Process parameter optimization in wire EDM of titanium alloy by Taguchi L16 orthogonal array approach

Naveen Kumar*, Nabendu Ghosh, Goutam Nandi
Department of Mechanical Engineering, Jadavpur University, Kolkata 700032, India
Corresponding author: Naveen Kumar*
Email: naveenkumar61294@gmail.com, naveenk.mech.rs@jadavpuruniversity.in

Abstract

Titanium alloy TC4 was machined using wire EDM. A robust Taguchi design was created to produce a smooth machined surface.In the design of the experiment, the four main process parameters (pulse on time, pulse off time, wire tension, and wire feed) of wire EDM were chosen as the factors and the arithmetic mean roughness (R_a) was chosen as the response.The roughness of the machined surface was captured using a contact-type profilometer.Based on the signal-to-noise (S/N) ratio value, an optimal combination of process parameters was selected to obtain a machined surface with the lowest arithmetic average roughness.The ANOVA results showed that thepulse on time (Ton) was the statistically most significant factor in producing a smooth surface.The microstructure of the machined surface observed by the optical microscope displayed some cracks and deformed grains on the edges of the workpiece.

Keywords- WireEDM, Titanium, Taguchi, Roughness

DOINumber:10.48047/nq.2022.20.16.NQ880351 **NeuroQuantology2022;20(16): 3458-3466**

1. Introduction

Today's mechanical engineering environment requires materials with high levels of hardness, toughness, impact resistance, excellent strength-to-weight ratio, low weight, excellent corrosion resistance, and many other properties.Hardening materials such as titanium and tungsten carbide are also moving forward to meet current demand.The machining of these materials is a serious problem as they are challenging to machine using conventional machining techniques.Therefore, to machine such difficult-to-machine materials, non-conventional machining techniques are required, including electrochemical machining, ultrasonic machining, abrasive jet machining, electrical discharge machines (EDM), etc.A non-conventional material removal technique known as wire electrical discharge machining (WEDM) is commonly used to create components with complex forms and profiles.Titanium alloys are very in demand or we can say most popular in various industries due to their good mechanical properties, high corrosion resistant, low density, and high-temperature resistance.Due to these properties, titanium alloys are widely used in the chemical industry, automobile industry, shipping industry, aircraft industry, military applications as well as medical equipment, etc.

Wire electrical discharge machining is a non-conventional machining process in which material is removed by a series of repeated electrical sparks between an electrode and a workpiece.The repeated electric spark causes heat to be generated between the electrode and the workpiece and this high temperature causes the workpiece to melt and the molten workpiece is removed by the pressurized dielectric fluid.In the wire EDM process, material removal is mainly the effect of erosion between the wire electrode and the workpiece material.Because of the inherent features, Wire EDM can easily and accurately machine complex components and hard metals.Wire EDM is commonly used in the aerospace industry and nuclear industry for machining various hard materials, irregular and complex shapes or profiles.The machining performance of wire EDM depends on various working parameters such as pulseon time, pulseoff time, wire tension, wire feed rate, voltage, peak current, and dielectric injection pressure to measure the output performance such as surface roughness and material removal rate, etc.[1].

The Taguchi approach optimizes the design parameters to minimize variation, before optimizing the design to obtain average target values for the output parameters.The Taguchi technique studies all design elements with the least possible number of experiments.An emphasis on the analysis and management of product variability, especially in situations where target average values of some characteristics are relatively simple to achieve and where excellent quality depends on low variability, is one of Taguchi's contributions to a new design.The Taguchi technique uses the signal-to-noise (S/N) ratio to calculate ideal values for each parameter and to analyze parameter changes.Here are two standard ratio equations that are more practical. When the response is at its highest, the "larger is better" condition can be taken into account to optimize the system. The "smaller is better" situation, when the response is the smallest, can be taken into account to optimize the system.

Various research has already been done in the field of process parameter optimization for wire EDM process, but it is always of research interest due to a large number of parameters[2].The material removal rate and surface roughness of titanium were optimized during machining by taking the pulse on time, pulse off time, gap voltage, and wire feed rate as input parameters. Their result suggested that the cutting speed was directly proportional to the rate of material removal[3]. The effect of various process parameters such as pulse width, pulse current, servo voltage, and wire tension were investigated on process performance parameters such as cutting speed, surface integrity, and wire rupture.It is found that the cutting speed increases with increasing pulse interval and peak current. and also found that the surface roughness increases with pulse width and decreases with pulse interval[4].Input parameters such as pulse on time, pulse off time, peak current, and servo voltage were optimized to maximize material removal rate, minimize kerf width and minimize surface roughness,for materials of titanium alloys by Taguchi orthogonal array L18 and gray relational analysis[5]. Machining with coolant gives a better surface finish than without coolant and machining with coolant increases tool life by up to 30%[6]. The changes in mechanical properties of titanium grade 5 alloys were studied after machining by the WEDM process with different feed rates.It was found that increasing peak current would increase MRR and SR, decreasing pulse time would decrease MRR and increase surface finish, and wire tension would have an effect on both surface roughness and MRR[7].The effect of fracture toughness and microstructure in titanium alloy Ti-6Al-4V after wire electrical discharge machining was investigated.It was determined that the material properties were not significantly affected by the WEDM process[8]. An artificial intelligence model was proposed to predict ideal electrical discharge machining (EDM) parameters for Ti-6Al-4V, using copper as the electrode and positive electrode polarity.The lowest value of the electrode wear rate was measured when the peak current was around 18 A.The MRR increased with a higher peak current and longer pulse on time[9]. The Ti-6Al-4V (Grade 5) ELI alloy was machined on a CNC lathe with the least energy, best surface quality, and least tool wear.Surface roughness, tool wear, and energy consumption were found to be linearly proportional to each other.This work demonstrated that energy use can be managed to maintain surface quality and limit tool wear[10]. Abdulgadir et al.,[11]reviewed the machinability of titanium alloy (Ti-6Al-4V) by turning process and improved the cutting process using an environment-friendly cryogenic coolant.Pulse on time and peak current were found to be the most effective parameters on both material removal rate and surface roughness compared to servo voltage and pulse off time[12]. The lead-induced titanium alloy (Ti-6Al-4V) was fabricated by a zinc-coated brass wire electrode on wire electrical discharge machining.The result showed that the peak current was the main responsible parameter and the significant factors were the spark gap voltage and pulse on time[13].The optimum conditions of the wire feed rate of 3.85 mm/min, pulse on time of 1µs and pulse off time of 17µs were obtained by the Box-Behnken approach[14].Dwaipayan De et al., [15]found that both the surface roughness and material removal rate values increase simultaneously with the increase of pulse on time.One study found that the surface roughness is inversely proportional to the discharge voltage and directly proportional to thecapacitance.Capacitance is a more prominent parameter for machining performance[16].

In the present study, an attempt was made to reduce the arithmetic mean roughness (R_a) of the machined surface of titanium alloy by different combinations of process parameters in a wire EDM machine.A Taguchi design of experiment was created in Minitab to obtain an optimal process parameter for the smooth machined surface.The roughness value was captured by a contact-type profilometer. The microstructure of the machined surface was also observed by optical microscopy.

2. Materials and methodology

A rectangular-shaped titanium sheet of dimension 16 × 10 × 0.2 cm^3 was taken as the starting work-piece material. The titanium type was TC4, or grade 5, according to ASTM standards, with the chemical composition listed in Table 1.

Table 1. Chemical composition of titanium alloy.

Element	Al	V	Fe	C	N	H	O	Ti
Weight %	6.15	4	0.3	0.1	0.05	0.015	0.2	Balance

Four factors and their four levels were selected and experiments were carried out on a wire EDM machine (Electronica Hitech).Pulse on time, pulse off time, wire tension, and wire feed were the process parameters.Various test experiments were conducted on different factor settings to select the final factors for the present research.The most important factors and their levels used to create the Taguchi L16 design are tabulated in Table 2.The design was made in Minitab 20 software. Due to the low resolution of the design, interaction effects were not estimated.The surface roughness was the response in this design of experiment whose minimum value was desired from these factor settings.Parametric optimization was performed for the minimum value of the arithmetic mean roughness (R_a) for a better understanding of the machined surface.During machining, DI water was applied as the dielectric fluid and 0.25 mm diameter brass wire as the electrode.The servo voltage of 20 V, a peak current of 1 A, and a servo feed of 60 units were fixed during machining.The final dimension of the machined sample was 10 × 10 × 2 mm^3.After machining, cross-sectional images were taken with the help of an optical microscope(OLYMPUS, BX53M).Surface roughness was assessed using a contact-type surface profilometer (Taylor Hobson, Surtronic 3+) with a spacing of 4 mm.A total of

3 readings were taken at 3 different locations on each machined surface and their average was taken as the final roughness value.

Table 2. Factors and their levels.

Factors	Units	Code	Levels			
			1	2	3	4
Pulse on time (Ton)	µs	A	10	12	14	16
Pulse off time (Toff)	µs	B	50	52	54	56
Wire tension(WT)	kgf	C	7	9	11	13
Wire feed (WF)	m/min	D	6	7	8	9

All factor settings and roughness results for each factor setting are presented in Table 3.In the current robust Taguchi design, a statistical signal-to-noise (S/N) ratio gives optimal factor settings that constitute the mean and variance.This S/N ratio should be the maximum for each factor, regardless of response type, maximization, or minimization.Because in a class the teacher tries to speak loudly so that the noise made by the students can be removed for better results. There are four types of S/N ratios, smaller-the better, nominal-the best, larger-the better, and fraction defective[17]. In this present work an attempt was made to obtain the minimum surface roughness and for this the smallerthe better the S/N ratio (η) was selected during the design of the experiment in Minitab, which is given in equation 1.In this equation n is the number of measurements, and Y is the value of the response

.

$$\eta = -10\log[\frac{1}{n}\sum_{i=1}^{n} Y_i^2] \qquad (1)$$

Surface finish includes surface roughness. It is a measure of how far the real surface deviates from its ideal form in the direction of the normal vector.The surface is considered rough if these variations are substantial and smooth if they are minimal.Roughness is often considered in surface metrology as the high-frequency, short-wavelength component of the measured surface.How a real object will interact with its surroundings is greatly affected by its roughness. In tribology, rough surfaces often have higher friction coefficients and wear more quickly than smooth surfaces.Because surface irregularities can serve as starting places for cracks or corrosion, roughness is often a reliable indicator of how well a mechanical component will function.Ra is by far the most popular roughness parameter;amplitude parameters describe a surface based on the vertical departure of the roughness profile from the mean line.Ra, for example, is the arithmetic mean value of the filtered roughness profile, calculated from the departure from the center line inside the evaluation length.

Table 3. L16 orthogonal array (OA) with the response value.

Experiment number	Factors				Response
	A	B	C	D	Roughness, R_a (µm)
1	10	50	7	6	1.99
2	10	52	9	7	2.15
3	10	54	11	8	2.10
4	10	56	13	9	2.12
5	12	50	9	8	2.25
6	12	52	7	9	2.07

7	12	54	13	6	2.55
8	12	56	11	7	2.20
9	14	50	11	9	2.26
10	14	52	13	8	2.44
11	14	54	7	7	2.54
12	14	56	9	6	2.38
13	16	50	13	7	2.98
14	16	52	11	6	2.34
15	16	54	9	9	2.46
16	16	56	7	8	2.28

3. Result and discussion

3.1 Microscopic examination

Figures 1 and 2 show the microstructure of the machined surface captured by the optical microscope at different magnifications.These are images of a sample that has a lower surface roughness than all other samples.A clear, fine, and complete microstructure along withthe edges of the machined surface is visible in Figure 1.The grain was slightly deformed at the edges after machining via wire EDM, with no effect on other core parts of the surface.Some debris, cracks, and craters can be seen in Figure 2 of the microstructure.This is due to the high pulseoff time which results in microscopic surface topography[14].This superior titanium surface production was probably also due to the lower resistivity of the brass wire[4]

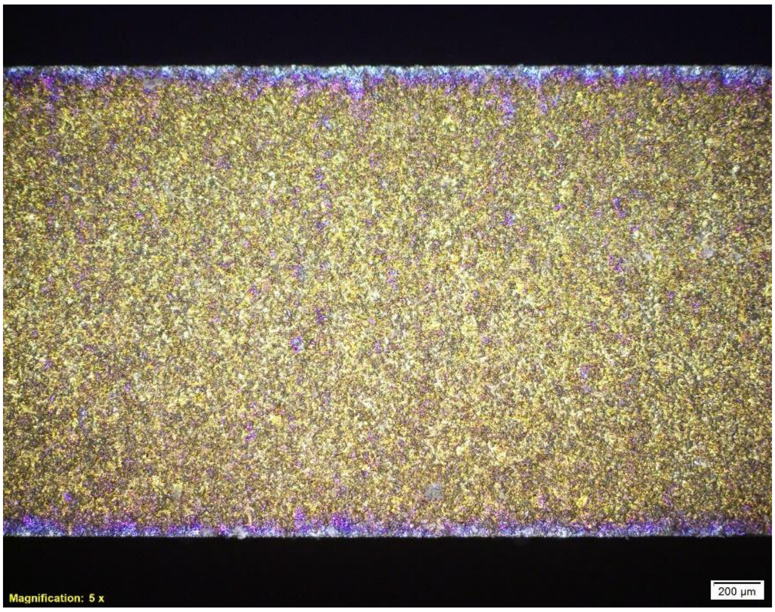

Figure 1. Microstructure of the machined surface at 5x magnification.

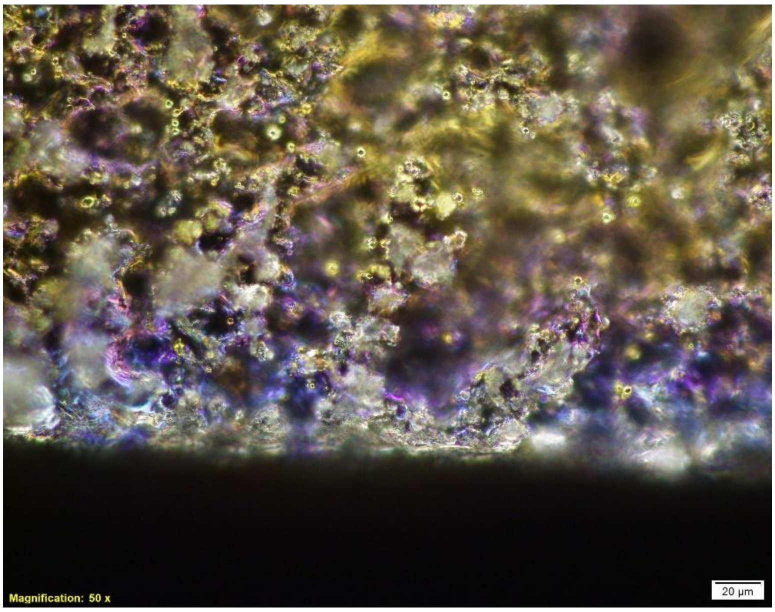

Figure 2. Microstructure at 50x magnification.

3.2 Taguchi Result

Main effect plots for response means and S/N ratios of all main parameters are shown in Figure 3.This is the original plot of the Taguchi design from which the optimal parameters were chosen.The present work aimed to optimize the process parameters to reduce surface roughness.Therefore, the factor setting with the lowest mean value was the optimal process parameter.The factor settings of A1B4C1D4 are the optimal parameter setting according to the mean plot which can be seen in Figure 3(a).But according to Figure 3(b), the factor setting with the maximum S/N ratio was the optimal parameter setting.As discussed earlier, whether the response objective is minimization or maximization, the maximum value of the signal-to-noise (S/N) ratio gives optimal parameter settings.And, it will be the same for both the mean plot and S/N ratio plot, which is A1B4C1D4, i.e., the first level of factor A (pulse on time), the fourth level of factor B (pulse off time), the first level of factor C (wire tension) and the fourth level of factor D (wire feed).

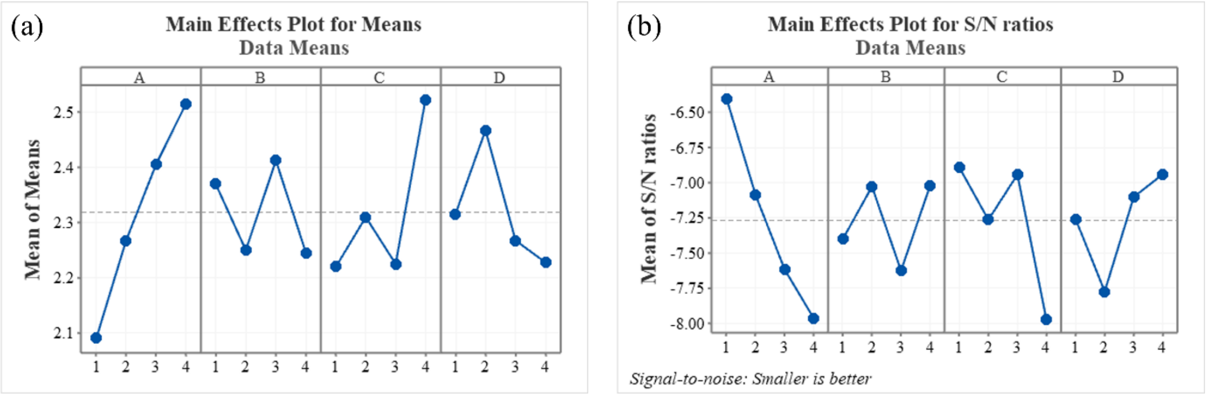

Figure 3. Main effects plot for (a) means; (b) S/N ratios.

An analysis of variance (ANOVA) was also performed, the results of which are presented in Table 4.An attempt was made to know the statistical significance of the individual factor by looking at the P-value in this Table.The P-value is a level of significance that was chosen as 0.05 in the Minitab software during design.Factors whose P-value was less than

0.05 were statistically significant factors.Therefore, factor A (pulse on time) and factor C (wire tension) were statistically significant factors for the present model.Table 4 also gives the coefficient of determination (R-Sq or R^2) values which are a measure of how well the original model fits relative to the poor model.And the bad model here would be that y does not depend on x,i.e., the response is independent of the factors.The R-Sq value of 97.15% i.e., 0.9715 is close to 1, which means that the current model fits the data well.The residual sum of squared error is used to calculate the coefficient of determination, R^2.A large value of the F-statistic or F-value for factors A and C represents a statistically significant factor, as also verified by their P-values.

Table 4. Analysis of variance (ANOVA).

Source	Degree of freedom (DOF)	Sum of squares (SS)	Adjusted mean squares (MS)	F-value	P-value
A	3	0.40362	0.134540	15.97	0.024
B	3	0.08632	0.028773	3.42	0.170
C	3	0.24052	0.080173	9.52	0.048
D	3	0.13237	0.044123	5.24	0.104
Residual Error	3	0.02527	0.008423		
Total	15	0.88809			

S = 0.0917764, R-Sq or (R^2) = 97.15%, R-Sq (adj)=85.77%.

The value of the S/N ratio is also displayed in Table 5.Here a significant change in the value of the S/N ratio can be observed at different levels which confirms that all these four factors have a significant effect on the produced surface roughness.Here delta was the difference between the maximum and minimum S/N ratios for each factor.And the factor which has the highest value of delta is the most important [18][19]. This means that pulse on time (Ton) was the most important parameter in producing minimum surface roughness followed by wire tension (WT) and wire feed (WF).In this present work, pulse off time (Toff) had the least effect on the response.

Table 5. Signal-to-noise (S/N)ratio for surface roughness (R_a).

Level	Pulse on time (Ton), A	Pulse off time (Toff), B	Wire tension (WT), C	Wire feed (WF), D
1	-6.399	-7.397	-6.888	-7.256
2	-7.086	-7.025	-7.261	-7.770
3	-7.615	-7.623	-6.940	-7.099
4	-7.962	-7.016	-7.972	-6.937
Delta	1.562	0.606	1.084	0.833
Rank	1	4	2	3

Smaller is better.

The validity of the model was verified using the residual plot of surface roughness as shown in Figure 4.In this Figure, there are four different graphs of the normal probability plot, the residual versus fitted value plot, the histogram, and the residual versus observation order.In a normal probability plot, all points adjacent to the red straight line are not normally distributed.The farthest point from the line may be an outlier in the model.Similar things can be seen in the histogram of outliers as the two bars are far from the center.This can be a bell-shaped histogram that predicts a normally distributed variance.In the residual vs observation order plot, it can be seen that some observations had the same residuals.2,4,5,7,9,11,14 have an almost equal number of residues. This residual is the difference betweenthe actual and predicted response.

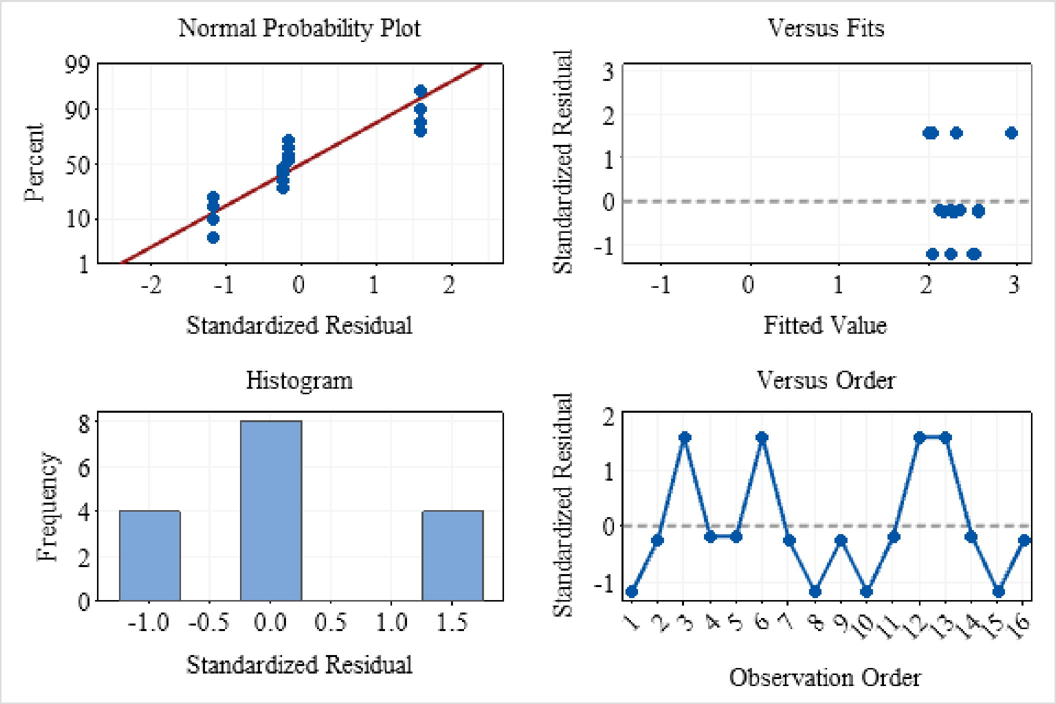

Figure 4. Residual plot for surface roughness (R_a).

3.3 Confirmation test

A confirmatory test was also performed on the optimal process parameters obtained by the Taguchi design of the experiment.The optimum process parameters were A1B4C1D4, i.e., first-level factor A (pulse on time), fourth-level factor B (pulse off time), first-level factor C (wire tension), and fourth-level factor D (wire feed).Therefore, the values for the optimal factor settings were pulse on time = 10 µs, pulse off time = 56 µs, wire tension = 7 kgf, and wire feed = 9 m/min.The response value at this optimal parameter settings was 1.97 µm, showing a small improvement from the initial design response value of 1.99 µm.The initial design response value was the value obtained from an experimental run performed using the Taguchi design[20]–[22].Its roughness profile is also shown in Figure 5, in which surface aberrations are visible.

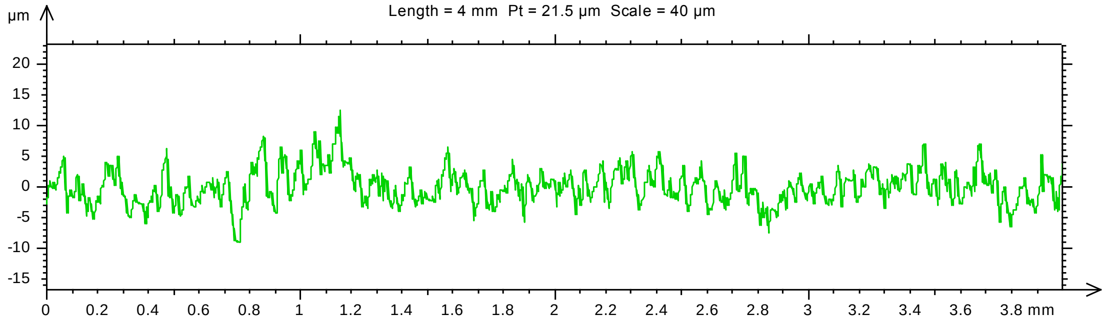

Figure 5. Surface roughness profile of optimal factor settings (A1B4C1D4).

4. Conclusions

The surface roughness of the titanium alloy machined by wire EDM was reduced by Taguchi'srobust design.The experiments were designed by selecting four factors namely pulse on time, pulse off time, wire tension, and wire feed.In various combinations of these factor settings, the surface roughness was captured.And the purpose of this work was to reduce the average roughness (R_a) of the machined surface.Based on signal-to-noise (S/N) ratio analysis, an optimal factor setting was obtained at which the roughness was a minimum of 1.97 µm.Of all the factors, pulse on time (Ton) was statistically the most important factor in producing a smooth surface.The two factors pulse on time (Ton) and pulse off time (Toff) had P-values less than 0.05 at a 95% confidence level.Coefficient of determination (R^2) values near 1 showed good fitting of the data to the present model.Some voids and cracks were observed from the microstructure, and grains at the edges were slightly deformed.

Conflict of Interest

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

Acknowledgment

The first author acknowledges the All India Council for Technical Education (AICTE) for awarding Ph.D. fellowships through the AICTE Doctoral Fellowship (ADF) scheme.The authors are also grateful to the Metrology Laboratory, Department of Mechanical Engineering, Jadavpur University for providing the testing facilities.

References

[1] N. Kumar, S. Kumari, K. Abhishek, G. Nandi, and N. Ghosh, “Study on various parameters of WEDM using different optimization techniques: A review,” *Mater Today Proc*, vol. 62, pp. 4018–4024, Jan. 2022, doi: 10.1016/j.matpr.2022.04.596.

[2] V. Kumar, B. B. Mandal, and B. Oraon, “Statistical analysis of activator and poly-alloy electroless coating on plain carbon steel by Full Factorial Design,” *NeuroQuantology*, vol. 20, no. 10, pp. 9396–9405, Aug. 2022, doi: 10.14704/nq.2022.20.10.NQ55917.

[3] A. G. Karthikeyan, V. P. Pradeep, and M. Maruthapandian, (2020). “Optimization of Multiple Input Process Parameters of WEDM on Titanium Ti 6Al-4v (Grade 5) By Taguchi Analysis,” *International Research Journal on Advanced Science Hub*, 2(6), pp. 1-10. doi: 10.47392/irjash.2020.29.

[4] F. Nourbakhsh, K. P. Rajurkar, A. P. Malshe, and J. Cao, “Wire electro-discharge machining of titanium alloy,” in *Procedia CIRP*, 2013, vol. 5, pp. 13–18. doi: 10.1016/j.procir.2013.01.003.

[5] P. Sai Kumar, M. S. R. Niranjan Kumar, and P. Gopala Krishnaiah, “Optimization of process parameters of wire cut electrical discharge machining on titanium grade-5 material using design of experiments,” *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 11, pp. 3937–3946, Sep. 2019, doi: 10.35940/ijitee.K1937.0981119.

[6] M. Namb and D. Paulo, “Influence of Coolant in Machinability of Titanium Alloy (Ti-6Al-4V),” *J Surf Eng Mater Adv Technol*, vol. 01, no. 01, pp. 9–14, 2011, doi: 10.4236/jsemat.2011.11002.

[7] G.T.Suriyaprabakaran, M.Kavin, R.Govindaraj, "Analyzing The Effect of Machining Parameters For Titanium (Grade 5) Alloy," *SSRG International Journal of Material Science and Engineering*, vol. 6, no. 2, pp. 9-22, 2020. *Crossref,* doi: 10.14445/23948884/IJMSE-V6I2P102.

[8] Madyira, D.M. and Akinlabi, E.T., 2014. Effects of wire electrical discharge machining on fracture toughness of grade 5 titanium alloy. In *World Congress on Engineering* (Vol. 2).

[9] M.M. Rahman, “Modeling of machining parameters of Ti-6Al-4V for electric discharge machining: A neural network approach,” *Scientific Research and Essays*, vol. 7, no. 8, Feb. 2012, doi: 10.5897/sre10.1116.

[10] H. Akkuş and H. Yaka, “Optimization of Cutting Parameters in Turning of Titanium Alloy (Grade 5) by Analysing Surface Roughness, Tool Wear and Energy Consumption,” *Exp Tech*, vol. 46, no. 6, pp. 945–956, Oct. 2022, doi: 10.1007/s40799-021-00525-6.

[11] ABDULGADIR, M.M., AHMADI, A.E. and BOUHAWISH, W.Y., 2019. Machinability of Titanium Grade-5 Alloy (Ti-6Al-4V) During Turning Processes: A Review. *Int. Res. J. Eng. Technol.*, *6*.

[12] A. V. S. R. Prasad, Koona. Ramji, and G. L. Datta, “An Experimental Study of Wire EDM on Ti-6Al-4V Alloy,” *Procedia Materials Science*, vol. 5, pp. 2567–2576, 2014, doi: 10.1016/j.mspro.2014.07.517.

[13] Prasad, A.R., Ramji, K. and Kolli, M., 2019. An experimental investigation on machining parameters of titanium alloy using WEDM. *Materials Today: Proceedings*, *18*, pp.A12-A16.

[14] D. A. Raj and T. Senthilvelan, “Empirical Modelling and Optimization of Process Parameters of machining Titanium alloy by Wire-EDM using RSM,” in *Materials Today: Proceedings*, 2015, vol. 2, no. 4–5, pp. 1682–1690. doi: 10.1016/j.matpr.2015.07.096.

[15] D. Dwaipayan, N. Titas, and B. Asish, “Parametric study for wire cut electrical discharge machining of sintered titanium,” *StrojnickyCasopis*, vol. 69, no. 1, pp. 17–38, 2019, doi: 10.2478/scjme-2019-0002.

[16] Sivaprakasam P, Hariharan P, Gowri S. Analysis of Machining Parameters of μ-WEDM on Titanium Alloy. International Journal of Applied Engineering Research. 2014;9(26):8893-6.

[17] Krishnaiah, K. and Shahabudeen, P., 2012. *Applied design of experiments and Taguchi methods*. PHI Learning Pvt. Ltd.

[18] C. S. Rauta, G. Majumdar, and S. Sarkar, “Parametric Optimization of Microhardness of Electroless Ni-Zn-Cu-P Coating Using Taguchi Design and Artificial Neural Network,” *JOM*, Dec. 2022, doi: 10.1007/s11837-022-05489-5.

[19] P. Srinivasa Rao, K. Ramji, and B. Satyanarayana, “Effect of wire EDM conditions on generation of residual stresses in machining of aluminum 2014 T6 alloy,” *Alexandria Engineering Journal*, vol. 55, no. 2, pp. 1077–1084, Jun. 2016, doi: 10.1016/j.aej.2016.03.014.

[20] T. Chaudhary, A. N. Siddiquee, A. K. Chanda, M. H. Abidi, and A. Al-Ahmari, “Multi-response optimization for Nimonic alloy miniature gear fabrication using wire electrical discharge machining,” *Advances in Mechanical Engineering*, vol. 12, no. 10, 2020, doi: 10.1177/1687814020967580.

[21] K. Natarajan *et al.*, “Study on Optimization of WEDM Process Parameters on Stainless Steel,” *J Nanomater*, vol. 2022, 2022, doi: 10.1155/2022/6765721.

[22] A. Ikram, N. A. Mufti, M. Q. Saleem, and A. R. Khan, “Parametric optimization for surface roughness, kerf and MRR in wire electrical discharge machining (WEDM) using Taguchi design of experiment,” *Journal of Mechanical Science and Technology*, vol. 27, no. 7, pp. 2133–2141, Jul. 2013, doi: 10.1007/s12206-013-0526-8.