[1.]Dragan RODIĆ, [1.]Marin GOSTIMIROVIC, [1.]Milenko SEKULIC, [1.]Borislav SAVKOVIC, [1.]Andjelko ALEKSIC

OPTIMIZATION SURFACE ROUGHNESS IN POWDER MIXED ELECTRICAL DISCHARGE MACHINING OF TITANIUM ALLOY

[1.] Department of Production Engineering, Faculty of Technical Sciences, University of Novi Sad, 21000 Novi Sad, SERBIA

Abstract: To further improve the efficiency of electrical discharge machining of advanced materials, the possible technological improvement of the process is achieved by adding graphite powder to the dielectric. In this study, the Taguchi approach was applied to determine the effects of input parameters such as discharge current, pulse duration, duty cycle, and graphite powder concentration on surface roughness in machining titanium alloys. L9 orthogonal array, signal–to–noise ratio (S/N), and ANOVA were used to design and analyze the experiment. Discharge current was determined to be the factor that had the strongest influence on surface roughness. Based on ANOVA, pulse duration was the second influential parameter, followed by graphite powder and duty cycle. In addition, an optimum condition was found to improve surface roughness. A discharge current of 1.5 A, a pulse duration of 32 μs, a duty cycle of 30% and a powder concentration of 12 g/l resulted in minimum surface roughness.
Keywords: Taguchi, surface quality, graphite powder, ANOVA, PMEDM

INTRODUCTION

Due to the combination of excellent mechanical properties and outstanding biocompatibility, titanium alloys are often used as a material for the manufacture of complex components. This is precisely why titanium alloys are difficult to process using classical methods, especially from the point of view of tool wear. When it comes to the production of complex parts, it is necessary to analyze the use of electrical discharge machining. In EDM, no mechanical stresses are introduced into the workpiece during machining because there is no direct contact between the electrode and the workpiece.

However, when machining titanium alloys with aluminium impurities, the EDM process becomes unstable and inefficient. In order to establish process stability and improve EDM performance, various researchers have proposed adding powder to the dielectric. In this way, one of the innovative processes called powder–mixed electrical discharge machining (PMEDM) was created.

Electrically conductive powder added to the dielectric reduces the insulating properties and causes an increase in the gap distance between the tool and the workpiece. This increase means a more efficient circulation of the dielectric, i.e. a washout of the working space between the tool and the workpiece. In this way, EDM becomes more stable, which improves the machining performances such as higher machining productivity and lower surface roughness, and also leads to a lower wear rate of the tools. The powder particles change the properties of the discharge channel, which equalises the distribution of sparks among the powder particles and thus reduces the current density [1]. Due to this uniform distribution of the discharges, there is uniform erosion, i.e. flat craters on the workpiece, which leads to a reduction in surface roughness and thus to an increase in machining accuracy.

Various types of electrically conductive powder can be mixed with liquid dielectric, including: aluminum, graphite, silicon, copper, silicon carbide and others. For example, Wong used powders of different electrical conductivity, such as graphite, silicon, aluminum, crushed glass, silicon carbide, and molybdenum sulfate, and studied their influence on the roughness of the treated surface [2]. He concluded that the powders: graphite (grain size 40 μm) and silicon (grain size 45 μm) gave the best results of surface roughness. A significant reduction in the surface roughness was obtained, i.e. Ra = 0.62 μm with silicon powder, while Ra = 0.75 μm was obtained with graphite powder, i.e. a surface with high gloss (mirror effect), which is the opposite of classical EDM, where mostly dull surfaces are obtained. What types of powders can be used with liquid dielectric, what particle size, at what concentration, and what effect they have on the performance of the PMEDM process have been studied by a small number of researchers.

Therefore, the introduction of an additional parameter, for example, the concentration of powder in the dielectric in PMEDM, is a challenge for many researchers. The analysis of the change of the surface roughness depending on the input parameters in PMEDM with chromium powder was processed in the work [3]. The obtained results show that the discharge current and the concentration of the powder in the dielectric have the greatest influence on the surface roughness in machining carbon steel. By applying the response surface method, a model was created that allows the determination of optimal machining regimes, where the objective function was the minimum surface roughness. Interesting results of the research work on single–objective optimization of the PMEDM procedure are presented in the paper [4]. The aim of the research was to determine the optimal input parameters in PMEDM. Three types of tool steels were machined using three types of tools, first in a dielectric with aluminum mixture and then in a dielectric with graphite powder. In order to optimize the process, Taguchi method was applied according to the experimental plan L27. Based on the Taguchi method, different optimal machining input parameters were determined for the different steels, representing the complexity of the PMEDM system.

Determining the optimal processing parameters for PMEDM remains a topical problem, as evidenced by the numerous research papers on the subject. There is still no concrete answer to the question of which powder concentration gives the best processing performance. Therefore, the main objective of this research is to determine the optimal machining parameters using the Taguchi approach. A single–objective optimization was performed by adjusting input parameters such as discharge current, pulse duration, duty cycle, and graphite powder concentration to achieve minimum surface roughness when machining titanium alloys.

MATERIAL AND METHODS

In the present study, a titanium alloy ($TiAl_4V_6$) was chosen as the workpiece material. The experiments are carried out on an Agie Charmie SP1–U die–sinking EDM machine. A commercial graphite electrode TTK50 with a cross section of 10x10 mm was used as the tool. The pure graphite powder with a particle size of 19 µm (Asbury PM19) was chosen as an additive for the dielectric fluid. In addition, the surfactant Tween 20 $C_{58}H_{114}O_{26}$ is added. The role of the surfactant is to ensure a homogeneous mixture of powder and dielectric during PMEDM. In order to conduct the experiments, a tank with supporting elements for PMEDM was designed, figure 1.

Finally, four input parameters were selected for this study from the preliminary experiments and the available literature on PMEDM [5, 6]. The input parameters were discharge current (Ie), pulse duration (ti), duty cycle (τ), and graphite powder concentration (GR). The conditions for processing titanium alloy are shown in table 1.

The Taguchi plan is a method that allows reducing the number of experimental points by orthogonal arrangements and minimizing the effects outside the influential parameters. It was applied in this study with the aim of more accurately optimizing and analyzing the influence of the input parameters on the tool wear rate. The processing parameters and their values are listed in Table 2. An experimental design according to the Taguchi orthogonal array L9 (34) was established.

Figure 1. Setup of PMEDM.

Table 1. Machining conditions

Parameters of EDM	Label	Value	Units
Discharge current	I_e	1.5 ÷ 7.5	A
Pulse on time	t_i	24 ÷ 240	µs
Pulse off time	t_0	24 ÷ 240	µs
Open circuit voltage	U_0	100	V
Polarity	Pol	(–)	/
Duty factor	τ	30 ÷ 70	%

Table 2. Taguchi orthogonal array L9 (3^4) at PMEDM $TiAl_6V_4$

No.	Factor				Surface roughness	
	I_e (A)	t_i (µs)	τ (%)	GR g/l	Ra (µm)	S/N
1.	1.5	32	30	0	1.78	–5.01
2.	1.5	75	50	6	2.01	–6.06
3.	1.5	180	70	12	2.61	–8.33
4.	3.2	32	50	12	3.47	–10.81
5.	3.2	75	70	0	4.11	–12.27
6.	3.2	180	30	6	4.47	–13.01
7.	6.0	32	70	6	8.12	–18.19
8.	6.0	75	30	12	7.16	–17.09
9.	6.0	180	50	0	9.84	–19.86

RESULTS AND DISCUSSION

For single objective parameter optimization, the Taguchi method was used, where the output Ra was optimized based on the Taguchi orthogonal array L9 (3^4) for PMEDM titanium alloy. This method does not require the creation of a mathematical model and is an alternative approach to identifying optimal input parameters. The MiniTab 17 software tool was used for statistical data processing. Based on the measured Ra values, the S/N ratio was calculated for all 9 experiments. The values of the S/N ratio for Ra are calculated based on the Taguchi quality feature "Smaller is better", Table 2.

Table 3 shows the S/N ratios with each factor and the corresponding level for surface roughness. The factors with the largest difference in mean values (max–min) have the greatest influence on the output size. The table shows that discharge current has the greatest influence on Ra, followed by pulse duration, duty cycle and graphite powder concentration.

Table 3. Response table of S/N ratio for surface roughness

Factors	Levels			min–max	Rang
	1	2	3		
(A) Ie	–6.46	–12.03	–18.38	11.91	1
(B) ti	–11.33	–11.81	–13.73	2.39	2
(C) τ	–11.71	–12.24	–12.93	1.22	3
(D) GR	–12.38	–12.42	–12.07	0.34	4

The influence of individual input parameters on the output power of the processing process can be illustrated with the help of a reaction diagram showing the change of the S/N ratio at the moment of changing the level of the control parameter from 1 to 3. Accordingly, the influence of individual parameters on the output characteristics of the processing process is graphically expressed by an angle of the slope of the line connecting different levels of the parameters.

Looking at the slope of the lines, we can see that the steepest line applies to factor A, then B, then C, and finally D. This order corresponds to the calculated rank (Table 7–2). According to Figure 2, the highest S/N ratio indicates the optimal level of each factor. Therefore, based on the "smaller is better" criterion, the optimum combination of the PMEDM titanium alloy input parameters as a function of surface roughness is A=1, B=1, C=1 and D=3.

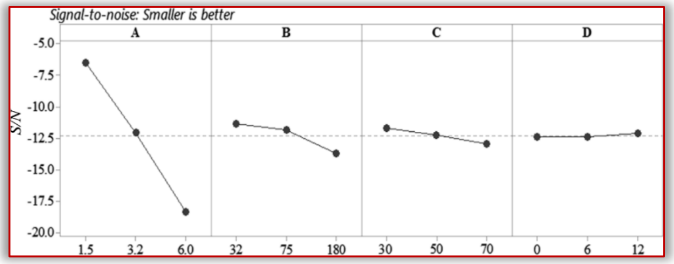

Figure 2. Graphic representation of the S/N ratio for Ra

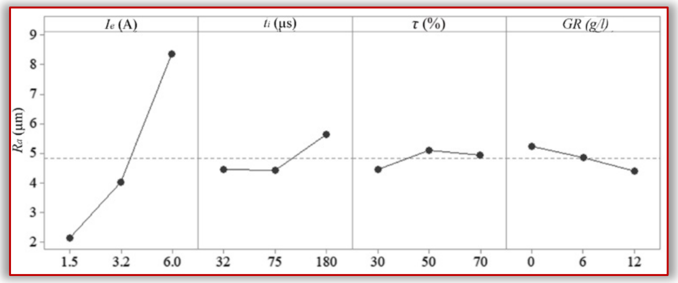

Figure 3. Response ANOVA graph for the Ra

The prediction of the output power value (Ra = 1.72 μm) and the calculation of the corresponding S/N ratio (S/N = –19.42) based on the optimal combination of input parameters can be found in Table 4.

Based on the ANOVA analysis performed using the F–test, the influence, i.e., the percentage involvement of each factor in PMEDM titanium alloy on surface roughness can be seen. Factors with an F–value of less than 1 were excluded from the analysis, which was the case for the impulse action coefficient (factor C) and the concentration of graphite powder (factor D). After excluding insignificant factors, the analysis ANOVA for the remaining members is shown in the reduced Table 5, where the percentage participation for factors A and B is given. Discharge current has the greatest influence on the mean arithmetic roughness of the treated surface, with a percentage of 93.08%. The percentage of 4.35% is taken by the pulse length for the set processing conditions. The presented ANOVA analysis confirms the results obtained with the Taguchi method.

Table 4. Optimal setting of input parameters with confirmation experiment

Input	Level	Value	Ra	Confirmation experiment
I_e (A)	1	1.5	S/N = –4.71	Ra=1.62 μm
t_i (μs)	1	32		
τ (%)	1	30	Ra = 1.72 μm	
GR (g/l)	3	12		

The average error between the EDM output values obtained by prediction based on Taguchi analysis and the values obtained after the verification experiments (with optimal input parameter values) was only 5.8%. Therefore, the single–objective optimization of the input parameters of the PMEDM can be considered successful. This analysis confirmed the order of influence of input parameters during processing compared to published research on PMEDM titanium alloys.

Table 5. Reduced ANOVA table for Ra

Source	DF	Sum sq	Mean sq	F–value	Percent %
A – I_e	2	61.465	30.7325	72.55	93.08
B – t_i	2	2.873	1.4367	3.39	4.35
D – GR	4	1.694	0.4236		2.57
Error	8	66.033			
Total	2	61.465	30.7325	72.55	93.08

In addition to discharge current, which had the greatest influence on Ra as expected, pulse duration, duty cycle, and graphite powder concentration had less influence than expected. This can be explained by the results of the preliminary tests. The explanation for excluding duty cycle from the analysis of ANOVA is justified by the fact that this parameter does not have a significant effect on surface roughness at relatively short pulse durations, up to 180 μs in this study. A significant effect of the pulse action coefficient is expected for values of pulse length greater than 200 μs, since a higher discharge energy occurs. A higher discharge energy has a detrimental effect on the surface roughness of titanium alloy if the pause duration is too short (calculated in τ > 90%), which has been confirmed in research [7].

CONCLUSION

The aim of this study is to optimize Ra using the Taguchi approach and to determine the influence of the main input factors. Based on the experimental and statistical results, the discharge current (Ie), pulse duration (ti), duty cycle (τ) and graphite powder concentration (GR) were the main factors that affected the Ra. According to the Taguchi method, the discharge current has the greatest influence on Ra, followed by the pulse duration, duty cycle, and graphite powder concentration. This statement was confirmed by the ANOVA analysis using the F–test. The influence, i.e. percentage participation of each factor in PMEDM titanium alloy on surface roughness for discharge current is 93.08%. The percentage of 4.35% is taken by the pulse duration for the specified machining conditions. Based on the "smaller is better" criterion, the optimal combination of PMEDM input parameters for the titanium alloy as a function of surface roughness is A=1, B=1, C=1, and D=3. The prediction of the output power gave a value of Ra = 1.72 μm, while the confirming experiment gave a value of 1.66 μm. Therefore, the single–objective optimization of the input parameters of the PMEDM can be considered successful. Although the analysis of ANOVA showed that graphite powder has no influence, the minimum Ra value is achieved with a concentration of 12 g/l. Future research should focus on wider intervals of input factors as well as on different powder types.

Acknowledgement

This paper has been supported by the Provincial Secretariat for Higher Education and Scientific Research through the project no. 142–451–1772/2022–01/01: "Research on the innovative process of electrical discharge machining of titanium alloy".

Note: This paper was presented at DEMI 2023 – 16th International Conference on Accomplishments in Mechanical and Industrial Engineering, organized by Faculty of Mechanical Engineering, University of Banja Luka (BOSNIA & HERZEGOVINA), co–organized with the Faculty of Mechanical Engineering University of Niš (SERBIA), Faculty of Mechanical Engineering University of Podgorica (MONTENEGRO), Faculty of Engineering Hunedoara, University Politehnica Timişoara (ROMANIA) and Reykjavik University (ICELAND), in Banja Luka (BOSNIA & HERZEGOVINA), in 01–02 June, 2023

References

[1] Ramana, P., Kharub M., Singh J.,Singh J. (2021). On material removal and tool wear rate in powder contained electric discharge machining of die steels. Materials Today: Proceedings, Vol. 38, pp. 2411–2416.
[2] Wong, Y.S., Lim L.C., Rahuman I.,Tee W.M. (1998). Near–mirror–finish phenomenon in EDM using powder–mixed dielectric. Journal of Materials Processing Technology, Vol. 79, pp. 30–40.
[3] Ojha, K., Garg R.K.,Singh K.K. (2013). Effect of chromium powder suspended dielectric on surface roughness in PMEDM process. Tribology – Materials, Surfaces & Interfaces, Vol. 5, pp. 165–171.
[4] Bhattacharya, A., Batish A., Singh G.,Singla V.K. (2011). Optimal parameter settings for rough and finish machining of die steels in powder–mixed EDM. The International Journal of Advanced Manufacturing Technology, Vol. 61, pp. 537–548.
[5] Hasçalık, A.,Çaydaş U. (2007). Electrical discharge machining of titanium alloy (Ti–6Al–4V). Applied surface science, Vol. 253, pp. 9007–9016.
[6] Huu–Phan, N., Tien–Long B., Quang–Dung L., Duc–Toan N.,Muthuramalingam T. (2019). Multi–criteria decision making using preferential selection index in titanium based die–sinking PMEDM. Journal of the Korean Society for Precision Engineering, Vol. 36, pp. 793–802.
[7] Kumar, M., Datta S.,Kumar R. (2018). Electro–discharge Machining Performance of Ti–6Al–4V Alloy: Studies on Parametric Effect and Phenomenon of Electrode Wear. Arabian Journal for Science and Engineering, pp. 1–16.

ISSN: 2067-3809