Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/AN15.20250312
Published: February 18, 2025

WEDM Process Parameters Investigation on the Concave Profile of Ti Implant Material Using the Desirability Approach

Anish Kumar
Department of Mechanical Engineering, Maharishi Markandeshwar Engineering College,
Maharishi Markandeshwar (Deemed to be University), Mullana
Ambala
anishrenu@gmail.com

M P Garg, Viveksheel Rajput
Department of Mechanical Engineering, Punjab Engineering College,
Chandigarh
mpgargacad@gmail.com, sheelrajput03@gmail.com

Renu Sharma
Department of Physics, Maharishi Markandeshwar Engineering College, Maharishi
Markandeshwar (Deemed to be University), Mullana, Ambala
renuailesh@gmail.com

Abstract

WEDM is used chiefly for machining Titanium and its alloys with good dimensional accuracy and surface finish. The research work has been done with the BBD of the RSM technique, and further multi-response optimization was done through the desirability function. The results of the research work shows that the effect of input variables pulse on-time (POT), pulse off-time (POFT,) spark gap voltage (SGV), and concave profile radius (CPR) on the output variables surface roughness (SR), and geometric error (GE) have been investigated. It observed that POT is the primary significant factor affecting the SR, and GE. With increases in CPR, Geometric error also increases. CPR is the most critical factor for the geometric error, with an 82.83% contribution. Experiment results also shows that POT and POFT significantly affected the surface integrity with the formation of pockmarks, overlapping craters, micro-cracks, and recast layer.

Keywords
Concave Profile, Geometrical error, Pure-Titanium and WEDM.

1. Introduction
With the increasing the number of research on titanium and its alloys, the applications of these alloys are increasing day by day in the area of aerospace, naval and automotive industries, also in various industrial areas like shipbuilding, and biomedical sectors due to its unique capability of anticorrosive, highly in strength /weight ratio. Titanium is a silvery gray metal, ductile with 22 elements in the model periodic table with an atomic weight of 47.9 and density of 4.67g/cm3. Along with the heat resistance, it possesses high strength too, which makes it difficult to machine material, which became difficult to process by conventional machining processes. Machining titanium offers many challenges to engineers in how easily and economically titanium is machined. Due to the unique properties of titanium, it has

become the most demanding material in aerospace and non-aerospace industries. The most demanding titanium material properties are high strength/weight ratio, anti-corrosivity, and strong fatigue properties that make it difficult to machine material (Kumar et. al 2012, Nayak and Mahapatra 2014, Maity 2020).

Titanium and its alloy have low young's modulus, which creates chatter and spring back during machining [Wasim et al. (2020)]**.** Titanium has high work hardening, and stickiness of the alloy resulting in the long continuous chip during drilling and turning that impedes and entangles the tool life (Joy et al. 2020, Sahoo et al. 2019). To overcome the problem of titanium machining, engineers use advanced machining processes rather than traditional machining processes. WEDM is mainly used for machining titanium and its alloys with good dimensional accuracy and surface finish. Many industries need to have machined their complex-shaped product with great accuracy and surface finish. WEDM provides the most viable solution for the above issues. Researchers have explored different methodologies to obtain the best results in optimizing the process parameters of WEDM while doing Taper cutting. A literature survey is shown as in Table 1.

Table 1. Literature Review on Taper cutting process on WEDM

Author Name	**Wire and workpiece material**	**Process parameter**		**Methodology used**	**Finding**
		Variable parameter	**Response parameter**		
Plaza et al. (2009)	AISI D2 tool steel with brass wire	Thickness, angle, open circuit voltage, pulse off time, discharge energy	Angular error	FEM model, trial and error experiment	75% of results show that the angular deviation is below 3'45" from the two models.
Kumar et al. (2018)	Inconel 718 with zinc-coated and uncoated wire.	Wire tension, pulse-on-time, flushing pressure, and discharge current	Surface roughness, corner error	L16 orthogonal array	Zinc-coated brass wire gives good surface roughness and less corner error. It was reduced by 21.89%
Nayak and Mahapatra (2018)	Austenitic stainless steel 304L with Bronco cut wire	part thickness, taper angle, discharge current, pulse duration, wire tension, and wire speed	Angular error	Support vector regression (SVR) model, Taguchi L27 orthogonal array	SVR effect the process parameter mostly with giving best solution of optimization.

From the literature review, it is clear that WEDM is the best alternative for producing small and micro-scale parts with high dimensional accuracy and a good surface finish. Much research has been conducted on optimizing process parameters (like POT, POFT, SGV, PC, WT, WP, etc.) considering output parameters, viz.: cutting speed, surface roughness, material removal rate, kerf width, etc. But limited research has been published considering input parameters in combination with concave profile radius (CPR) and output parameters with geometrical error while machining pure titanium-based implant material. Taper cutting was also the least identified area of researchers working on processing pure-Ti. Therefore, the pure-Ti is processed on WEDM at different POT, POFT, SGV, and CPR settings in the present research work. The response variables in the current work SR, and geometrical error are investigated. The morphological investigations of the machined surface were made with the help of SEM. The elemental analysis was accomplished with the help of EDX spectroscopy and XRD.

2. Material and Methods

The experiments were performed on a CNC WEDM machine manufactured by Electronica Machine Tools Limited, India, as depicted in Figure 1. Travelling brass wire of diameter 0.25mm is used as an electrode. Deionized water is used as a dielectric fluid to flush away the debris. Pure-Ti material was selected for the experimentations due to its applications in bio-implant, aerospace, and marine industries. Pure-Ti contains Carbon (C) 0.10, Nitrogen (N_2) 0.03, oxygen (O_2) 0.25, Iron (Fe) 0.30 %, and the rest is Titanium 99.03 % by weight. The work profile after pure-Ti machining on WEDM is depicted in Figure 2, where the concave radius is also presented.

Figure 1. Machine tool used in the present research.

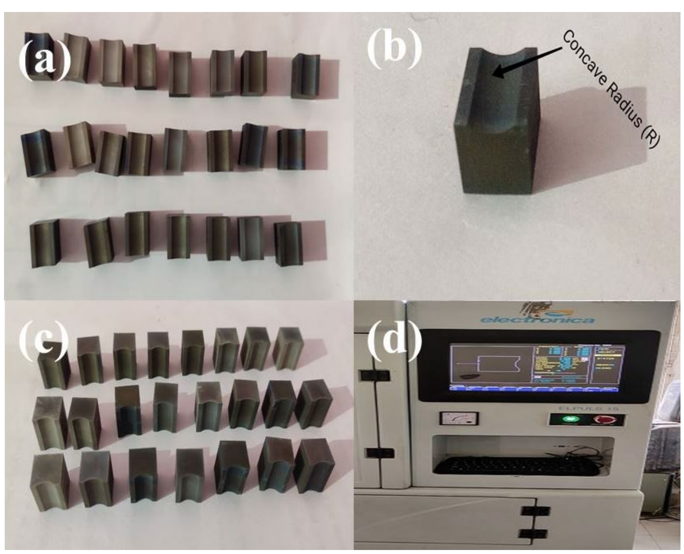

Figure 2. Complete profile job (a-d) after WEDM.

3. Selection of WEDM Process Parameters

The selection of parameters is one of the most essential steps in the experimentation and optimization of the WEDM process. All the machining parameters for this experiment have been selected based on a pilot study. POT, POFT, SGV, CPR were taken as the process parameters. The constant process parameters in the present work are WF, WT, PC and WP with values as 3 mm/min, 8N, 12A, and 7 kg/cm^2, respectively. The experimental array was designed according to the BBD based on the range of selected input parameters. The range of the process parameters were shown in Table 2. The Surface roughness was measured using Mitutoyo make surface roughness tester (SJ-301P) with least count 0.001µm as depicted in Figure 3a, Figure 3b. The Radius of the concave profile was measured on CNC profilometer (Mitutoyo make) as shown in Figure 3c.

Table 2. Range of Input parameters

Factor	Name	Units	Minimum	Maximum
A	POT	µs	107	130
B	POFT	µs	40	60
C	SGV	V	35	55
D	CPR (CPR)	mm	2.5	4.5

Figure 3. Measurement of responses

4. Results and Discussion

The effect of input parameters like POT, POFT, SGV, and concave radius on the responses like GE, SR, and CS are analyzed using the RSM technique, and further ANOVA was used to analyze the quadratic model for various response variables (Table 3).

Table 3. Design array and measured experiment result

Run	POT	POFT	SGV	CPR	SR	GE
	µs	µs	V	mm	µm	mm
1	123	50	45	4	2.49	4.39
2	123	50	45	3	2.39	3.05
3	123	60	45	4	1.58	4.12
4	123	40	45	4	2.16	4.45
5	115	45	40	3	2.18	3.95
6	130	45	50	4	2.44	4.72
7	123	50	35	4	2.45	4.45
8	130	45	40	3	2.75	3.85
9	130	45	40	4	2.45	4.85
10	115	55	40	4	1.79	4.55
11	123	50	45	4	2.51	4.42
12	123	50	45	4	2.39	4.44

13	123	50	45	4	2.42	4.49
14	130	55	50	4	2.31	4.65
15	130	45	50	3	2.61	3.55
16	123	50	45	4	2.36	4.25
17	115	45	40	4	1.95	4.65
18	115	55	40	3	1.86	3.55
19	123	50	45	5	2.46	5.06
20	115	55	50	3	1.55	3.35
21	108	50	45	4	1.35	4.02
22	130	55	50	3	2.34	3.61
23	115	45	50	4	1.65	4.41
24	130	55	40	3	2.33	3.85
25	123	50	45	4	2.34	4.45
26	123	50	55	4	2.09	4.15
27	115	45	50	3	1.75	3.55
28	115	55	50	4	1.61	4.35
29	130	50	45	4	2.51	4.55
30	130	55	40	4	2.34	4.85

4.1 ANOVA for SR, and GE

The ANOVA for SR and GE with the quadratic models (Eq. 1-2) is shown in Table 4. The P-value and model F-value is <0.0001 and 112.67, respectively, indicating that model is significant. ANOVA for SR shows the F-value is equal to 85.15, which indicates that model is significant for SR with all the main effect of POT, POFT, SGV, CPR, POT^2, $POFT^2$, SGV^2, POT and SGV, POFT and CPR. For the GE, the fit summary recommends the quadratic model where the additional terms are remarkable, and the model is not aliased. The ANOVA for GE shows the main effect of POT, POFT, SGV, CPR, the quadratic effect of POT, POFT, SGV, and CPR, and the interaction effect of the POT and POFT, and POT and CPR have a significant influence on GE. The Model F-value is 95.12, and the P-value is less than 0.050, which implies that the model is significant. Eq. 1 to Eq. 2 shows the empirical models for CS, SR and GE.

$$SR = (-34.8985) + (0.4661 \times POT) + (0.45381 \times POFT) - (0.102113 \times \text{SGV}) - (1.02 \times \text{CPR}) + (0.00175 \times \text{POT} \times \text{SGV}) + (0.01925 \times \text{POFT} \times \text{CPR}) - (0.00205201 \times \text{POT}^2) - (0.00544273 \times \text{POFT}^2) - (0.00144273 \times \text{SGV}^2) \quad \text{Eq-1}$$

$$\text{GE} = (-17.3951) + (0.204463 \times \text{POT}) + (0.0129879 \times \text{POFT}) + (0.12581 \times \text{SGV}) + (2.51162 \times \text{CPR}) + (0.00125 \times \text{POT} \times \text{POFT}) + (0.0108333 \times \text{POT} \times \text{CPR}) - (0.0011918 \times \text{POT}^2) - (0.0017803 \times \text{POFT}^2) - (0.0016303 \times \text{SGV}^2) - (0.40803 \times \text{CPR}^2) \quad \text{Eq-2}$$

Table 4. ANOVA of SR and GE

ANOVA for SR							
Source	**SS**	**df**	**MS**	**F-value**	**P-value**		**PC**
Model	3.86	9	0.4291	85.15	< 0.0001	Significant	
A-POT	1.88	1	1.88	372.68	< 0.0001		47.83
B-POFT	0.3290	1	0.3290	65.29	< 0.0001		8.30
C-SGV	0.1855	1	0.1855	36.81	< 0.0001		4.72
D-CPR	0.0198	1	0.0198	3.94	0.0611		0.50
AC	0.0689	1	0.0689	13.67	0.0014		
BD	0.0371	1	0.0371	7.35	0.0134		

A²	0.2183	1	0.2183	43.31	< 0.0001		
B²	0.5255	1	0.5255	104.28	< 0.0001		
C²	0.0369	1	0.0369	7.33	0.0136		
ANOVA for GE							
Source	**SS**	**df**	**MS**	**F-value**	**P-value**		**PC**
Model	6.85	10	0.6849	95.12	< 0.0001	significant	
A-POT	0.1753	1	0.1753	24.35	< 0.0001		2.50
B-POFT	0.0852	1	0.0852	11.83	0.0027		1.21
C-SGV	0.2625	1	0.2625	36.46	< 0.0001		3.75
D-CPR	5.79	1	5.79	804.37	< 0.0001		82.83
AB	0.0352	1	0.0352	4.88	0.0396		
AD	0.0264	1	0.0264	3.67	0.0067		
A²	0.0735	1	0.0735	10.21	0.0048		
B²	0.0553	1	0.0553	7.68	0.0122		
C²	0.0464	1	0.0464	6.44	0.0201		
D²	0.2905	1	0.2905	40.35	< 0.0001		

4.2 Interaction effect on SR and GE

From the analysis results provided that POT was the outstanding factor that affecting the SR. Also, POFT and SGV show some significant effects on the SR. With increases in POT the SR also increases, whereas with increases POFT and SGV the SR decreases. The interaction plot of combined factor of SR was shown in Figure 4. It was noted that the combined effect of POT and SGV will increase the SR of 22.01%, while with the combine effect of POFT and CPR there was decrease in SR with 10.57%. The combined effect for GE is as shown in Figure 5**.** With the combined effect of POT and POFT increases from 4.31mm^3/min to 4.39mm^3/min there was decrease in GE with their 1.86% contribution. An increase in geometric error with 31% contribution of combine interaction of POT and CPR (increase from 3.71mm^3/min to 4.80mm^3/min).

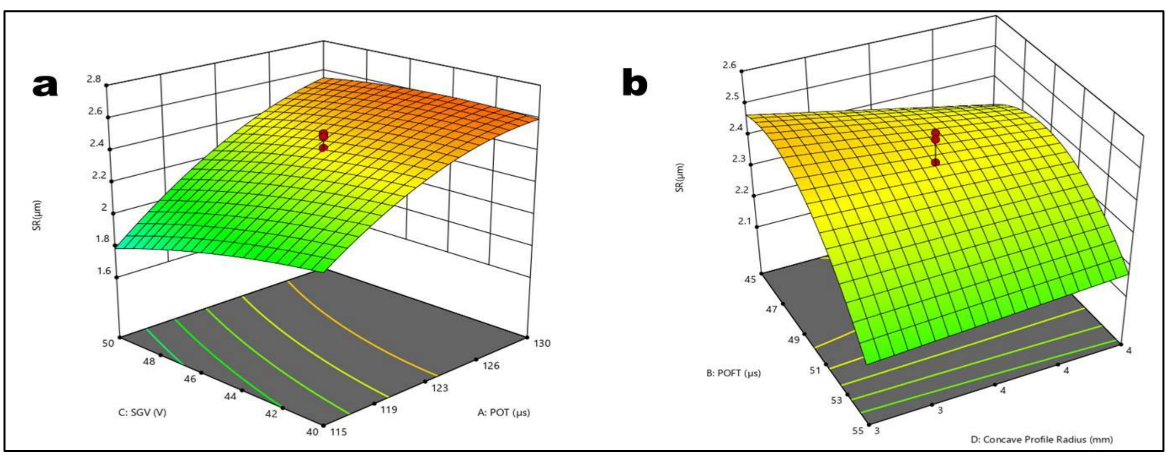

Figure 4. Interactions plot for SR

4.3. Numerical Analysis

This research aims to obtain a minimum SR of 1.35µm, and a reduction in GE. Equal weights are assigned to SR, and GE that have been used to produce the optimum results. For obtaining attractive optimal solutions, a desirability function was used. After using the desirability function, some optimal solutions were found, and out of those 5 best solutions are shown in Table 5. The maximum desirability obtained after analysis is 0.827, which is close to 1.

4.4 Validation of the Developing Model

There is 5 confirmation experiments have been carried out to validate the experimental model. A validation test has been carried out to check whether the desirable optimal solutions, which are obtained, are responsible for optimization. Validation is also used for calculating the error between the actual and predicted experiment values. Table 6 shows the prediction performance of the RSM model. The given formula calculates the prediction error percentages, as shown in Eq 3.

$$Prediction\ error\ (\%) = [Experimental\ results - Predicted\ results] \times 100 \qquad \text{Eq-3}$$

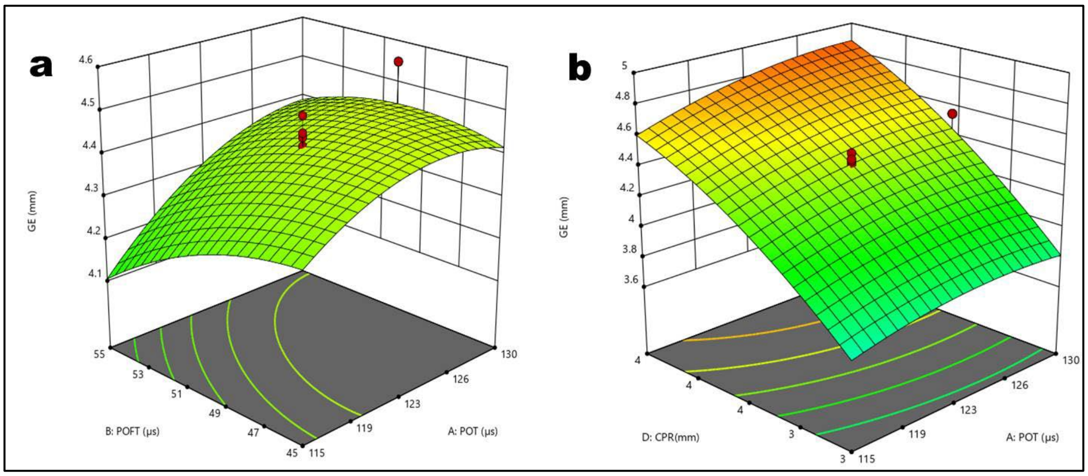

Figure 5. Interactions plot for GE

Table 5. Optimal solution after desirability function

Number	POT	POFT	SGV	CPR	CS	SR	GE	Desirability
1	115	55	50	3	0.575	1.516	3.407	0.827
2	115	55	49	3	0.575	1.518	3.408	0.827
3	115	54	50	3	0.576	1.518	3.418	0.826
4	115	54	49	3	0.574	1.523	3.410	0.825
5	115	55	49	3	0.587	1.552	3.422	0.824

Table 6. Validation development model

Exp. No.	Experimental results			RSM prediction model			Prediction error %		
	CS	SR	GE	CS	SR	GE	CS	SR	GE
1	0.58	1.55	3.42	0.575	1.516	3.407	0.5	3.4	1.3
2	0.58	1.55	3.42	0.575	1.518	3.408	0.5	3.2	1.3
3	0.59	1.56	3.44	0.576	1.518	3.418	1.4	4.2	2.2
4	0.60	1.54	3.43	0.574	1.523	3.410	2.6	1.7	2
5	0.61	1.60	3.44	0.587	1.552	3.422	2.3	4.8	1.8

5. Microstructural Analysis

In this research work, SEM was done on a curve surface, flat surface, brass wire electrode, and recast layer to find the effect of various process parameters on the workpiece sample. Figure 6 (a-b) shows the SEM images of the curve surface of the sample at different process parameter settings. From the SEM analysis, it was observed that larger amounts of voids, cracks and globules of debris can appear on the images. During every electrical discharge, high cycle temperature melts and vaporizes the materials.

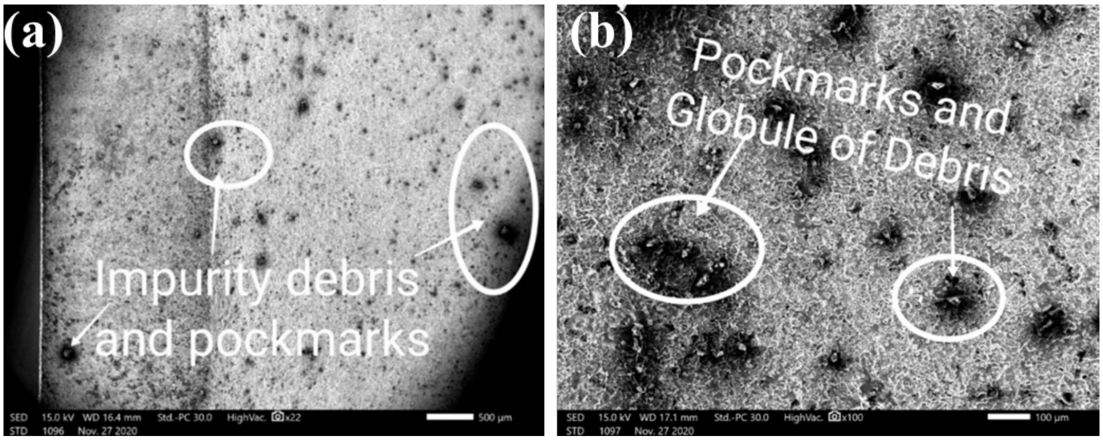

Figure 6. SEM picture of curve surface of Pure Titanium at a) Run No 1, (at POT 123µs, POFT 50µs, SGV 45V, CPR 4mm), b) Run no.5, (at POT 115µs, POFT 45µs, SGV 40V, and CPR 3mm)

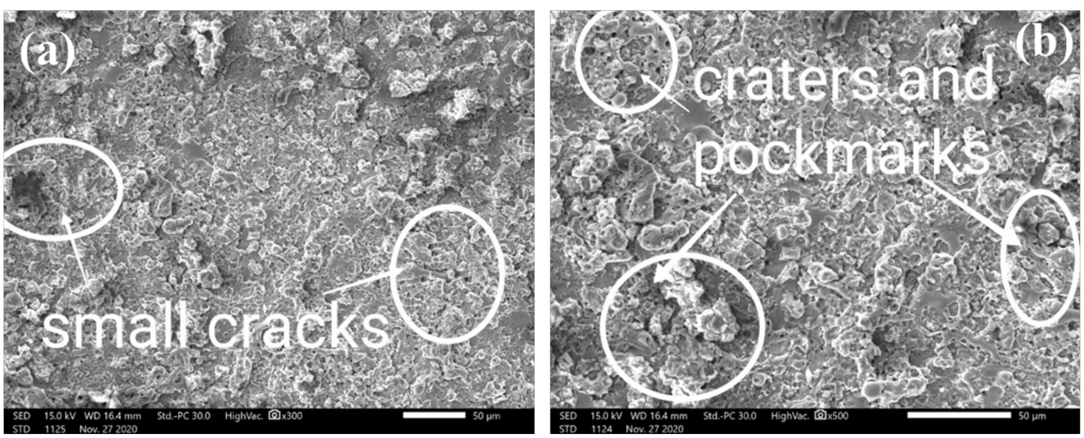

Figure 7. SEM picture of Flat surface of Pure Titanium after WEDM Process at a) Run No 1, (at POT 123µs, POFT 50µs, SGV 45V, CPR 4mm), b) Run no.5, (at POT 115µs, POFT 45µs, SGV 40V, and CPR 3mm)

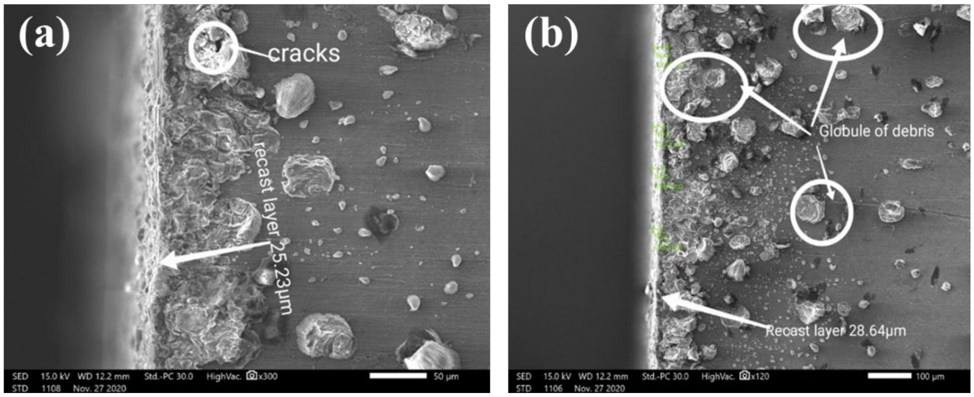

Figure 8. SEM picture of Recast layer of Pure Titanium after machining at a) Run No 1, (at POT 123µs, POFT 50µs, SGV 45V, CPR 4mm), b) Run no.5, (at POT 115µs, POFT 45µs, SGV 40V, and CPR 3mm)

Craters and overlapping cracks are high at high discharge energy level. The melting material was then connected with the dielectric fluid, reducing the temperature of the material and causing a quenching effect on the melting surface (Singh et al. 2019, Garg et al. 2012). As a result of this quenching, voids, cracks, and globules are found on the machined surface. It was observed that some amount of the discharge energy always presents in every discharge cycle, so the complete reduction of the voids and craters was impossible. The same effect of the SEM was also examined on the material sample's flat surface as in Figure 7. The SEM image (Figure 8) of the machined surface (Figure 8(a)) has small cracks due to an intermediate amount of discharge energy. In Figure 8 (b), the discharge energy is smaller (POT 115µs, POFT 45µs, SGV 40V, and CPR 3mm); thus, craters and pockmarks are observed.

6. Conclusions

The present research applied the RSM approach to the WEDM process to find the best solution for SR, and GE of pure titanium. From the study, the important conclusions are as follows:

- SR is varied from 1.35µm to 2.61µm. POT was the most influential factor, whose contribution for evaluation of SR is 47.83% followed by POT and SGV with 8.30% and 4.72% respectively.
- For GE the CPR shows the most important factor with 82.83% contribution. However, the SGV shows the significant (3.75%) effect on the GE.
- ANOVA shows that POT is main remarkable factor for SR and GE. CPR plays the pivotal role followed by POT.
- Cracks, voids, and globules of debris were found in SEM analysis. These irregularities on the machined surface, was observed at high discharge energy parameters.

References

Garg, M.P., Jain, A. and Bhushan, G., Modelling and multi-objective optimization of process parameters of wire electrical discharge machining using non-dominated sorting genetic algorithm-II, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 226, no. 12, pp. 1986-2001, 2012**.**

Joy, R., Manoj, I.V. and Narendranath, S., Investigation of cutting speed, recast layer, and micro-hardness in angular machining using slant-type taper fixture by WEDM of Hastelloy X, *Materials Today: Proceedings*, vol. 27, pp. 1943-1946, 2020.

Kumar, A., Abhishek, K., Vivekananda, K. and Maity, K.P., Effect of wire electrode materials on die-corner accuracy for wire electrical discharge machining (WEDM) of Inconel 718, *Materials Today: Proceedings*, vol. 5, no. 5, pp. 12641-12648, 2012.

Kumar, A., Kumar, V. and Kumar, J., An investigation into machining characteristics of commercially pure titanium (Grade-2) using CNC WEDM, *Applied Mechanics and Materials*, vol. 159, pp. 56-68, 2012.

Maity, H. M., Performance analysis in WEDM of Titanium Grade 6 through process capability index, *World Journal of Engineering*, vol. 17, no. 1, pp. 144-151, 2020.

Nayak, B.B. and Mahapatra, S.S., A hybrid approach for process optimization in taper cutting operation using wire electrical discharge machining, *Applied Mechanics and Materials*, vol. 619, pp. 83-88, 2014.

Nayak, B.B. and Mahapatra, S.S., An intelligent approach for prediction of angular error in taper cutting using wire-EDM, *Materials Today: Proceedings*, vol. 5, no. 2, pp. 6121-6127, 2018.

Plaza, S., Ortega, N., Sanchez, J. A., Pombo, I., and Mendikute, A., Original models for the prediction of angular error in wire-EDM taper-cutting, *International Journal of Advanced Manufacturing Technology*, vol. 44, pp. 529-538, 2009.

Sahoo, S.K., Bara, A., Sahu, A.K., Mahapatra, S.S., Kiran, D.S., Teja, G.S., Teja, E.S. and Reddy, S.P., Analysis and optimization of wire EDM process of titanium by using GRA methodology, *Materials Science Forum*, vol. 969, pp. 678-684, 2019.

Singh, M., Ramkumar, J., Rao, R.V. and Balic, J., Experimental investigation and multi-objective optimization of micro-wire electrical discharge machining of a titanium alloy using Jaya algorithm, *Advances in Production Engineering & Management*, vol. 14, pp. 251-263, 2019.

Wasif, M., Iqbal, S.A., Fatima, A., Yaqoob, S. and Tufail, M., Experimental investigation for the effect of wire EDM process parameters over the tapered cross-sectional workpieces of titanium alloys (Ti6Al-4V), *Mechanical Sciences*, vol. 11, pp. 221-232, 2020.

Biographies

Dr. Anish Kumar is working as a Professor in the Department of Mechanical Engineering at M.M. Engineering College, Mullana-Ambala (Haryana), India. He has received his BE in Mechanical Engineering from S.L.I.E.T(Deemed to be University) and an ME &PhD in Industrial and Manufacturing Engineering from Thapar University, Patiala, Punjab, India. The twenty-two postgraduate theses have been supervised in the area of Industrial engineering, conventional and non-traditional machining methods. He has teaching experience of 24Years in UG and PG Programs. The 48 research papers have been published in the Scopus/Web of Science/ referred journals and conference proceedings at the national and international levels. He has supervised one PhD thesis currently. His areas of interest include industrial engineering, non-traditional machining, and optimisation.

Dr. Mohinder Pal Garg is working as Associate Professor in Mechanical Engineering Department at Punjab Engineering College (Deemed to be University), Chandigarh. He holds PhD from National Institute of Technology, Kurukshetra and M.E in CAD/CAM and Robotics from Thapar Institute of Engg. and Technology, Patiala and a B. Tech in Mechanical Engineering from SLIET, Longowal, Punjab. During his academic career of 19 years, he has contributed 45 research papers in International/ National journals of repute (Sage, Springer, Elsevier, Inder science Publishers) as well as conferences at national and international level. He supervised one Ph.D and 20 Postgraduate theses in the area of conventional and non-traditional machining methods. His areas of interest are composite materials, non-conventional machining processes, machining of difficult to machine materials, finite element analysis apart from statistical modelling and analysis.

Dr. Renu Sharma is working as an Associate Professor in the Department of Physics at M.M. Engineering College, Mullana-Ambala (Haryana), India. She has received her PhD in Nuclear Physics from M.M. (Deemed to be

University) Mullana-Ambala. The Five postgraduate thesis have been supervised in the area of Nuclear Physics. The 15 research papers have been published in the Scopus/Web of Science/ referred journals and conference proceedings at the national and international levels. She has supervised one PhD thesis currently. Her areas of interest include Nuclear and Quantum Physics. She has teaching experience of 18Years in UG and PG Programs.

Dr. Vivek Sheel Rajput is presently working as an Assistant Professor in Mechanical Engineering Department at Punjab Engineering College (Deemed to be University), Chandigarh. He was formerly worked as a project scientist in Sophisticated Analytical Instrumentation Facility (SAIF), Panjab University, Chandigarh, under DST-STUTI Project. He has completed his Doctorate degree from the Department of Production and Industrial Engineering, Punjab Engineering College, Chandigarh, in the field of non-conventional machining processes. His research work includes the development of adaptive tool feed system for enhancing the performance of electrochemical discharge machining (ECDM). He has also worked in the field of polymer composite materials, self-healing composite materials, finite element methodology (FEM), ergonomics and advanced machining processes. During his academic & Research career of 07 years, he has published 40 research papers and book chapters in the reputed international journals/conferences. He is a former Assistant Professor in the Department of Mechanical Engineering, LPU, Jalandhar, Punjab.