 mm [25].

2.2 Pulsating minimum quantity lubrication system and lubricant details

Industrial standard minimum quantity lubrication setup manufactured by DROPSA, Italy is utilized to supply the lubricant in pulse mode. Nowadays, pulsating minimum quantity lubrication concept is emerging as a novel concept to enhance the minimum quantity lubrication performance especially for hard to cut metals. Pulsating mode of coolant supply exhibited an interrupt flow of coolant during cutting which is becoming beneficial for machining of hard metals. Pulsating mode of coolant supply can be understood by a suitable example as follows: suppose pulse time of minimum quantity lubrication is 3 s, that is, when minimum quantity lubrication system starts, the coolant is supplied for 3 s then stop for next 3 s and this process is repeated further. The current work utilized 4 different pulse times in such as 1, 2, 3 and 4 s. Coolant utilization is

directly associated with pulse time, that is, with increasing pulse time minimum quantity lubrication flow rate decreases. The coolant flow with irrespective of pulse time measured and found as about 40, 20, 13 and 10 ml/h for pulse time 1, 2, 3 and 4 s respectively. The schematic view of flow of Pulse MQL is displayed in Figure 3. Initially, the air compressor supplied the controlled compressed air into solenoid valve via pressure regulating valve. Pressure regulating valve is utilized to control the pressure of air. Further from solenoid valve, it is delivered into the moisture control valve through air pressure control valve and into oil control valve. Further, moisture control valve supplied moisture free compressed air into the mixing chamber. Simultaneously, lubricant from oil tank is entered into mixing chamber by gravity mode. In mixing zone, the lubricant and moisture free air mixed properly and then through flow control valve, the mixture of air and lubricant is supplied into the cutting zone through CH10 5/16 type spray nozzle. The impingement position of nozzle is kept fixed at 45° from the feeding direction of tool and 40 ± 2 mm from tool tip. The coolant utilized for this research is iron-aluminium LRT 30 (viscosity = 24 cSt at 40° , specific weight = 900 g/l at 15° , flammability temperature = 220°C). It possesses good anti-corrosion feature which is advantageous towards harm of machine tool parts [26].

2.3 Experimental plan and methodology

The turning test is planned according to Taguchi L_{16} (4^4 i.e. 4 factors with 4 levels of each) design. The four cutting factors like depth of cut (D_c), feed (S_o), cutting speed (V_c) and pulse time (P_t) are selected as input terms for the turning tests as listed in Table 1. The machining attributes like surface roughness (R_a), surface

texture, tool-work temperature (T), and flank wear (VBc) are studied. Surface roughness data is taken through Taylors Hobson roughness tester, Surface texture (surface profile, amplitude distribution curve, Bearing area curve, and Power spectrum) is measured using Surftest SV-2100 (Mititoyo) with ISO 1997 standard. Length of stylus travel, sampling length, Gaussian filter cut off length and evaluation length are consider as 11.5, 3, 2.5 and 9 mm respectively. Surface image and flank wear image are capture through OLYMPUS STM 6 microscope with 200 μm scale. Wear width measurements are accomplished by stream basic software available in microscope. Accuracy of wear width measurement is found within $\pm 1\%$. Fluke (Ti32 model) infra-red thermal camera is utilized to take the tool-work interface temperature in the course of cutting. The measurement accuracy of fluke camera is $\pm 2^\circ$.

3 Results and analysis

The L_{16} turning test design and results are listed in Table 2.

Table 1. Input terms.

Factors	Symbol	Units	Values
Depth of cut	Dc	mm	0.2, 0.3, 0.4, 0.5
Feed	So	mm/rev	0.05, 0.15, 0.25, 0.35
Cutting speed	Vc	m/min	60, 120, 180, 240
Pulse time	Pt	second	1, 2, 3, 4

Table 2. Turning results.

Test no.	Input terms				Responses		
	Dc (mm)	So (mm/rev)	Vc (m/min)	Pt (s)	Ra (μm)	T ($^\circ\text{C}$)	VBc (mm)
1	0.2	0.05	60	1	0.35	110.9	0.109
2	0.2	0.15	120	2	0.54	169.1	0.171
3	0.2	0.25	180	3	0.87	296.8	0.285
4	0.2	0.35	240	4	1.21	443.9	0.572
5	0.3	0.05	120	3	0.42	224.7	0.214
6	0.3	0.15	60	4	0.88	214.3	0.168
7	0.3	0.25	240	1	0.83	259.6	0.438
8	0.3	0.35	180	2	1.59	275.1	0.376
9	0.4	0.05	180	4	0.43	279.3	0.319
10	0.4	0.15	240	3	0.66	307.1	0.447
11	0.4	0.25	60	2	1.84	156.1	0.145
12	0.4	0.35	120	1	2.10	151.2	0.209
13	0.5	0.05	240	2	0.40	255.1	0.371
14	0.5	0.15	180	1	1.06	178.4	0.260
15	0.5	0.25	120	4	1.91	305.2	0.265
16	0.5	0.35	60	3	2.90	273.0	0.161

3.1 Effects of pulsating MQL onto the machining outputs

Pulsating MQL exhibited rapid heat dissipation phenomena from the machining zone due to formation of uniform velocity pattern of pulsating jet over cutting area. According to Mia et al. [27], as pulse jet moves from the stagnation point, then the velocity of pulsating jet increases which exhibited a uniform velocity pattern along the radius thus intensity of turbulence increases which attributed the enhanced mode of heat transfer from the cutting region. Also, Nusselt number is leading with turbulent intensity for pulsating jet relative to steady flow and it is proportional to heat transfer coefficient.

In the current work, four levels of pulse time (1, 2, 3 and 4 s) have been utilized. Based on the pulsating concept, 1 s pulsating time exhibited more frequent impingement of cooling jet compared to 2, 3 and 4 s which keeps the interface zones (tool-work and tool-chip) lubricated effectively and exhibited the superior cooling effect on tool and work surfaces. The obtained average value of tool-work temperature (Fig. 4a), surface roughness (Fig. 4b) and flank wear (Fig. 4c) are lowest at pulsating time of 1 s. Higher pulsating time exhibited the lack of lubricant availability during pulse gap period. In higher pulsating time especially for 3 and 4 s, there is sufficient time gap available in which some amount of lubricant falls down due to gravity force and remaining portion of lubricant is evaporated by removing the heat from the cutting zone [27]. Thus the tool-work temperature and flank wear are comparatively very high in 3 and 4 second pulsating time. One second pulsating time produced 11.2%, 57.3% and 77.5% lower tool-work temperature compared to 2, 3 and 4 s respectively. Similarly, 4.6%, 8.9% and 30.3% lesser

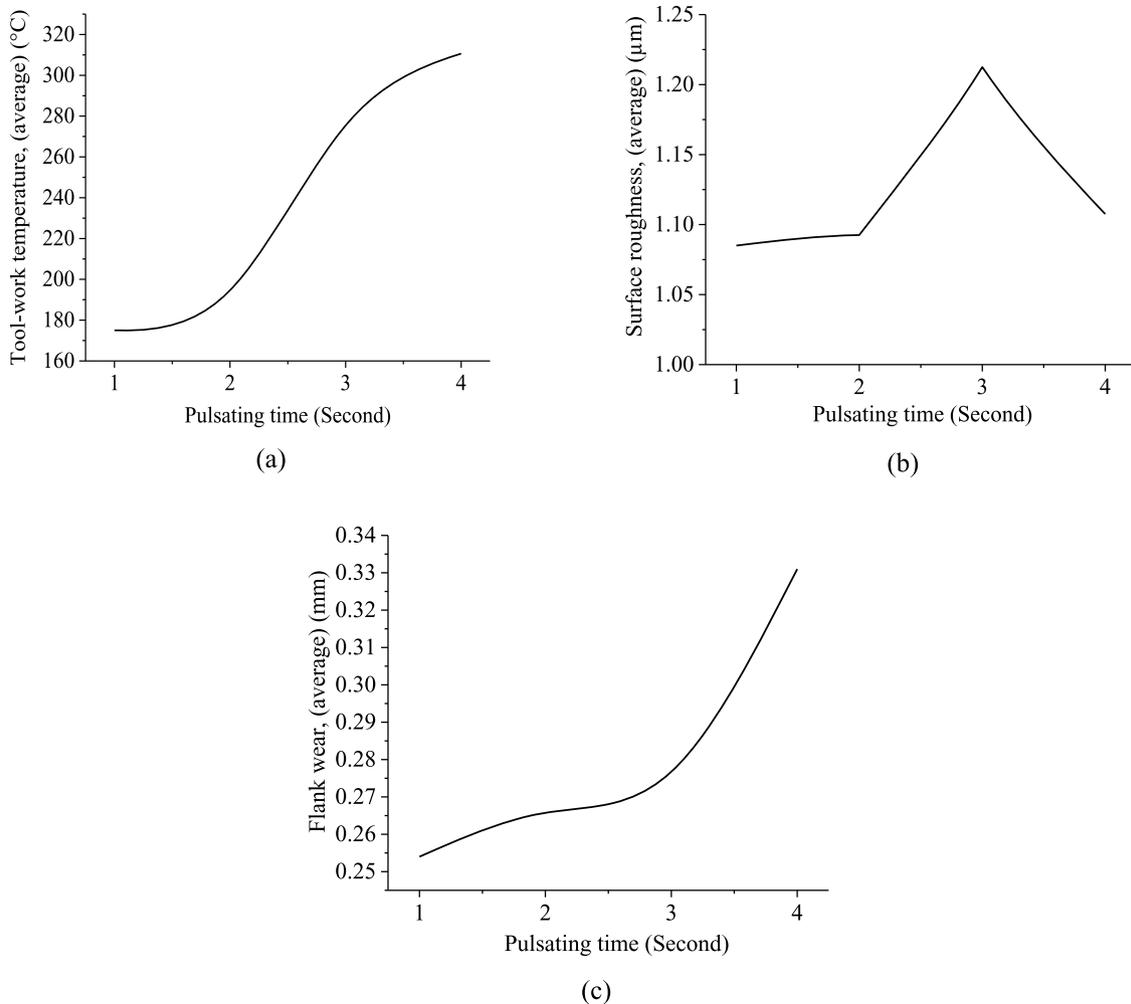


Fig. 4. Effects of pulsating time on (a) surface roughness (b) tool-work temperature and (c) flank wear.

flank wear noticed in 1 second pulsating time relative to 2, 3 and 4 s respectively. Impact of pulsating time on surface roughness is not much very effective because theoretically feed is the dominant factor which influences the surface roughness largely. Surface roughness under 1 and 2 s pulsating time is almost same but for 3 and 4 s pulsating time, it seems to be larger. Compared to 1 s pulsating time, 3 and 4 s pulsating time exhibited 11.7% and 2% more surface roughness. However, it can be concluded that the impact of pulsating minimum quantity lubrication on considered machining attributes are relevant.

3.2 Surface roughness analysis

Surface roughness analysis was done based on the average value of roughness. In the current research, surface roughness is measured at five different locations along the length of the workpiece and the average of these five readings is considered as the final roughness value indicated in Table 2. Further, the standard error is estimated for each test run and graphically shown in Figure 5. The average standard error was found to be ± 0.021 ($\pm 2.19\%$). Pulsating MQL significantly lessens

the surface roughness (Ra), as comparatively lower Ra ($0.35\text{--}2.9\ \mu\text{m}$) is noticed (Tab. 2) even at larger feed ranges ($0.05\text{--}0.35\ \text{mm/rev}$). The obtained result of Ra at run 1 ($60\ \text{m/min}$) is almost equivalent to result obtained by Rahman et al. [22] under different nanofluid environments at cutting speed of $55\ \text{m/min}$. The current Ra result is more favorable than the Ra obtained by Ibrahim et al. [15] at similar feed range ($0.15\text{--}0.35\ \text{mm/rev}$) in dry turning. At highest feed $0.35\ \text{mm/rev}$, they found Ra as $4\text{--}5\ \mu\text{m}$ at speed of $55\ \text{m/min}$, $3\text{--}4\ \mu\text{m}$ at speed of $75\ \text{m/min}$ and about $2\text{--}3\ \mu\text{m}$ at speed of $95\ \text{m/min}$ while in the current work at largest feed $0.35\ \text{mm/rev}$, the lowest Ra ($1.21\ \mu\text{m}$) is noticed at speed of $240\ \text{m/min}$ and largest Ra ($2.9\ \mu\text{m}$) is found at $60\ \text{m/min}$. Also in dry turning of grade 23 alloy, Pradhan et al. [7] found Ra values in between $0.76\ \mu\text{m}$ ($112\ \text{m/min}$) and $0.973\ \mu\text{m}$ ($65\ \text{m/min}$) while Kechagias et al. [8] noticed Ra in range of $1.27\ \mu\text{m}$ ($0.18\ \text{mm/rev}$) and $14.73\ \mu\text{m}$ ($0.33\ \text{mm/rev}$) in turning of same alloy.

3.3 Surface texture analysis

Surface texture is one of the key importance aspects which need to be considered before using the machined item in

actual practices. Therefore, the current research presented the surface texture analysis using machined surface optical image, surface profile, amplitude distribution curve, bearing area curve and power spectrum. The details of

surface texture for test runs 13–16 are as displayed in Figures 6–9 respectively.

In the optical micrographs of machined surface (Figs. 6a, 7a, 8a and 9a), feed marks in form of groves are clearly found. Spacing between two adjacent groves are increasing with feed rate and it is confirmed by the surface profile graph as the gap between two consecutive peaks are increasing with feed rate (i.e. runs 13–16) as shown in figures (Figs. 6b, 7b, 8b and 9b). Also, the measured Ra values are increasing with feed rate and the same is confirmed by the surface profile graphs as the average height of peak (from zero line) is increasing with feed rate.

The amplitude distribution curve is very informative towards overall analysis of the surface topology. Smith [28] stated that, if amplitude distribution curve pattern is symmetric, then it ratifies the symmetry of the surface profile; conversely, an asymmetrical surface profile will be the indication of a skewed amplitude distribution curve. Skewness also demonstrates the distributions of peaks and valleys obtained in machined surface profile. In the current finding, amplitude distribution curve is almost symmetrical for combinations of lower feeds (0.05 and 0.15 mm/rev) and larger speeds (240 and 180 m/min) ranges but for higher ranges of feed (0.25 and 0.35 mm/rev) and lower speeds (120 and 60 m/min) it is unsymmetrical as shown in respective figures (Figs. 6c, 7c, 8c and 9c). However, it can be stated that the lower feed with larger speed assisted

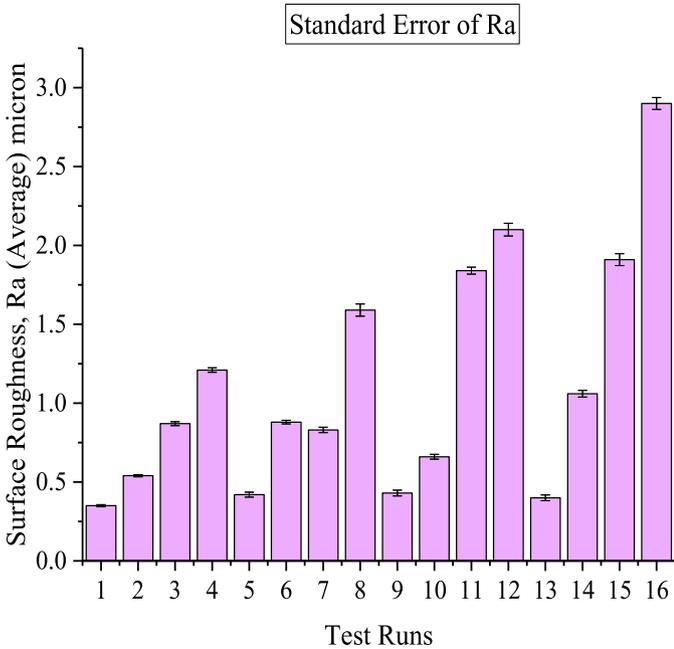


Fig. 5. Results of surface roughness with standard error bar.

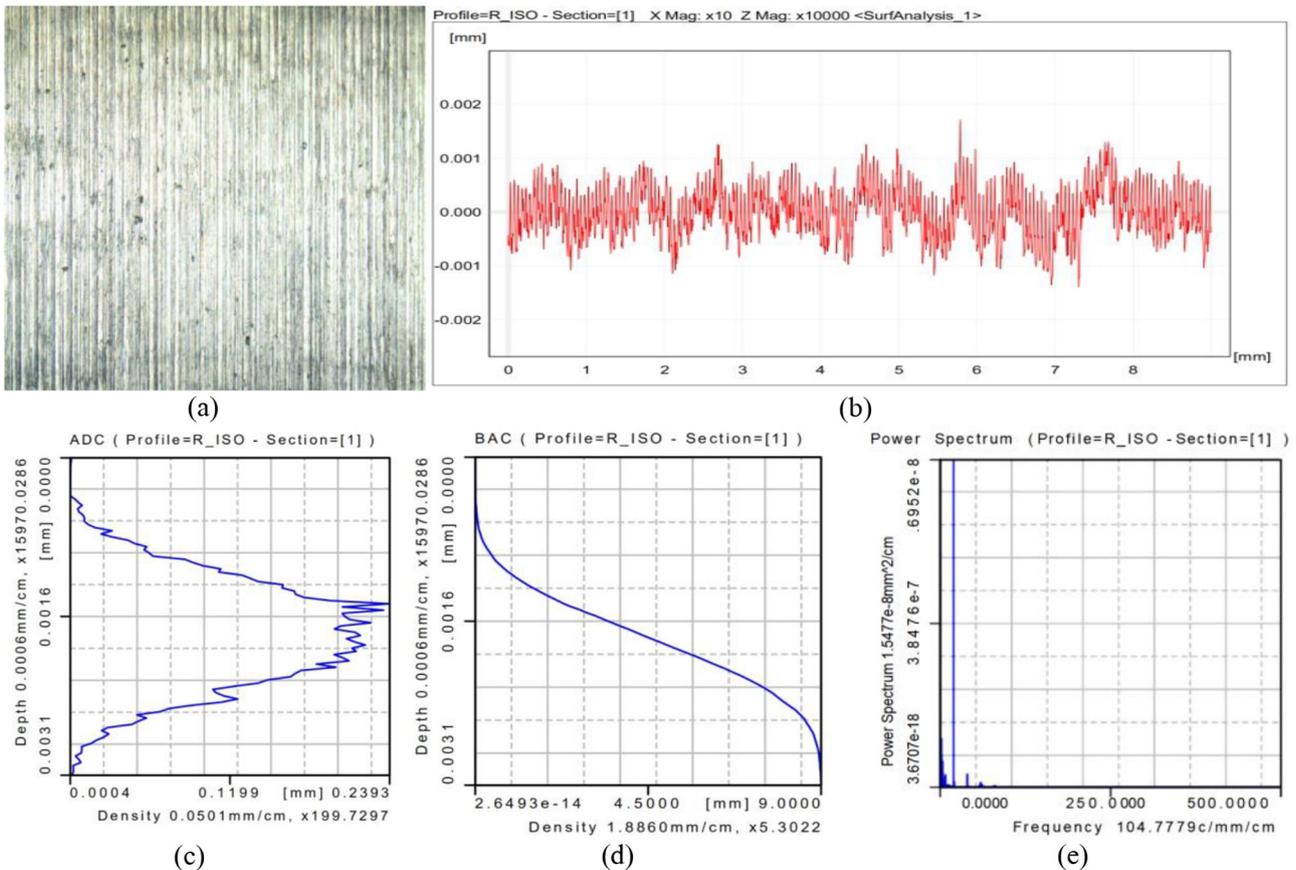


Fig. 6. (a) Surface topology (b) surface profile (c) amplitude distribution curve (d) bearing area curve (e) power spectrum for run 13.

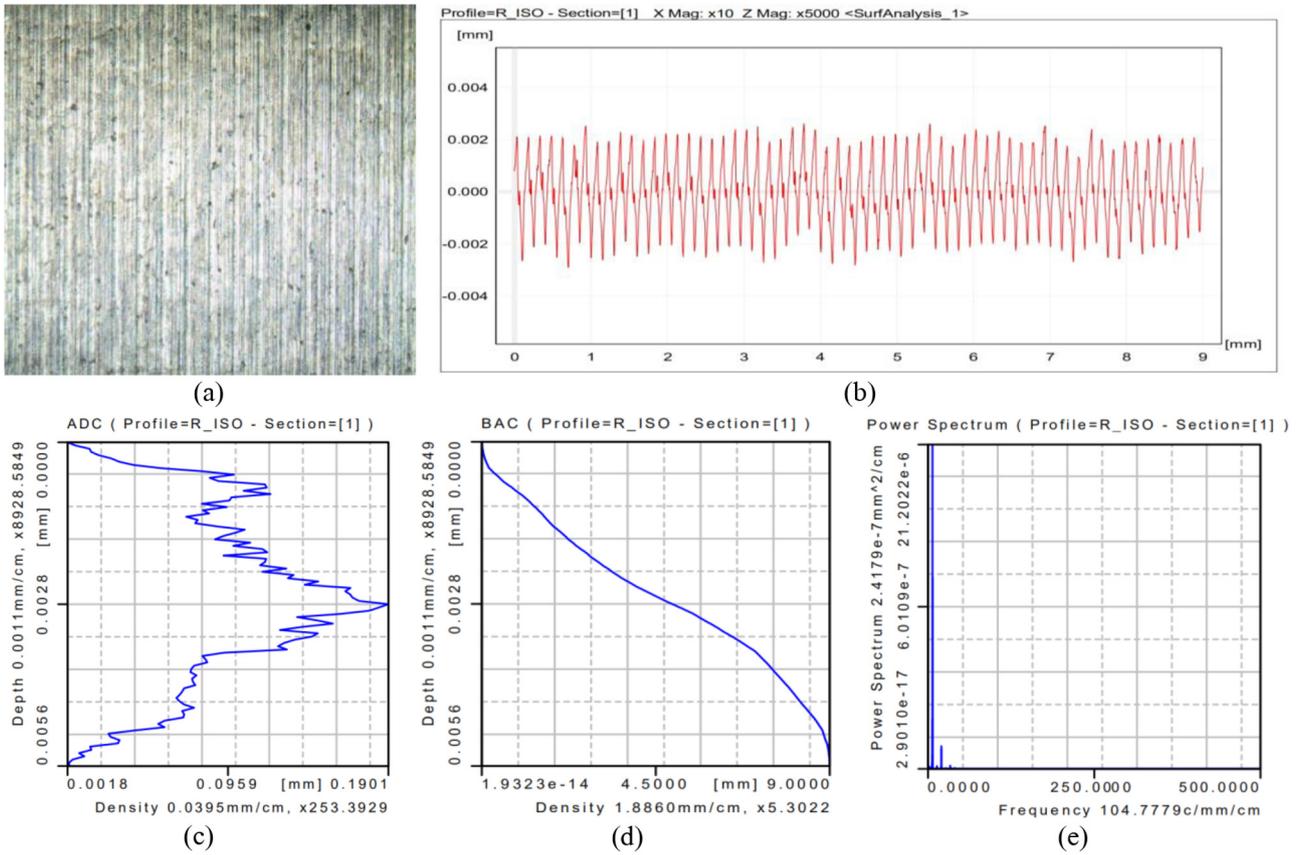


Fig. 7. (a) Surface topology (b) surface profile (c) amplitude distribution curve (d) bearing area curve (e) power spectrum for run 14.

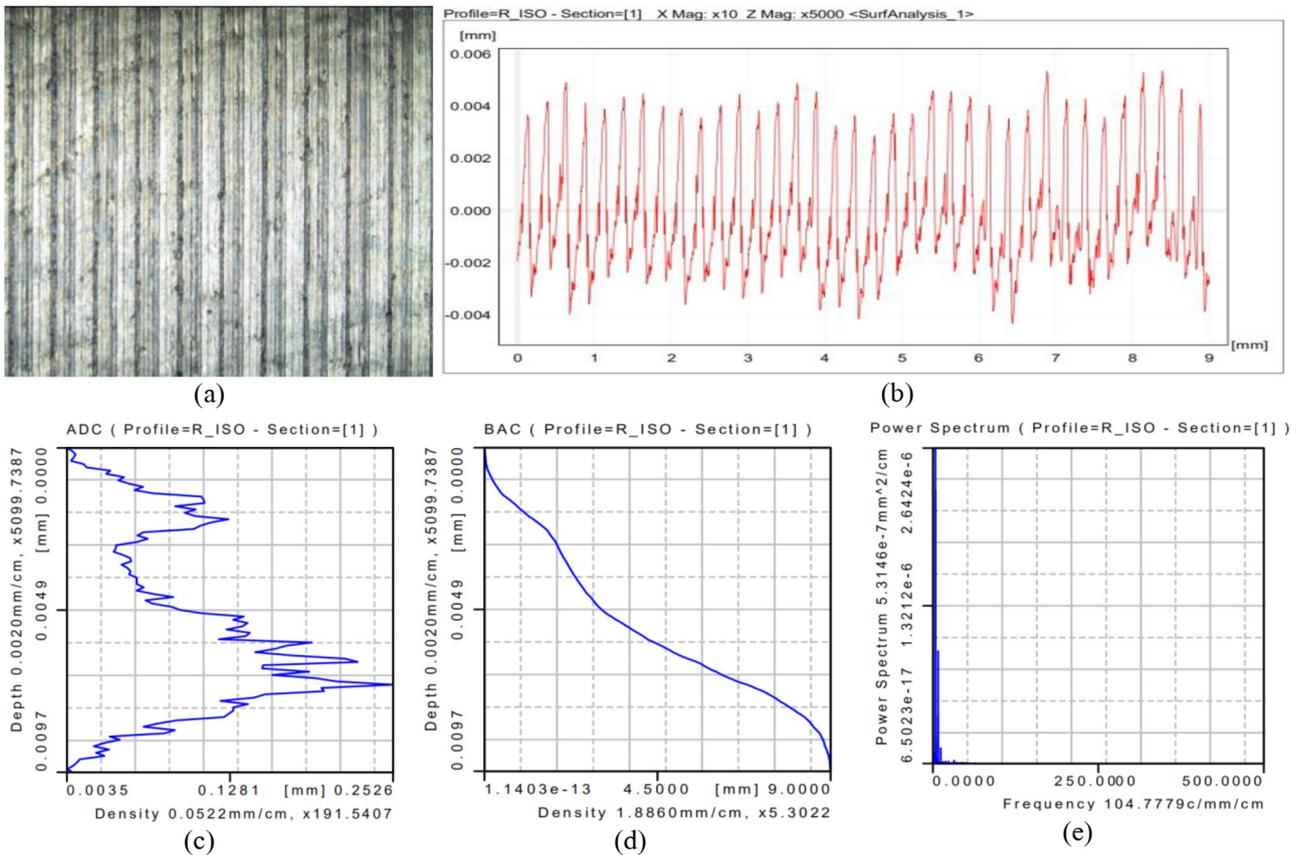


Fig. 8. (a) Surface topology (b) surface profile (c) amplitude distribution curve (d) bearing area curve (e) power spectrum for run 15.

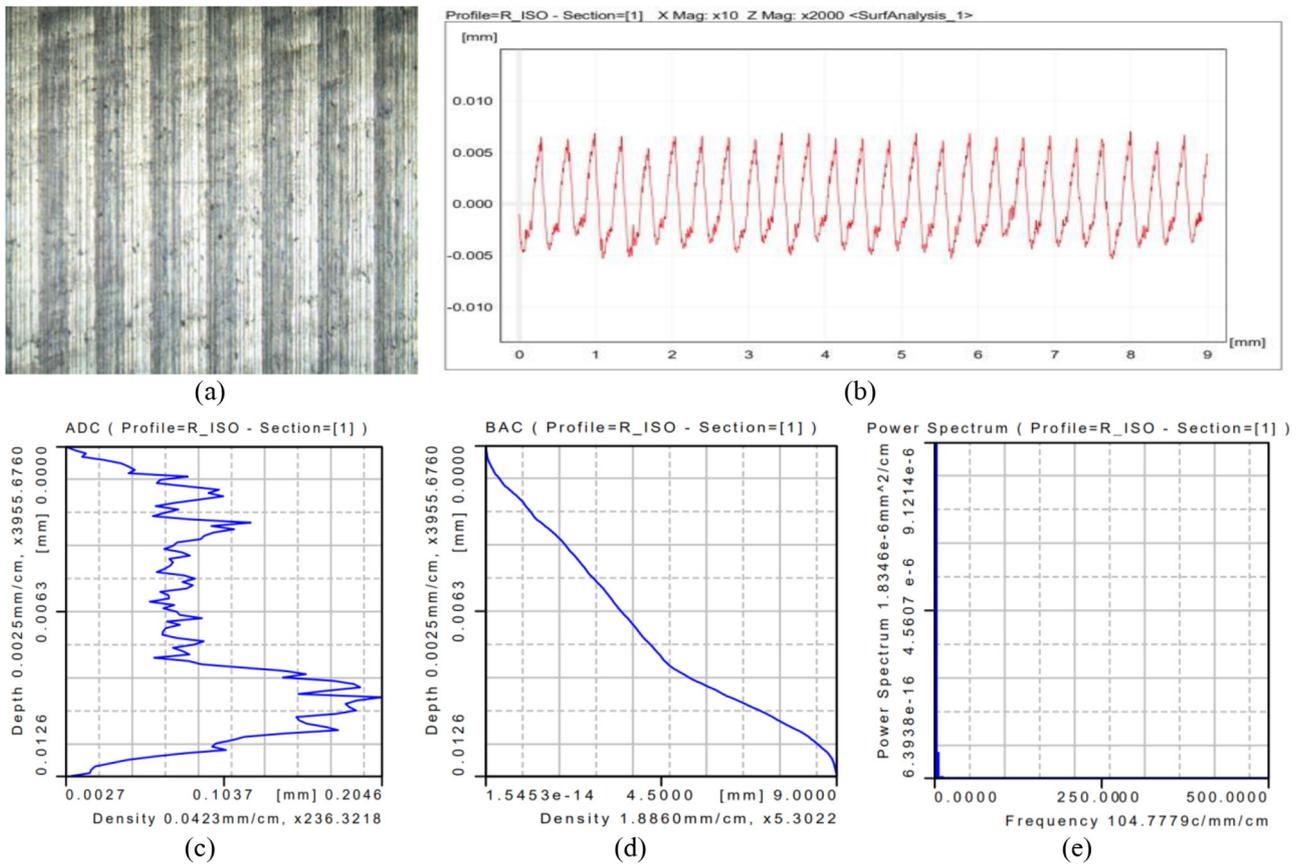


Fig. 9. (a) Surface topology (b) surface profile (c) amplitude distribution curve (d) bearing area curve (e) power spectrum for run 16.

machining attributed the better distributions of peaks and valleys throughout the cutting length and exhibited almost uniform roughness.

The bearing area curve, also called as Abbott-Firestone Curve has been initially utilized in 1933 by Abbott and Firestone to analyze the finished surface [29]. According to Zhu and Huang [30], the shape of bearing area curve is commonly nearly to ‘S’ shape which meets the current pattern of bearing area curve obtained in different set of experiments (Figs. 6d, 7d, 8d and 9d). More perfect ‘s’ shape and lower slope of bearing area curve is found at lowest feed and largest speed condition which indicates the lower surface roughness compared to other conditions [31]. Also, bearing area ratio from run 13 to 16 is reduces hence surface roughness increases [31].

The power spectrum of machined surface analysis shows the variations in surface with respect to different frequencies. The power spectrum is one of the Fourier transform form of auto-correlation function of the developed signal, containing the power over a range of frequencies [32]. This allows empathy of the frequencies that can be observed in the signal. In the current work, frequencies vs power spectrum graph is studied for run 13–16 as located in respective figures (Figs. 6e, 7e, 8e and 9e). The form of surface profile obtained in each run is noticed as sine waves. For these sine waves, the power spectrum has a single peak at the respective frequency. Also, the critical frequency (i.e. largest peak of power

spectrum) reduces from run 13 (lowest feed and largest speed) to run 16 (highest feed and lowest speed) which may exhibit the probable cause for increment in R_a from run 13 to run 16. Also, the effect of cutting terms (feed and speed) on surface texture is clearly noticed as frequency reduces with leading feed and reducing speed.

3.4 Tool-work temperature

Tool-work temperature (T) influences the other machining responses. Higher T accelerates the wear growth thus responsible for lesser tool life. Also, intense amount of heat promotes the chip adhesion on to the finished surface which causes the poor surface finish. Currently, pulse mode of minimum quantity lubrication considerably reduced the tool-work temperature as it varies in between 110.9 and 443.9°C as shown in Table 2 and Figure 10. Pradhan et al. [7] found 566°C cutting temperature in dry turning when speed was 124 m/min. In another work, the temperature in dry turning was found very low (56–219.5°C) due to very low operating speed (30–70 m/min) [9]. Rahman et al. [22] noticed about 875°C chip-tool interface temperature in canola based MoS_2 nanofluid (0.5% vol.). However, relatively low magnitudes of temperature observed under current lubrication scenario even at high speed range (80–240 m/min) turning condition. This implies that the pulsating minimum quantity lubrication coupled with LRT 30 lubricant effectively cool the cutting zone which

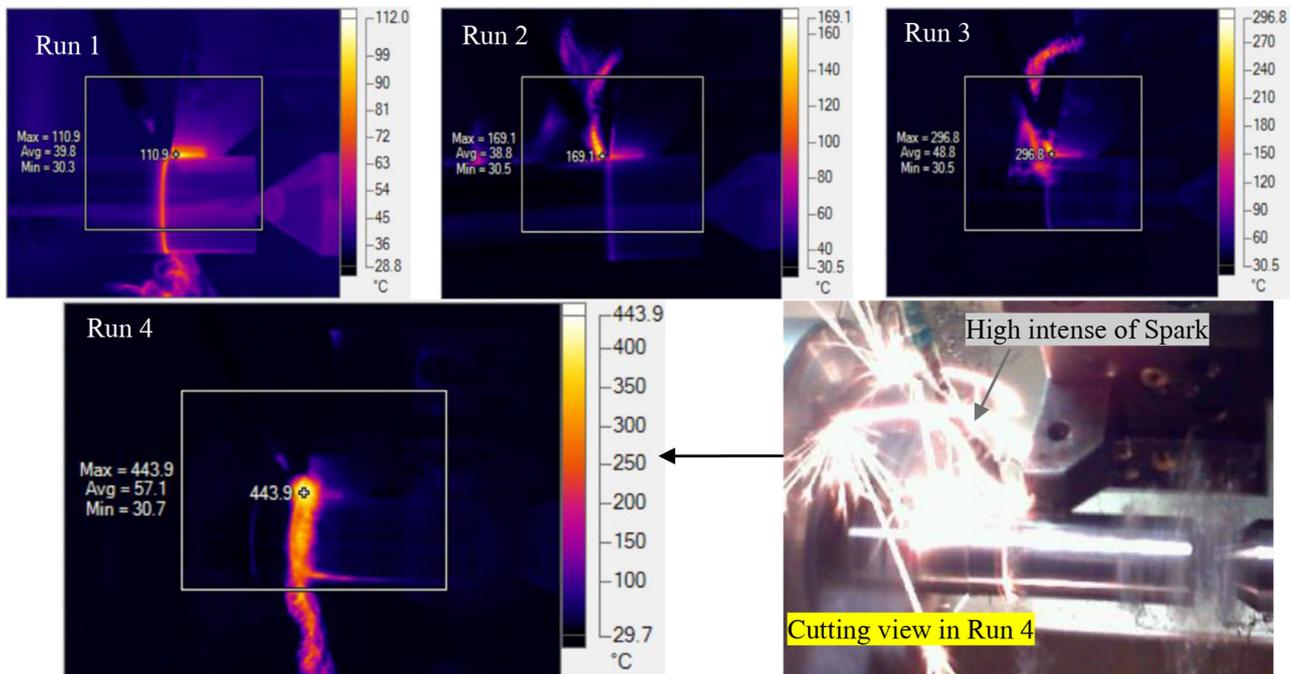


Fig. 10. Infrared image of temperature.

enhances the cutting performance with larger tool life. Similar findings were reported by Roy et al. [33]. Also, at largest parameters conditions (run 4), intense amount of spark generated as shown in Figure 10, which attributed the highest tool-work temperature thus tool got catastrophically fail by plastic deformation.

3.5 Flank wear

Flank wear is main crucial factor which affects the surface quality and overall expenditure towards machining. The measured flank wears width (VBc) for entire test runs are mentioned in the Table 2. In machining of titanium alloys, the flank wear at insert nose is found to be precarious because it exhibited the geometrical loss of cutting edges and machined workpiece. Development of flank wear is the result of both the continuous interaction of tool-workpiece and chipping effect on edge by removal of adhered materials on to the cutting edge [17]. In the current work, abrasive mode of wear is clearly noticed with non-uniform width in entire test runs. Notch wear (Fig. 11) is also noticed at higher cutting speeds range (120–240 m/min). Highest cutting speed (240 m/min) machining exhibited the catastrophic tool-tip failure (Fig. 11) due to generation of intense amount of temperature by insufficient cooling and lubrication capability of pulsating minimum quantity lubrication at 240 m/min of cutting speed. Burnt mark is also found in entire test runs expect run 1 (cutting speed and pulse time is lowest). In run 1, as pulse time is least (1s), minimum quantity lubrication supplied sufficient lubricant into the tool-work contact zone as a result the generation of temperature is very less (110.9°C) hence burnt mark is not produced on to the tool-flank face. Notch wear is also found on tool tip (Fig. 11) at moderate levels of

input parameters. Adhesion promotes the notch wear phenomena [34]. In titanium alloys machining, adhesion phenomena (some fine pieces of work materials cling on to the edge or face of tool) is frequent and with the progress of cutting, these adhered materials come off from the cutting edge and pull-out the tool coatings, thus this removal of coatings produced the notch wear as shown in Figure 11 [35]. Notch wear is not favourable as it dominantly affects the finishing quality. Also, built-up edge is noticed at lowest speed (80 m/min) with largest feed (0.35 mm/rev) and depth of cut (0.5 mm) conditions as displayed in Figure 11, and it is agreed with the work reported by Rao [36]. Also, due to development of built-up edge in run 16, very high Ra (2.9 μm) is noticed.

3.6 Analysis of contour plots

Contour plots (Fig. 12a and b) revealed that the Ra is rising with So and up to 0.15 mm/rev of So with any combinations of other input parameters exhibited a better Ra ($\leq 1.3 \mu\text{m}$). Similarly from Figure 12c and d, increment in Pt and Vc exhibited the higher T due to lack of lubricant penetration into cutting zone because of less frequent supply of lubricant at higher pulse time gap. Further from Figure 12e and f, VBc is snowballing with leading Vc, and up to 120 m/min Vc is recommended to achieve below 0.3 mm of wear width. Further, feed is the topmost impact term on Ra next to Dc and Vc. The impact of Pt on Ra is almost negligible. Similarly, Pt exhibiting the largest impact on T succeeded by Vc and So while the impact of Dc is minute only. Further, the monopoly of Vc on VBc is clearly observed through the wear width values mentioned in Table 2. Similar findings are stated by Panda et al. [37].

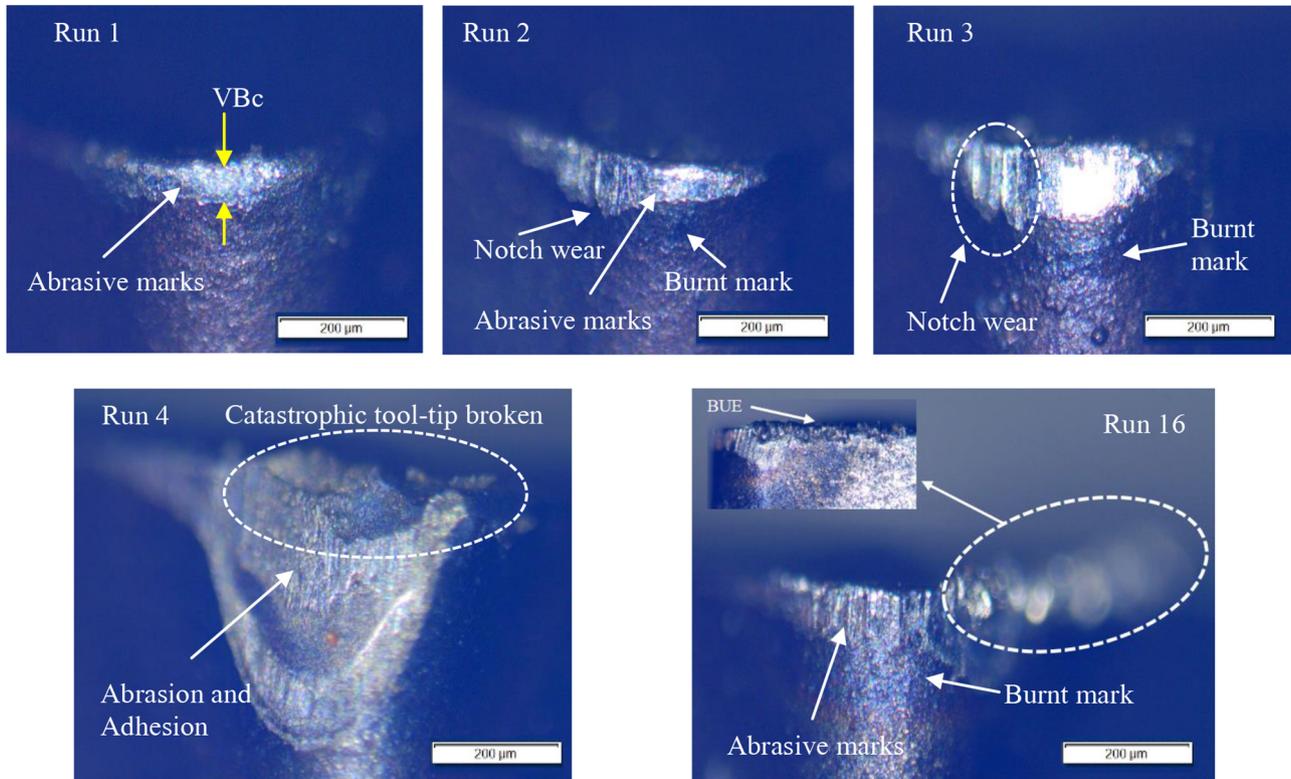


Fig. 11. Wear image of tool-tip.

4 Conclusion

Current work emphasized on machinability study of bio-medical Ti-6Al-4V ELI grade alloy using CVD coated carbide tool under novel pulsating minimum quantity lubrication cooling circumstances. Some major observations are summarized as follows:

- 1 s pulsating time exhibited better performance relative to other higher pulsating times. 1 s pulsating time produced 11.2%, 57.3%, and 77.5% lower tool-work temperature compared to 2, 3, and 4 s respectively. Similarly, 4.6%, 8.9% and 30.3% lesser flank wear noticed in 1 s pulsating time relative to 2, 3 and 4 s respectively. Compared to 1 s pulsating time, 3 and 4 s pulsating time exhibited 11.7% and 2% more surface roughness.
- Overall, pulsating minimum quantity lubrication significantly lessens the surface roughness (R_a), as comparatively lower R_a ($0.35\text{--}2.9\ \mu\text{m}$) is noticed even at larger feed ranges ($0.05\text{--}0.35\ \text{mm/rev}$). Feed exhibited the largest impact on R_a succeeded by D_c and V_c .
- Surface topology shows the leading gap between two adjacent groove marks when feed rate increases and it is also confirmed from surface profile graphs. A symmetric amplitude distribution curve ratifies the symmetry of the surface profile. Amplitude distribution curve is almost symmetrical for combinations of lower feeds (0.05 and $0.15\ \text{mm/rev}$) and larger speeds (240 and $180\ \text{m/min}$) ranges but for higher ranges of feed (0.25 and $0.35\ \text{mm/rev}$) and lower speeds (120 and $60\ \text{m/min}$),

it is unsymmetrical hence it is concluded that that the lower feed with larger speed assisted machining attributed the better distributions of peaks and valleys throughout the cutting length and exhibited almost uniform roughness.

- The recommended shape of bearing area curve is ‘S’ shape. More perfect ‘S’ shape and lower slope of bearing area curve are found at the lowest feed and largest speed condition which indicates the lower surface roughness compared to other conditions.
- Pulsating MQL considerably reduced the tool-work temperature ($110.9\text{--}443.9^\circ\text{C}$) and it is comparatively low for titanium machining concern. Pulse time (Pt) largely influenced the tool-work temperature trailed by V_c and S_o .
- Abrasion, notch-wear, and adhesion mode of wears are identified. The diffusion mode of wear is noticed at the highest speed ($240\ \text{m/min}$) of machining condition. Cutting speed is the leading impactful term towards flank wear.

Overall, pulsating minimum quantity lubrication assisted high speed turning exhibited the positive outcomes in terms of surface roughness, surface texture, tool-work temperature and flank wear. The efficiency of coolant supply (in terms of pulsating rate) without reference to cutting conditions may be considered in the future work. Also, the study of the chemical interaction of non-biocompatible hard alloy i.e. coated carbide cutting insert with biocompatible material (Ti-6Al-4V ELI) can be considered in the future study.

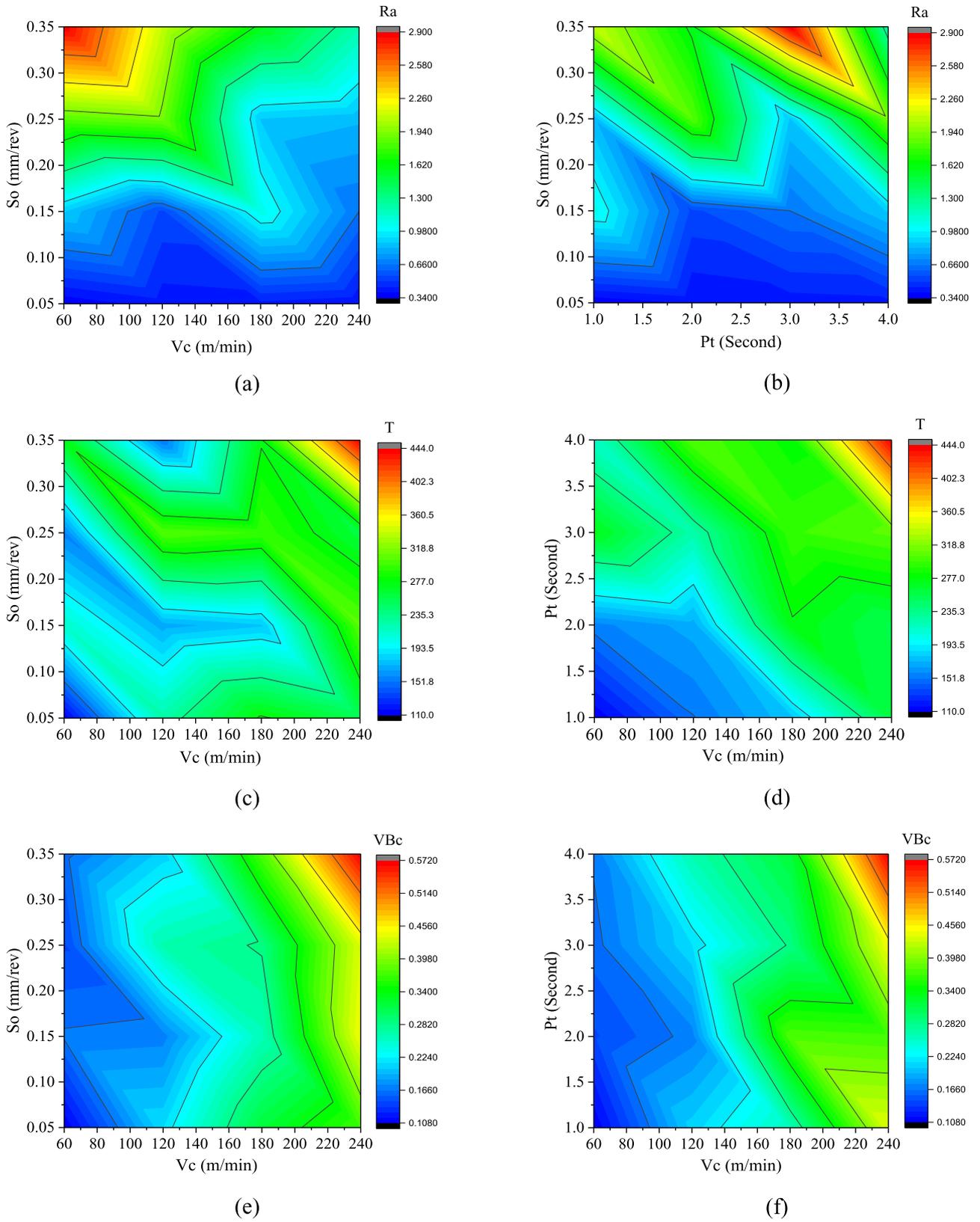


Fig. 12. Contour plots for (a and b) surface roughness (c and d) tool-work temperature (d and e) flank wear.

Conflict of interest

No conflict of interest was stated by contributors.

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