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Investigation on Surface Roughness and MRR in WEDM of Titanium Grade 7 (Ti-0.15Pd) Alloy using Statistical Techniques

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ABSTRACT

Wire Electric Discharge Machining (WEDM) of Titanium grade alloys with coated electrodes has several advantages over the traditional machining process such as increased productivity, reduction of processing cost, and improved material properties. The main objective is to create a relationship between WEDM parameters such as Pulse-on (T_{ON}), Pulse-off (T_{OFF}), and Indicated Power (IP) with surface roughness (Ra) and Material Removal Rate (MRR). In the present work, the performance of zinc-coated brass electrodes for WEDM of Titanium Grade-7 alloy was assessed and optimized with statistical technique. ANOVA analysis is used to analysis of the MRR and Ra and validated with regression. The ANOVA analysis results indicated that T_{ON} is the highest statistically significant and followed by T_{OFF} and IP on MRR and surface roughness. The optimum combination of higher IP(6 A) and T_{ON} time(60 µs) and lower T_{OFF} time (12 µs) is lucrative for a higher MRR of 8.5682 mm3/min and lower surface roughness of 1.66 µm. The SEM images showed homogeneous solidification, columnar grain structure, recast layer surface, and minor surface crack density were noticed at higher cutting conditions. The predicted model and confirmation test results were close to each other with minimum error (<5%), so the model is adequate.

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Introduction

Titanium (Ti) based alloys are having excellent physical and mechanical properties including strength-to-weight ratio, corrosion, and wear resistance. These alloys are the best material choice for many applications like space crafts, aerospace, automotive, nuclear, sports, chemical plant, and medical applications. However, these alloys are challenging to cutting by regular conventional machining process due to high thermal resistance accelerates to tool wear, and induces residual stress and oxidation on the machined surface. Certain advanced machining methods like laser cutting and electric discharge machining are suitable in cutting high-strength alloys. During the machining of advanced alloy materials, surface integrity is one of the significant parameters for assessing the surface integrity of finished components. Besides, surface, and subsurface alterations, micro/macro cracks, machining burns (heat affect zone), surface cavities, material side flow, residual stress, fatigue strength and stress corrosion factors are serious issues due to safety aspect and also sustainability concerns [1]-[4].

Various researchers have employed the WEDM process to study the machinability characteristics of Ti alloys under different cutting conditions and optimized the process parameters through mathematical models [5]-[8]. Ramamurthy et al. [6] illustrated that surface roughness decreased with increased pulse-on-time duration and discharge/peak current during WEDM of Ti alloy. Prakash et al. [7] deliberated the impact of WEDM factors and Ti-Nb electrode material on surface modification during Ti alloy processing. The authors detected that the machined surface roughness has considerably reduced by a trim cut strategy during WEDM of titanium alloy. Devarasiddappa et al. [8] examined the effect of pulse-off time, pulse-on time, peak current, and wire speed on WEDM of titanium alloy with reusable wire electrode using modified teaching learning-based optimization method. The authors noticed reduced surface roughness values at settings of higher peak current and lower T_{ON} time. Debnath and Patowari [9] recommended a mathematical model and test analysis to find the impact of machining parameters on surface and sub-surface characteristics of Ti alloys based micro-fins fabrication using the WEDM process. They revealed that the pulse time, current intensity, and duty cycle shows substantial outcome on surface superiority.

Pramanik et al. [10] evaluated the dimensional accuracy of WEDM-processed Ti alloy parts. They showed that the lower peak current and higher pulse-on-time aid to improve machined surface quality. Also, proposed that the choice of machining parameters are precise in the cutting of Ti alloys. Gohil [11] examined the EDM of Ti-6Al-4V alloy with various cutting parameters using mathematical models. They observed that the recast layer formed was prejudiced by higher pulse duration, discharge current, and spark energy. The authors demonstrated that the peak current and pulse-on time considerably influences surface roughness and MRR. Torres et al. [12] measured the surface and sub-surface modifications in WEDM of hard-to-machine alloys with zinc and brass wire electrodes. The obtained results demonstrated the significant influence of wire feed and single pulse discharge energy on machined surface quality.

Tonday et al. [13] analysed the machining parameters effect on MRR and surface integrity during WEDM of Ti-based alloy with copper electrode. The authors observed that the discharge current is the most vital parameter on machined surface characteristics and MRR. Thus, to enhance machinability characteristics and productivity of the EDM process, continuous pulsation and higher peak current are very important [14]-[16]. However, better-machined surface integrity characteristic is much essential for preventive maintenance and better product performance. The surface topography of components encompasses surface and sub-surface alterations, microhardness, residual stress distribution, and recast layer. Compared to the bulk material, recast layer have a dramatic drop in surface hardness. It is due to considerable thermal degradation of the machined components [17]-[20].

Gupth et al. [21] studied the effect of wire feed speed, wire tension, and servo voltage on surface roughness and cutting speed in the machining of pure and heat-treated Ti-6Al-4V alloy using Response Surface Methodology (RSM). The analysis results indicate the wire tension and servo voltage were the highest impact on surface roughness of and cutting speed of 1.75 mm/min during machining of annealed Ti-6Al-4V alloy when compared to other heat-treated Ti-6Al-4V alloy. Thangaraj et al. [22] optimized the WEDM process parameters on surface quality during the machining of titanium alloy using Taguchi–Grey analysis-based (TGRA) method. The analysis results show the best input parameters combination in attaining optimal surface measures such as discharge current (15 A), gap voltage (70 V), and duty factor (0.6) when the WEDM process of titanium. The authors also suggested that the selection of wire electrodes and dielectric fluid are most influential on the surface quality in the machining of titanium, due to its importance in creating the spark energy. Similar results can be found elsewhere [23]-[26].

The above literature review reveals that the work carried out on the effect of WEDM process parameters on MRR and Surface roughness in machining Ti grade 7 alloy is minimum using zinc-coated brass wire electrodes. The study reported herein is continuing effort to examine cutting parameters effect on productivity enhancement and quality of surface during WEDM of titanium-based alloy using statistical techniques. The current work aims to study the influence of process parameters on surface roughness and MRR during titanium grade 7 alloy with Zn-coated brass wire electrode machining of using the design of experiments technique (L_{27} orthogonal array).

The surface and sub-surface discrepancies occur with WEDM of titanium grade 7 alloy using scanning electron microscopy (SEM) analysis.

Experimentation

Material and methodology

Titanium (Ti) grade 7 alloy is the material of research interest in recent years due to its extensive use in a chemical plant, marine, medical and aerospace, desalination, brine concentration/evaporation equipment, and pulp/paper bleaching/washing equipment, hydrometallurgical extraction applications. The composition of the grade 7 alloy and its mechanical properties are illustrated in Tables 1 and 2, respectively. The high yield strength and tensile strength of Titanium grade 7 make it a more suitable material for applications where strength is critical. The elongation property allows it to withstand stress and deformation without fracturing, suitable for high-temperature applications. Titanium grade 7 alloy size of 20x20x100 mm^3 was used as workpiece material, which was pre-machined by CNC Wire-EDM using an appropriate sequence of cuts including roughing and finishing cut. The tests were carried out using the 'CONCORD CNC WEDM', Model: DK-7732VC, which controlled input process parameters to be selected from a restricted level of potential values. The wire EDM machining process was carried out with a diameter of 0.25 mm zinc (Zn) coated brass wire electrode for WEDM processing of Titanium grade 7 alloy. Zinc liquefies at a lower temperature than brass and absorbs heat as it boils away. As a result, less heat enters the wire to retain its strength. Coated wire typically enhances material removal by 10 to 15 percent. Coated wire usually comes in three grades, hard, semi-hard, and soft. Hard wires are used for machining when high tensile strength is required. Soft brass wires are typically used while cutting tapers [20]. The properties of brass wire with Zn-coated electrode are in Table 3.

Test trials were accompanied by different levels of the peak current (IP), pulse-off time (T_{OFF}), and pulse-on time (T_{ON}) during WEDM processing of Ti grade 7 alloy. Some parameters of wire EDM such as wire tension, wire speed, and servo control voltage were maintained as default machine settings. Some studies have been done on surface roughness (*Ra*) and material removal rate (MRR) in WEDM using brass wire-coated zinc as electrode. Owing to its fast-cooling rate and low viscosity, WEDM uses deionized water as an alternative to hydrocarbon oil as the dielectric fluid. The WEDM setup and employed samples are presented in Figure 1.

Table 1: Chemical composition (weight %) of Ti grade 7 alloy

Fe	O	C	N	H	Pd	Ti
0.30	0.25	0.08	0.03	0.015	0.15	Bal.

Table 2: Mechanical properties of Ti grade 7 alloy

Tensile strength, ultimate (MPa)	Yield strength (MPa)	Modulus of elasticity (GPa)	Elongation (%) at break	Shear modulus (GPa)	Rockwell hardness (HRB)
344	375	105	20	45	75

Table 3: Electrode material properties

Wire material	Zn-coated brass wire
Tensile strength	900 N/mm^2
Wire grade	A1 Hard
Wire diameter	0.25 mm

Figure 1: Working setup of WEDM machining process and machined samples

Experimental design

In this work, three process parameters T_{OFF} time, T_{ON} time, and IP were considered for wire EDM machining. The process parameters and their levels are illustrated in Table 4. They were chosen considering material properties and suggestions taken from EDM machine experts. The MRR is reliant on the various input parameters which affects the productivity of any process. The experimental plan was employed as per Taguchi's experimental design (L_{27} Orthogonal Array) using Minitab-17 software. It aids to capture experimental response data in a systematic manner. The L_{27} orthogonal array and responses like surface roughness and MRR are tabulated in Table 5. The shape machined by WEDM was 20x20x5 mm^3 in thickness. The tests were carried out for each trial 2 times and the average response reading was considered for analysis. The machined surface roughness was determined using a roughness tester ('Model: SJ201; Make: Mitutoyo') and surface morphology analysis was carried out with SEM images. The MRR is measured using the relation in Equation 1.

$$MRR = \frac{Volume\ of\ material\ removed}{Machining\ time} \quad (1)$$

Table 4: Parameters and their levels considered in the study

Sl. No.	Description	Level 1	Level 2	Level 3
1	T_{ON} (µs)	20	40	60
2	T_{OFF} (µs)	10	14	18
3	IP (A)	2	4	6

Results and Discussion

The MRR and surface roughness (*Ra*) are major parameters that affect the quality and throughput of any production industry. MRR represents the total workpiece material volume removed within a unit working time. It indicates the machinability efficiency of the production machine. Correspondingly, surface roughness also has significant effects on the performance of WEDM machined parts. In general, the surface quality is measured as the average surface roughness (*Ra*) of machined parts [2], [27]-[28]. In addition, machinability characteristics are influenced by the type of electrode, work contact, dielectric fluid supply, accuracy, friction, and deformation.

In the present study, titanium grade 7 alloy was machined by WEDM at different machining conditions, and statistical analysis was supported and correlated with the assistance of a regression model. In the second half, enumerate the integrity of the machined surface such as process parameters that define the surface morphology and modifications on the machined components were discussed with SEM images.

Table 5: Orthogonal array (L_{27}) and obtained results

Sl. no.	T_{ON} (µs)	T_{OFF} (µs)	IP (A)	MRR (mm^3/min)	Surface roughness (*Ra*), µm
1	20	12	2	7.1221	2.146
2	20	12	4	7.9026	2.281
3	20	12	6	8.7630	2.493
4	20	16	2	7.0346	2.964
5	20	16	4	7.3682	2.130
6	20	16	6	7.4214	2.655
7	20	20	2	6.9842	2.872
8	20	20	4	7.1256	2.894
9	20	20	6	7.5682	2.869
10	40	12	2	7.4568	1.623
11	40	12	4	8.3850	1.884
12	40	12	6	8.8346	1.967
13	40	16	2	6.9824	2.142
14	40	16	4	6.9024	2.467
15	40	16	6	7.5248	2.566
16	40	20	2	6.9246	2.737
17	40	20	4	7.5728	2.904
18	40	20	6	8.1282	2.957
19	60	12	2	8.1456	1.912
20	60	12	4	8.5682	1.667
21	60	12	6	8.9412	1.846
22	60	16	2	8.1236	1.765
23	60	16	4	8.5248	2.162
24	60	16	6	9.3846	2.257
25	60	20	2	9.1264	1.396
26	60	20	4	9.3346	1.862
27	60	20	6	9.9624	2.134

Statistical analysis

The obtained results were evaluated through analysis of variance of MRR and *Ra* as illustrated in Tables 6 and 7, respectively. The analysis of variance (ANOVA) demonstrates that existing statistical models are viable for the prediction of surface roughness and MRR at a 95% confidence level. The experimental results were examined for the identification of influencing parameters on MRR and surface roughness with a confidence level of 95%. The attained results are established by using main effects plots for mean and normal probability plots. Interaction terms of cutting parameters were included in the assessment [14], [20].

Table 6: ANOVA of MRR

Parameters	DOF	SS	MS	F	Test F	% of contribution
Pulse-on (µs)	2	16.386	8.194	120.75	8.66a	58.81
Pulse-off (µs)	2	3.627	1.815	26.73	8.66a	12.64
Peak current (A)	2	5.183	2.593	38.20	8.66a	18.23
Pulse-on * Pulse-off	4	1.444	0.362	5.32	3.85b	4.26
Pulse-on * peak current	4	0.409	0.103	1.52	--	0.00
Pulse-off * peak current	4	0.051	0.014	0.19	--	0.00
Residual error	8	0.543	0.067			6.06
Total	26	27.65				100.00

* SS = Sum of squares; DOF = degree of freedom; MS= Mean Square; Test F=Fisher's Value; a 99% Confidence; b 95% Confidence; %C = percentage of contribution

Table 7: ANOVA of surface roughness

Parameters	DOF	SS	MS	F	Test F	% of contribution
Pulse-on (µs)	2	2.598	1.304	306.530	8.66a	33.20
Pulse-off (µs)	2	2.843	1.419	333.520	8.66a	36.11
Peak current	2	0.150	0.073	17.140	8.65a	6.75
Pulse-on * Pulse-off	4	2.141	0.534	125.610	8.66a	22.09
Pulse-on * Peak current	4	0.063	0.016	3.850	3.85b	0.00
Pulse-off * Peak current	4	0.004	0.001	0.210	--	0.00
Residual error	8	0.033	0.004			1.85
Total	26	7.834				100

* SS = Sum of squares; DOF = degree of freedom; MS= Mean Square; Test F=Fisher's Value; a 99% Confidence; b 95% Confidence; %C = percentage of contribution

The ANOVA analysis of MRR for WEDM of Ti grade 7 alloy is presented in Table 6. It revealed that the effects of T_{OFF} time, T_{ON} time, and peak current are the highest statistical significance. The interaction effect between T_{ON}*T_{OFF} is partially significant, while other interaction effects of parameters are insignificant. The obtained results indicated the significance of T_{ON} on MRR during WEDM process of Ti grade 7 alloy is greater (58.81%) followed by IP (18.23%) and T_{OFF} (12.64 %) (Table 6). Whereas, ANOVA of surface roughness has shown that effects of peak current, pulse-on, and the interaction effect between T_{OFF}*T_{ON} are statistically significant and are shown in Table 7. The T_{OFF} is the highest (36.11%) significance on surface roughness trailed by T_{ON} (33.20 %), T_{OFF}*T_{ON} (22.09%), and IP (6.75%). Besides, the impact of T_{ON}*IP and T_{OFF}*IP was found insignificant.

Figures 2 and 3 correspondingly illustrate main effects plots for the mean for MRR and *Ra*. It indicates that MRR was found to enhance with increased levels ofT_{ON}, while *Ra* was found to diminish. Whereas the upsurge of T_{OFF} has caused the decrease of MRR initially, a further increase of T_{OFF} from level 2 to level 3 has led to greater value of MRR value (Figure 2). However, surface roughness and MRR were increased with increased peak current values. The reason is that significant energy is supplied when the IP with sufficient T_{ON} time was increased to maximum. Thereby, it influences on the cutting speed. Consequently, increase in large discharge energy in turn improves drastically MRR. It indicates that the MRR was found to be greater in the combination of the upper level of IP and T_{ON}. Based on the above discussion, it can be revealed that the maximum MRR can be obtained using positive polarity of electrode. It suggests that positive polarity of the electrode and dielectric fluid are favored for the machining of titanium grade 7 alloy using WEDM process. Similar experimental results were found by other researchers [10], [12]-[13].

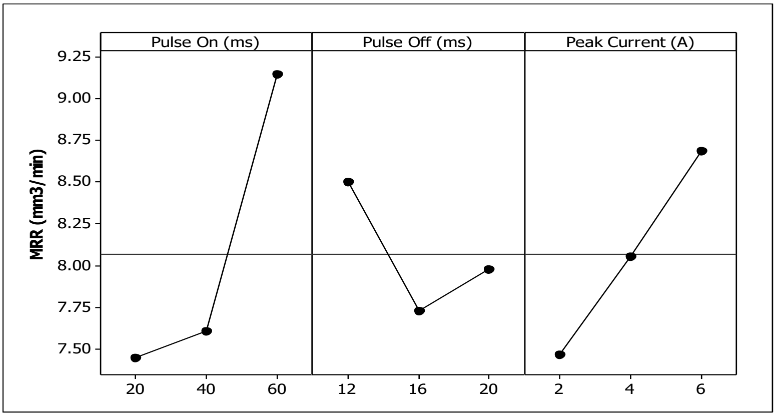


Figure 2: Main effects plot illustrating effect of individual process parameters on MRR

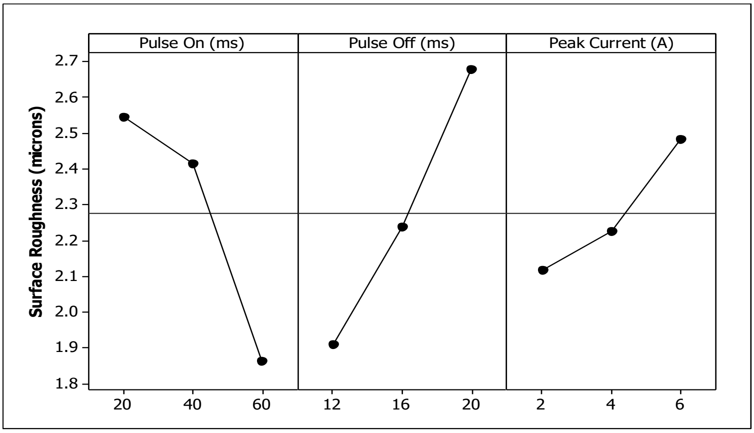


Figure 3: Main effects plot illustrating the effect of individual process parameters on surface roughness

The regression models represent an established correlation between WEDM parameters with responses like MRR and *Ra*. Consequently, obtained regression models of MRR and *Ra* are presented as Equations 2 and 3, respectively. The R-Sq and R-Sq(Adj.) values of developed models are greater than 89%, also the difference between *R-Sq* and *R-Sq(pred.)* is within 20%. Therefore, it can be inferred that established models are feasible and adequate to predict responses within the studied range of parameters.

$$MRR\ (mm^3/min) = 18.76 - 0.466 * Pulse\text{-}On - 0.998 * Pulse\text{-}Off + 0.5356 * Peak\ Current + 0.00812 * Pulse\text{-}On * Pulse\text{-}On + 0.03155 * Pulse\text{-}Off * Pulse\text{-}Off + 0.00482 * Pulse\text{-}On * Pulse\text{-}Off \quad (2)$$

R-sq(adj)- 91.75%; R-sq-93.60% and R-sq(pred)- 88.05%

$$Ra\ (\mu m) = -3.222 + 0.1363 * Pulse\text{-}On + 0.4549 * Pulse\text{-}Off + 0.0889 * Peak\ Current - 0.001378 * Pulse\text{-}On * Pulse\text{-}On - 0.00619 * Pulse\text{-}Off * Pulse\text{-}Off - 0.00717 * Pulse\text{-}On * Pulse\text{-}Off \quad (3)$$

R-sq(adj.):89.70%; R-sq:92.40% and R-sq(pred.):84.15%

The normal probability plots and Anderson–Darling test of residuals versus predicted response for MRR and *Ra* is shown as Figure 4 and Figure 5, respectively. The test values of responses (MRR and *Ra*) are normally distributed on the 45° line. It explains that the P-value is higher than the alpha (α) with a significance level of 0.05 and the null hypothesis cannot be rejected. Hence, data recorded from the established setup is rationally good agreement with adequate range. Also, it confirms that the employed statistical method is adequate as shown in Figure 4 and Figure 5. Further, it is a typical model to predict WEDM process parameters for Ti grade 7 alloy.

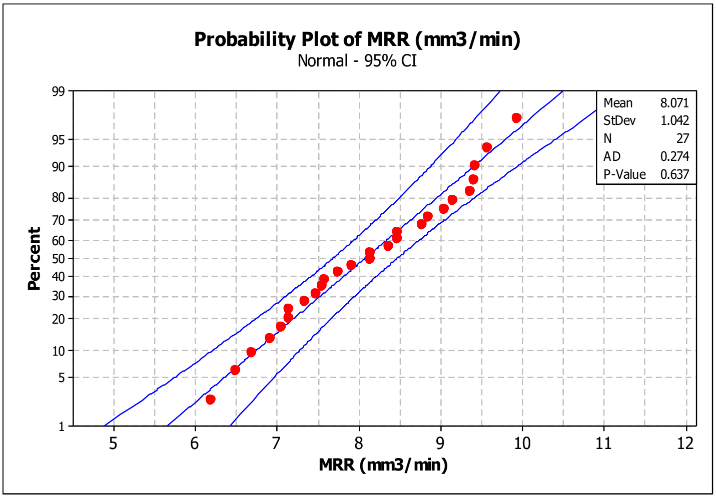


Figure 4: Probability plot for MRR

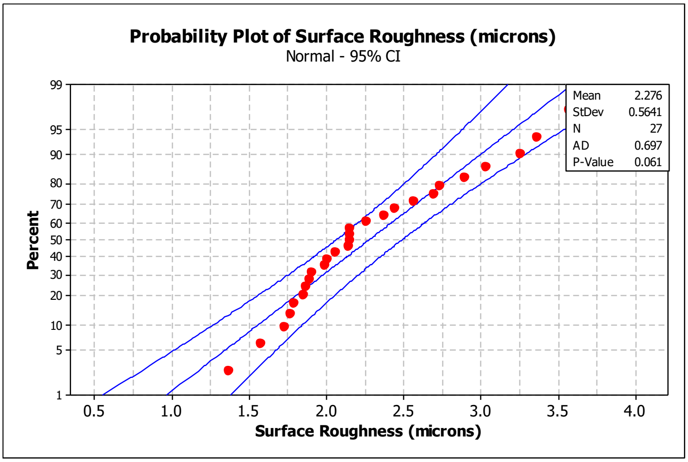


Figure 5: Probability plot for surface roughness

Confirmation test results

For validation purposes, new experimental trials were conducted with Ti grade 7 alloy during the WEDM process. The new WEDM parameters used for confirmation tests are shown in Table 8. Table 9 shows the experimental results attained where a comparison was done between the expected values from the developed regression models (Equation 2 and Equation 3) with new experimental trials. From the comparison analysis of Table 9, it is observed that the intended error for MRR (maximum of 2.204% and minimum of 1.68%) and surface roughness (maximum of 5.965% and a minimum of 4.142%). Therefore, MRR and surface roughness with the WEDM parameters with rational degrees of estimate.

Table 8: Experimental trials for comparison tests

Trials no.	New trials	T_{ON} (µs)	T_{OFF} (µs)	IP (A)
1	A	30	12	3
2	B	50	16	5

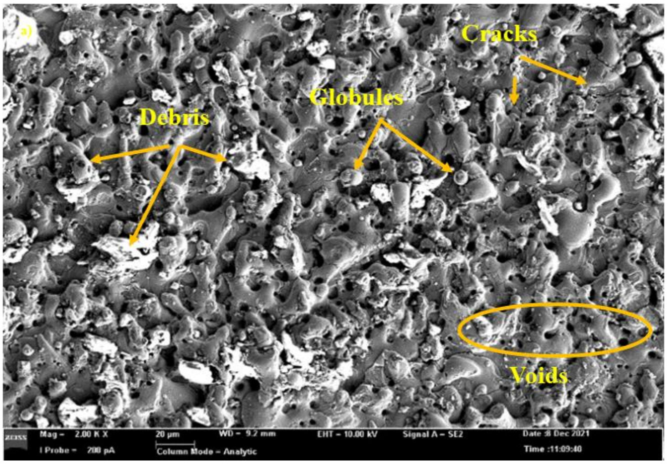
Table 9: Experimental results compared with regression model results

Sl. No.	Trials	Model results	Experimental results	% of error
1. MRR (mm^3/min)				
	A	7.6972	7.5680	1.680
	B	8.928	9.1248	2.204
2.Surface roughness (Ra), µm				
	A	2.548	2.70	5.965
	B	1.69	1.76	4.142

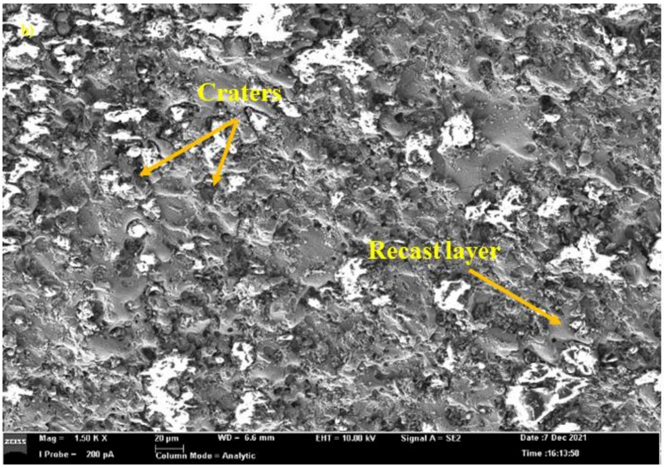
Surface integrity assessment

Surface quality is an important machining aspect, which signifies the performance and reliability of the products. In such cases, surface integrity is essential and is exaggerated by the machining process with surface and subsurface degradation. The surface integrity includes surface topography, recast layer formation, and stresses distributions on the machined components. Especially, the wire EDM process is inevitable for improved surface quality and greater throughput in industrial sectors.

Figure 6 demonstrates SEM images of WEDMed surface of Ti grade 7 alloy at various considered WEDM parameters. The description of SEM images indicates experimental results obtained for minimum *Ra* and maximum MRR attained machining conditions. The optimized parametric results and SEM image demonstrated in Figure 6a reveals the surface alterations at a pulse-off time of 12 µs, pulse-on time of 40 µs, and peak current of 6 amps. It is noticed that topography of surface defects like globules, micron-size cracks, and voids as well as recast layers on machined surfaces. It depicts the machined surface produced at high IP and low T_{ON} time settings succeeding in maximum MRR. It may be because residual gases are produced and tend to get entrapped on the metal surface [21]-[22]. While these entrapped gases try to escape, they, initiate defects like bubbles, micro voids, and micro cracks.



(a)

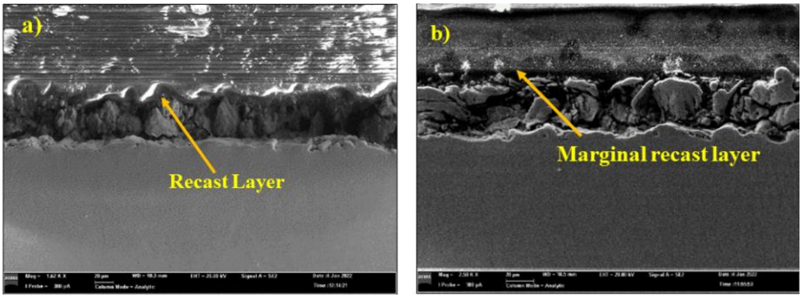


(b)

Figure 6: SEM images show the machined surface of titanium grade 7 alloy at (a) T_{on} = 40 µs, T_{off} = 12 µs and peak current = 6 A, and (b) T_{on} = 60 µs, T_{off} = 12 µs and peak current = 2 amps

Similarly, SEM micrographs demonstrated in Figure 6b show a smooth surface free from craters, voids, and cracks at T_{OFF} time of 12 µs, T_{ON} time of 60 µs, and peak current of 2 amps. However, a limited amount of debris, globules, and minor cracks of recasted metal could be comprehended. It describes that the surface roughness is commensurate to high T_{ON} time with low IP. As peak current increases, increased energy discharged creates a large amount of molten materials. It further transforms into globules resulting in better surface finish. Also, the presence of slight cracks is apparent owing to impinged higher energy sparks over machined surface. Similar experimental results were found by other researchers [8], [18]-[19].

The cross-sectional SEM microstructure reveals the amount of recast layer corresponding to WEDM parameters depicted in Figure 7. Besides, recast layer thickness in case of T_{ON} time of 40µs, T_{OFF} time of 12 µs, and IP of 6 A is shown in Figure 7a. In addition, MRR has increased with increased pulse-on, while *Ra* has decreased. As the T_{ON} time increased to 60 µs, the T_{OFF} time of 12 µs and IP of 2 A is depicted in Figure 7b. The surface roughness decreased with increased pulse-on time. However, the recast layer thickness decreased as a result of reduced peak current. It shows that a lower peak current causes less molten material and re-solidification. At the same time, it depicts the lower MRR. It can be concluded that higher T_{ON} time, lower T_{OFF} time, and IP are recommended for WED machining of Ti grade 7 alloy.



(a) (b)

Figure 7: Cross section SEM surface of WEDM machined surface of titanium grade 7 alloy at (a) T_{on} = 40 µs, T_{off} =12 µs and peak current = 6 A, and (b) T_{on} = 60 µs, T_{off} = 12 µs and peak current = 2 amps

Conclusions

The current experimental study was made to assess the WEDM parameters on surface roughness and MRR during Ti grade 7 alloy machining. The following conclusions were drawn from the experimentation and successive statistical analysis.

- The experimental results indicate the MRR is strongly influenced by pulse-on time (T_{ON}) and peak current (IP). It owes maximum discharge energy at greater levels of T_{ON} and IP.
- The pulse-off (T_{OFF}) time is highly significant (58.81%) on MRR followed by IP (18.23%) and T_{ON} time (12.64 %)
- The T_{OFF} time is highly significant (36.11%) on surface roughness trailed by T_{ON} time (33.20 %), T_{OFF}*T_{ON} (22.09%), and IP (6.75%).
- The material removal rate decreases as the T_{OFF} time increases due to reduced spark discharges in a certain duration.
- Surface quality significantly worsens with the increase in peak current due to high discharge energy affecting the surface quality and creating more cracks, globules, microvoids, and craters on the machined surface.
- Surface defects reduce with lower peak current (IP) and higher T_{ON} time. It is due to low discharge energy producing fine microstructure surfaces.
- Cross-sectioned SEM images indicate the minimum recast layer thickness at higher T_{ON} time with lower T_{OFF} time.
- Cross-sectioned SEM images indicate the minimum recast layer thickness at higher T_{ON} time with lower T_{OFF} time.
- The predicted model results and confirmation test results were close to each other with minimum error (< 5%), so the model is adequate.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All the authors together reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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