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Optimization of Surface Roughness and Surface Characterization of WED Machining of Titanium Ti-6Al-4V Alloy by Response Surface Method

Deepak Doreswamy[1], D. Sai Shreyas[1], Sachidananda H K[2], Subraya Krishna Bhat[3,*]

[1]Department of Mechatronics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, 576104, India.
[2]School of Engineering and IT, Manipal University, Manipal Academy of Higher Education, Dubai, UAE - 345050.
[3]Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka - 576104, India.

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Abstract

Wire-Electric Discharge Machining (W-EDM) is one of viable advanced machining techniques for machining of hard materials like Titanium alloys precisely. It is critical to determine the optimum settings for control parameters to achieve desired levels of surface finish and dimensional tolerance. Considering this, this research investigates the effects of current, pulse on time (Ton) and pulse off time (Toff) on surface roughness (Ra) of WED machined Ti-6Al-4V alloy. The study showed that, increase in current from 2 A to 6 A resulted in increase of Ra by 13.92 % and increase in Ton from 20 µs to 50 µs caused an almost linear increase in Ra by 8.95 %. But increase in Toff from 20 µs to 30 µs led to a sharp reduction in Ra by about 20.44 %. Further, a regression model is developed to predict the surface roughness with R2=72.5%. The machined surfaces are characterised by the presence voids and microcracks on the recast layers, formation of micro-globules, ridges and craters due to thermal effects. Within the range of study Toff showed significantly larger influence on Ra compared to other parameters of the study.

Keywords: Wire-EDM, Titanium, Ti-6Al-4V, ANOVA, Peak current, pulse on time, pulse off time

1. Introduction

Titanium alloys are widely used in a variety of engineering domains due to their desirable mechanical properties such as, excellent strength to weight ratio, corrosion resistance, and their operating capability at high temperatures [1]. However, their relatively lower Young's modulus and thermal conductivity, in conjunction with their high chemical reactivity cause prominent deflections of workpiece, drastic rise in cutting temperatures, and significant tool wear rates during machining [2]. Additionally, their capability of maintaining their strengths at high temperatures causes excessive work hardening, resulting in extremely large machining forces and vibration related challenges, thus making it difficult to machine using conventional machining techniques [3]. Even though several non-conventional machining techniques provide a better solution while machining such hard materials, some of those like Abrasive Water Jet Machining, Electro Chemical Machining, Laser Beam Machining, and Ultrasonic Machining have concerns related to environmental safety due to the hazardous effects of disposal of chemicals and limitations pertaining to affordability to achieve high levels of surface finish [4]. Thus, Wire Electro Discharge Machining (WEDM) is a preferred choice for machining titanium alloys over other competing techniques [5].

WEDM deals with the erosion of material by conversion of electrical energy into thermal energy in the form of electric sparks [6]. The work material is eroded by generating repeated controlled sparks between an electrode (called as the wire) and the workpiece. These electric sparks create extreme temperatures around 8,000oC-12,000oC. The generated electric sparks cause a fractional amount of material to be evaporated or eroded, which is then flushed away by a flow of dielectric fluid medium, which is typically deionized water [6]. A list of process parameters such as, pulse on time (Ton¬), pulse off time (Toff), wire speed, wire feed rate, wire tension, discharge current, voltage, and dielectric flow rate can be varied to achieve the desired levels of output characteristics of WEDM [7,8]. Out of these parameters, Ton¬ is the discharge time and Toff is the duration without discharge in between Ton durations [6]. Wire speed, feed rate, and tension are related to the arrangements of the wire, whereas current and voltage values quantify the total power utilized for machining [6].

Optimization of process parameters of WEDM is critical for achieving the required levels of machining performance. Optimization techniques such as, Grey Relational Analysis [9], Principal Component Analysis [10], Taguchi method [11,12], Response Surface Methodology (RSM) [13-16], etc., and their combinations have been applied to analyze the performance of WEDM in the machining of titanium alloys. RSM aims to determine the optimum variable values at which a particular operation can be performed to satisfy certain output requirements. But many of the times, in other optimization techniques, the optimal values of process parameters estimated from the respective mathematical analysis are unrealistic since there are possibilities where the determined parameter combinations are absent in the

*E-mail address: sk.bhat@manipal.edu
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machines utilized for machining [13]. The present paper employs the RSM technique for the optimization.

The wire electrode materials and the dielectric fluid media are important topics of research in the field of WEDM [6]. Materials such as, aluminum, brass, copper, graphite, tungsten carbide, steel, etc., have been employed for the WEDM of titanium alloys [13, 17-19]. It has been found that, infusion of copper on graphite [18] and coating zinc on brass [13] results in an improvement in the material removal rate (MRR) of titanium alloys. However, much lesser attention has been paid to the applicability and performance of molybdenum electrode wires on the WEDM of titanium alloys, and their relationship with the operating parameters [20,21]. With regard to the dielectric fluid media, oil and water have been investigated, and water has been found to exhibit higher stability and lower amount of electrode wear rate compared to oil [22]. In the present study, molybdenum was chosen as the electrode material with deionized water being used as the dielectric fluid medium.

Numerous studies have been conducted to study the output performance characteristics such as, slot width (also called kerf width), MRR, and surface roughness (SR), with respect to changes of the important process parameters of WEDM [23-33]. Specifically, researchers have focused on the WEDM machining of Titanium alloy Ti-6Al-4V by studying the effects of different process parameters on the various output response characteristics. Using copper as the electrode material, the effects of current, voltage, feed rate and T_{on} on SR has been investigated [34,35]. Effects of current, T_{on} and T_{off} on SR has been investigated using brass wire electrodes [36-38]. Further, with the use of molybdenum electrodes, the effects of current, T_{on} and T_{off} on SR has been studied in [27,39]. However, there is a need to investigate a much wider range of these operating control settings than that studied in [27,39]. That is an important gap which is being filled by the present research paper. Furthermore, the optimization of these control parameters (current, T_{on} and T_{off}) using RSM, ANOVA (Analysis of Variance) and regression modeling with a goal of minimizing SR, as well as the verification of machined cut surfaces via surface morphology analysis is also a contribution of the present paper.

Machining of titanium alloys is a demanding field, and WEDM has shown excellent promise in this path. Nevertheless, the literature shows that there is still scope for improving the understanding regarding the effects of various process parameters of WEDM on the machining performance of titanium alloys. Particularly, usage of molybdenum wires as the electrode material in combination with deionized water as the fluid medium, and utilization of RSM in investigating the optimum input process parameters remains to be further investigated in detail and with various optimization goals. Moreover, comparatively lesser studies have focused on surface characterization of titanium alloys machined using WEDM and analysis of the microlevel impact on the machined surface has been receiving less attention [40], which does play an important part in the mechanical integrity of the machined components. Thus, the goal of the present paper is to investigate the optimum values of the three pivotal WEDM process factors [41,42], i.e., peak current, durations of T_{on} and T_{off}, for minimizing SR using molybdenum wire as wire electrode material and deionized water as the dielectric fluid, during machining of Titanium alloy Ti-6Al-4V sheet metal through the utilization of optimization and analysis techniques such as, ANOVA, regression analysis and RSM. Furthermore, scanning electron microscopy is employed for surface characterization and morphological analysis of the resulting machined surfaces.

2. Material and Methodology

2.1. Experimental Setup

The machining operation were carried out on Concord CNC Wire-EDM machine (Fig. 1) with table size 320 mm × 400 mm. Firstly, the titanium plate is cut into a slab of size of 150 mm × 50 mm × 2 mm (Fig. 2), which is considered as the work material in the current study. Then, the machining is carried out by varying some of the process parameters for a length of 10 mm for each trial. After machining, 15 pieces are removed and marked from the test sample to measure the surface roughness along each side. Reusable single strand molybdenum metal wire of diameter 0.18 mm is used as the wire-electrode material and a dielectric fluid consisting of cleanser gel, de-ionized water is used for machining of test samples. The material composition of Ti-6Al-4V alloy samples was tested at Varsha Bullion Elemental Analab, Mumbai, India, and the results are presented in Tab.1.

Fig. 1. Experimental setup.

Table 1. Material composition of Ti-6Al-4V.

Chemical composition	Ti	Al	V	Fe	C	Cr	Cu
Percentage	89.54	5.60	4.50	0.23	0.01	0.03	0.09

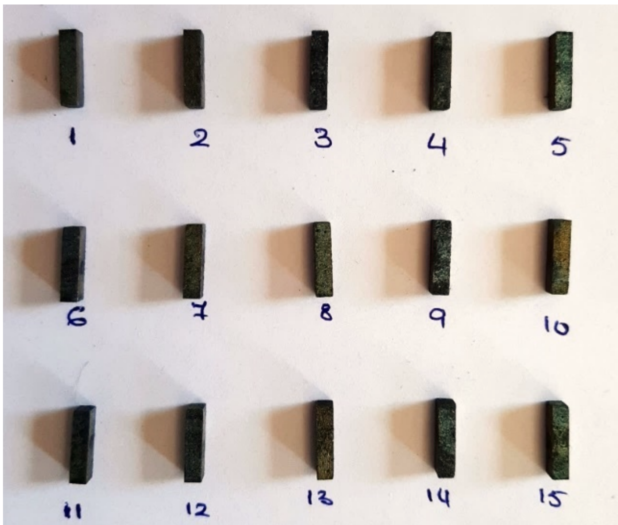

Fig. 2. Wire-EDM machined test samples.

2.2. Design of Experiments
The WEDM involves various control parameters such as T_{on}, T_{off}, peak current, wire tension, dielectric fluid composition and its supply pressure, servo voltage, wire speed, etc., which influence the machining performance viz., SR. Based on the results of earlier experiments by the authors [41,42] on different materials using this experimental setup, three important control factors T_{on}, T_{off} and peak current are chosen in the present study. The wire speed and tension, dielectric fluid composition and its supply pressure and voltage were set constant throughout the study. For the purpose of attaining an optimum utilization of the resources, the experiments are designed using the central composite design of RSM. Tab.2 shows the variable control factors with values set for the present investigation and Tab.3 presents the experimental plan and the corresponding results obtained.

Table 2. Wire-EDM variable control parameters.

Parameters	Unit	Level 1	Level 2	Level 3
T_{off}	µs	10	20	30
T_{on}	µs	20	35	50
Current	A	2	4	6

Table 3. Experimental plan (coded) and corresponding results.

Std Order	Run Order	Blocks	Pt Type	Current	T_{on}	T_{off}	R_a (µm)
1	1	1	1	1	1	2	6.32
2	2	1	1	2	2	2	7.35
3	3	1	1	1	3	2	8.36
4	4	1	1	3	2	1	8.34
5	5	1	1	2	1	3	5.59
6	6	1	1	3	1	2	8.37
7	7	1	1	2	3	3	7.04
8	8	1	1	1	2	3	6.93
9	9	1	1	2	2	2	9.63
10	10	1	1	3	3	2	9.88
11	11	1	1	2	2	2	7.54
12	12	1	1	1	2	1	7.50
13	13	1	1	3	2	3	6.56
14	14	1	1	2	3	1	7.75
15	15	1	1	2	1	1	7.98

2.3. Measurement of Surface Roughness (SR) and Morphological Analysis
SR (R_a) of cut surfaces of the machined samples were measured using Surtronic surface roughness tester (Make: Taylor Hobson). The stylus probe was made to move for a sampling length of 2.5 mm for each measurement. For each sample, readings were recorded at four different locations and its average R_a values are presented in Tab.3. Typically, the measurements were made at the upper, middle, and lower regions of the cut kerf surface. Surface morphology of the cut surface is studied using scanning electron microscope (Make: Zeiss) and Mitutoyo Inverted metallurgical microscope (Model: IM 7000).

3. Results and Discussion

3.1. Effects of T_{on}, T_{off} and Peak Current on R_a
The Figure 3 shows the main effect plot of different control factors on R_a. From Fig. 3 (a) it is observed that with increase of current from 2 A to 6 A there is an increase in R_a by 13.92%. With a change in the current from 2 to 4 A, there is a slight increase of R_a by 3.84%, but from 4 A to 6 A, there is an increase of 9.71%. This is attributed to the fact that, due to increase in current energy, there is an intense rise in spark energy which results in melting and evaporation of deeper and wider regions on the cut surfaces. This leads to formation of surface texture into deeper craters and valleys as observed in the Fig. 7. Hence, R_a increases with the increase in current.

Further, the effect of T_{on} on R_a is shown in Fig. 3 (b). It is observed that with increase in T_{on} from 20 µs to 50 µs, there is an almost linear increase in R_a by 8.95%. The spark energy developed during each sparking cycle also depends on the duration of T_{on}. Higher the T_{on}, longer will be the spark discharge duration for machining. And as explained earlier, there will be localized melting and evaporation of material deeper into the workpiece. The resulting recast layer as well as craters formed during this melting process leads to increase in the surface roughness. However, the effect of T_{on} is comparatively lower than the effect of T_{off} and the current. The effect of T_{off} on R_a is shown in Fig. 3 (c). Increase in T_{off} from 10 µs to 30 µs resulted in an initial rise in R_a and then a decrease in R_a as T_{off} increases. Increasing T_{off} from 10 µs to 20 µs resulted in increase of R_a by 3.98%, whereas further increasing the value of T_{off} from 20 µs to 30 µs caused a decrease by 20.44%. The surface roughness is found to reduce beyond the settings of 20 µs. This is because of the fact that, increasing the T_{off} mainly decreases the spark frequency. This means the number of sparks involved in machining decreases. This results in generating sufficient duration for deionization of the dielectric fluid. During this period, the molten products would also be flushed out effectively making the flatter recast layer. Hence, longer T_{off} duration results in lesser surface roughness.

3.2 ANOVA of Surface Roughness
ANOVA is carried out on the experimental results to analyse the significance of the effect of T_{on}, T_{off} and current on surface roughness. The analysis is carried out at 95% confidence level. The Tab.4 shows the ANOVA of the control factors on R_a. From the standard Fisher's table, F critical value is found to be 3.29 (error degree of freedom (DF) – 3). If the F-value for an input parameter is greater than the F critical value, it indicates that it has a significant influence on the output.

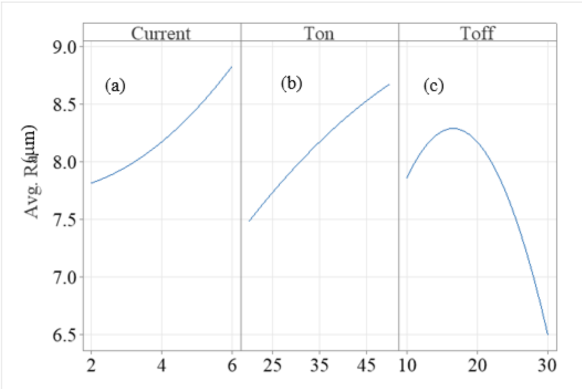

Fig. 3. The effect of current, Ton and Toff on Ra.

Table 4. ANOVA of surface roughness (R_a)..

Source	DF	Adjusted sum of squares	Adjusted mean square	F-Value
Current	1	2.0503	2.05031	1.99
T_{on}	1	2.8382	2.83815	2.76
T_{off}	1	3.7196	3.71963	3.61
Current*Current	1	0.0826	0.08262	0.08
T_{on}*T_{on}	1	0.0310	0.03103	0.03
T_{off}*T_{off}	1	3.6310	3.63103	3.53
Current*T_{on}	1	0.0689	0.06891	0.07
Current*T_{off}	1	0.3630	0.36301	0.35
T_{on}*T_{off}	1	0.7056	0.70560	0.69
Lack-of-Fit	3	1.9463	0.64878	0.41

From the table, it is seen that F-value of T_{off} is greater the F critical value, which demonstrates that it is a significant control factor, whereas current and T_{on} are insignificant control factors since their F-values are less than the critical F value. Further, the interaction effect of T_{off} and T_{off} is also greater than the critical F value. Thus, in view of minimizing the R_a, it is advised to keep T_{off} close to 30 µs. Tab.5 shows the average R_a at each level of the control parameters and the maximum change caused by varying each of them. From the table it is evident that while increasing T_{off} decreased the surface roughness, increasing current and T_{on} increased it.

Table 5. Average R_a for each level of the control parameters and its maximum change.

Parameters	Level 1	Level 2	Level 3	Max. change
Current	7.28	7.55	8.29	1.01
T_{on}	7.58	7.37	8.26	0.68
T_{off}	7.89	8.20	6.53	-1.36

3.3 Analysis of Interaction Effect by Response Surfaces

The interaction effect of T_{on} and current, T_{off} and current, T_{on} and T_{off} with respect to R_a is shown through the surface plots Figure 4 (a), (b), (c), respectively. Fig. 4 (a) shows that both T_{on} and current cause a significant increase in R_a with their increase. The minimum R_a is achieved at lowest settings of both T_{on} (20 µs) and current (2 A). Fig. 4 (b) shows that R_a can be increased by increasing the current, while T_{off} has a contradictory effect. At any constant settings of T_{off}, the R_a decreases by decreasing the current. Further, it is found that the maximum R_a is achieved at T_{off} – 20 µs, current – 6A and minimum R_a is obtained at current – 2 A and T_{off} – 30 µs. Fig. 4 (c) shows that R_a increases with increasing T_{on} and decreasing T_{off}. The minimum R_a is observed at least value of T_{on} (20 µs) and the highest value of T_{off} (30 µs). The ANOVA table (Tab.4) demonstrated that, that among the three interaction effects, T_{off} and T_{on} has the maximum significance, followed by current and T_{off}, and current and T_{on}. This is identical to the results obtained in the response surfaces, which show the same order of significance of interaction effects between the control parameters.

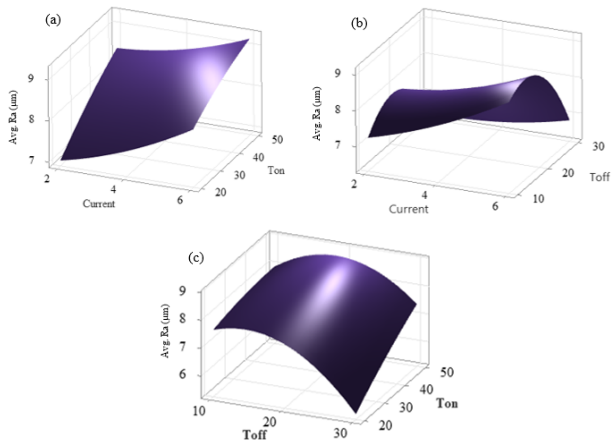

Fig. 4. Interaction effects of (a) Ton and current (b) Toff and current (c) Ton and Toff on surface roughness (Ra).

3.4 Optimization of Surface Roughness

Response Surface method is used for optimization with an objective to minimize the R_a. Fig. 5 shows the optimization plot for R_a. It is observed that, the R_a increases with increase in current. The minimum R_a is seen at settings of 2 A current. Also, the R_a increases with increase in T_{on} and minimum R_a is observed at 20 µs. Further, it is also observed that, surface roughness is higher at shorter duration of T_{off} and the lowest R_a is obtained at 30 µs. Hence, these settings, i.e., current – 2 A, T_{on} – 20 µs, T_{off} – 30 µs are the optimized settings to machine the Ti-6Al-4V alloy by Concord CNC Wire-EDM machine using molybdenum electrode. The estimated R_a at these optimized conditions is 5.21 µm. Further, confirmation experiments were carried out at these settings, and the results are shown in Tab.6.

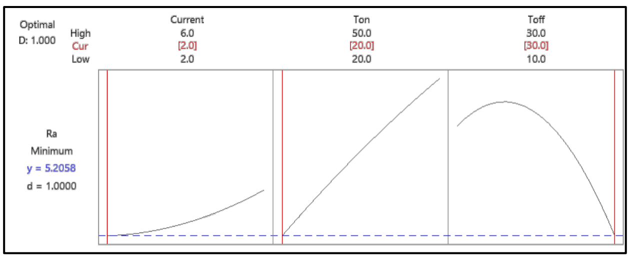

Fig. 5. The optimization plot of R_a.

Table 6. Comparison of predicted and experimental R_a.

Trial No.	Optimized R_a (m)	Experimental R_a (m)	Error (%)
1	5.21	5.05	3.15
2		5.10	2.08
3		4.95	5.19
4		4.99	4.32
5		5.01	3.98

3.5 Regression Modelling of Surface Roughness

A polynomial type of regression model is developed to develop a relationship between the control parameters (I_c: Current, T_{on}: Pulse-on time, T_{off}: Pulse-off time) with the output parameter (R_a) given by the equation (1). The coefficient of determination (R^2) for the developed model is 72.5%. The reliability of the prediction of this model is verified with the experimental data. Table 7 shows the confirmation of the developed model with experimental results under the same operating settings. The model can be used within the operated range: 2 A ≥ I_c ≤ 6 A, 20 μs ≥ T_{on} ≤ 50 μs, 10 μs ≥ T_{off} ≤ 30 μs.

$$R_a = 3.41 + 0.41I_c + 0.030T_{on} + 0.291T_{off} + 0.037I_c^2 - 0.00041T_{on}^2 - 0.00992T_{off}^2 - 0.0044I_c \times T_{on} - 0.0151I_c \times T_{off} + 0.00280T_{on} \times T_{off} \quad (1)$$

Table 7. Comparison of the predicted and experimental R_a..

Trial No.	I_c (A)	T_{on} (μs)	T_{off} (μs)	Predicted (μm)	Experimental (μm)	Error (%)
1	2	20	10	6.81	6.03	13.00
2	3	25	15	7.64	7.11	7.46
3	4	35	20	8.18	8.97	8.83
4	5	45	25	8.25	9.12	9.51
5	6	50	30	7.64	8.66	11.77
6	2	10	30	4.29	4.95	13.43

Results of the residual analysis for R_a are shown in Fig. 6 (a-d). It is observed from the probability plot (Fig. 6 (a)) that the residuals are spread closely within a line of fit (except one). A good correlation is found between the predicted and experimental R_a since only one outlier residual data sets is found. The scatter plot of residuals over the mean value (Fig. 6 (b)) shows a random spread of residuals around the mean value without formation of clustered regions indicating the unbiasedness of the results. The histogram plot of residuals (Fig. 6 (c)) shows that the frequency distribution of residuals follows a half-normal distribution. Fig. 6 (d) shows that most of the residuals at different experimental trials are randomly scattered around the mean values. Thus, the regression model developed is in line with the linearity, homoscedasticity and normality conditions required in linear regression analyses.

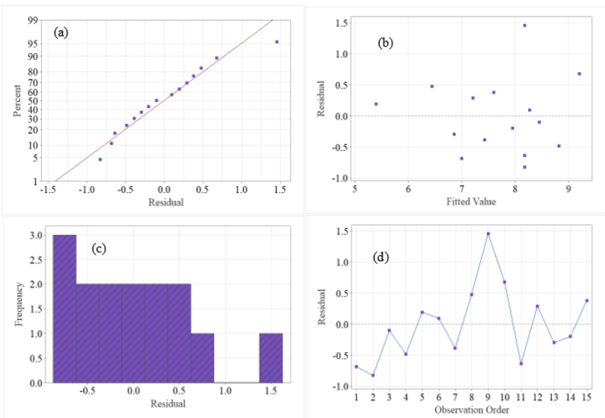

Fig. 6. Distribution of residuals.

3.5 Analysis of Machined Surface Morphology

Fig. 7 shows the surface characterization of cut surfaces of the machined titanium alloy was by scanning electron microscopy (SEM). At 2000X magnification the machined surface (Fig. 7 (a)) shows the formation of micro-globules and microcracks. These are created when metal in the molten state gets solidified because of exposure to dielectric fluid media (deionized water) [43]. Fig. 7 (b) shows the ridge and crater formations and void formations on the machined surface at 3000X magnification. Such voids are formed due to the vapor inflow into the microscopic gaps between the molten pool during solidification [44-46]. At 5000X magnification the presence of microcracks is revealed as shown in Fig. 7 (c). Cracks of this type are formed due to rapid cooling of the molten metal during the period of deionization [47]. As described earlier in section 3.1, further microstructural investigation at 8000X magnifications demonstrated the wavy formations (Fig. 7 (d)) in region of junction of the solidified layers.

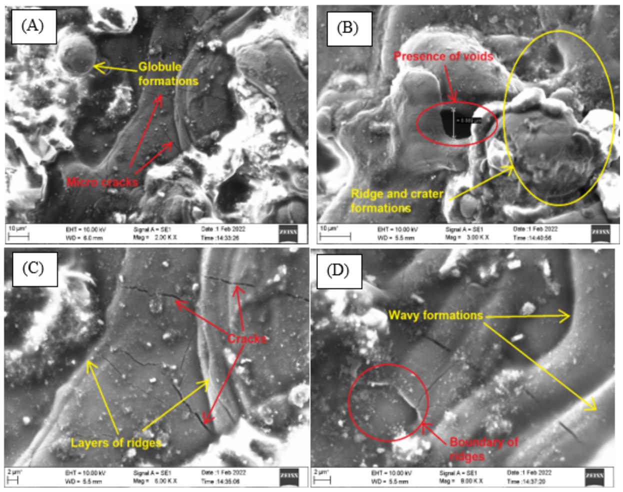

Fig.7. Micrographic SEM images of the machined surface showing (a) Globule formation at 2000X, (b) Ridge and crater and void formations at 3000X, (c) Microcracks at 5000X and (d) Wavy formation magnifications at 8000X magnification.

4. Conclusions

From the study of the effects of peak current, T_{on}, and T_{off} on surface roughness (R_a) of Ti-6Al-4V using molybdenum wire electrode, the following conclusions are drawn. Increase in peak current from 2 A to 6 A and Ton from 20 μs to 50 μs showed an increase in R_a by 13.92% and an almost linear increase by 8.95%, respectively. Increase in Toff from 10 μs to 20 μs caused a minute increase in R_a by 3.98%. However, with increase in Toff from 20 □s to 30 □s, a significant reduction in R_a by 20.44% was observed. Morphological study of machined cut surfaces showed the presence of recast layer on which microcracks were present. Further, the presence of globules, wavy formations, ridge and crater formations and voids were revealed at the microscopic level. The developed regression model can predict the R_a with an

R^2=72.5%, within the range: 2 A ≥ Ic ≤ 6 A, 20 μs ≥ Ton ≤ 50 μs, 10 μs ≥ Toff ≤ 30. At optimum conditions (Ic – 2 A, Ton – 20 μs, Toff – 30 μs) and the corresponding surface roughness is 5.21μm.

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