Indian Journal of Science and Technology, *Vol 10(22), DOI: 10.17485/ijst/2017/v10i22/113355, June 2017*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Parameters Optimized Specifying for EDM with PM/ Conventional Electrodes on M2 Tool Steel using Taguchi and TOPSIS

Dinesh Kumar[1]*, Hoshiar S. Payal[2] and Naveen Beri[3]

[1]Department of RIC, I. K. Gujral Punjab Technical University, Kapurthala - 144603, Punjab, India; dinesh123badhan@gmail.com
[2]Department of Mechanical Engineering, St. Soldier Institute of Engineering and Technology, Jalandhar - 144622, Punjab, India; payal_hs@yahoo.com
[3]Department of Mechanical Engineering, Beant College of Engineering and Technology, Gurdaspur - 143521, Punjab, India; nav_beri74@yahoo.co.in

Abstract

Objectives: The scope of this experimental work of electrical discharge machining (EDM) process with and without the addition of abrasive powder while executed on M2 tool steel for the advancement in surrounding safety factors to meliorate the surface quality. **Methods/Statistical Analysis:** Taguchi's L36 mixed orthogonal array is used after identification of most appropriate six input parameters (polarity, electrode type, concentration of abrasive, discharge current, and gap voltage and duty cycle) for maximum MRR and minimum TWR, and SR. **Findings:** To recognize the significant factors ANOVA is used and TOPSIS determine the 10.47% overall improvement in all responses with the optimal level of process parameters after confirmatory test. Energy dispersive X-ray (EDS) and Scanning electron microscope (SEM) analysis applied to examine the surface quality. **Application/Improvements:** This study finds the downfall of titanium from powder metallurgy tool electrode (CuTi) and deposition of aluminium material from PMEDM may also be implemented to improve the method of computation and precision.

Keywords: ANOVA, EDM, EDS, M2 Tool Steel, SEM, TOPSIS

1. Introduction

With the development of technologically advanced industries, the scientists and technologists in the field of manufacturing are facing more challenges because of demanding high strength temperature resistant materials. Researchers know a day's moves towards improvements in cutting tool materials so that productivity is not hampered. In this study M2 tool steel is used as a work-piece machining with electric discharge machining (EDM) process. EDM is also used for making micro holes on AISI 304 stainless steel for multi-objective optimization through RSM[1].The practical application of modeling and multi-optimization on WEDM with gaseous medium is vast[2].The range of material removal during μ-EDM is varies from 1–500 μm through melting and evaporation. The erosion occurs between the two electrodes by a series of discrete sparks with zero machining forces[3]. The addition of abrasive in dielectric Al-Mg2Si gives better results in the aerospace and automotive industries[4]. The WEDM process with multi-response optimization for optimal input parameters setting of pure titanium were analyzed through RSM, EDX, SEM and XRD by using brass electrode for MRR and overcut[5]. Dry EDM process is used for drill holes in AISI D2 steel followed Taguchi's and grey relation analysis for optimal level to analyse surface morphology and microstructure[6]. Micro-WEDM on titanium alloy (Ti-6AL-4V) with fuzzy logic strategy

**Author for correspondence*

and to developed Particle Swarm Optimization (PSO) algorithm for identifying the significant factors with optimum parameters setting[7]. EDM of various die steels with titanium as abrasive powder to identify the best parameters that influenced the MRR was performed by using Taguchi and ANOVA. A powder concentration increased the MRR by 42.1 %, as compared with no-powder during machining[8]. The micro-EDM process on AISI 304 steel optimized by using TOPSIS indicates the improvement in overall performance[9] and pure (Cp) titanium by Taguchi method-based grey relational analysis for MRR, TWR and OC[10]. A multi-objective particle swarm algorithm (MOPSO) analysis provides selective information for controlling the overall parameters during machining of EDM to improve the accuracy of the components[11]. The Entropy-GRA technique is used to solve the problems generated through toxic materials during EDM and more precise results it compared with the Fuzzy-TOPSIS and Taguchi-VIKOR methodology[12]. The prototype experimental study on Si3N4-TiN with conventional Copper tool electrode by EDM with various input and output parameters individual influence were investigated by ANOVA based on Grey relational analysis. W-EDM of tungsten tool with four inputs and three outputs SR, WLT and SCD were taken for central composite design (CCD) processing according to (RSM) to increase the surface integrity and to verify the efficiency of the optimization methods for implementation in industrial application[13,14]. The main aim of the current research is to find out the best optimal parameters through multi-objective optimization using TOPSIS for maximum MRR and minimum TWR and SR by using aluminium powder mixed to the dielectric fluid with different tool electrodes and ANOVA generated by Minitab 17 statistical software was used for the overall improvements. The deposition of abrasive powder material and powder metallurgy tool electrodes material during powder mixed EDM has been carried out through micro-structural SEM analysis.

2. Materials and Methods

The experiments were conducted on Electronica (S50) ZNC EDM with straight and reverse polarity. Standard EDM oil was used as dielectric fluid with storage tank capacity of 400 litres for the circulation during machining when abrasive in not mixed. For the machining with abrasive powder mixed EDM a detachable tank was designed to avoid the wastage and best use of abrasive powder, a pump and stirring arrangement is used for proper mixing throughout the experimentations. The detailed study during electric discharge machining of M2 tool steel having hardness 64 HRC has been carried out to find the six machining parameters with their designation (polarity-A, electrode type-B, concentration of Al abrasive-C, current-D, voltage-E and duty cycle-F) affect MRR, TWR and surface roughness. Taguchi's design of experiments (DOE) technique with L36 mixed orthogonal array has been carried out to conduct the experiments to determine the impact of process variables on the without powder and powder mixed EDM performance. The six parameters with 2 levels of polarity and 3 levels for other parameters having 2x3x3x3x3x3=486 runs were required in the experiments but by using Taguchi's DOE the number of experiments reduced to 36 experiments shown in Table 1. M2 Tool Steel selected as a Workpiece material is widely used in cutting tools industries. The composition by elements weight percentage of C (0.78-1.05), Mn (0.15-0.40), Si (0.20-0.45), Cr (3.75-4.50), Ni (0.3), Mo (4.50-5.50), W (5.50-6.75), V (1.75-2.20), P (0.03), S (0.03) and rest of being iron. Aluminium as a abrasive powder was mixed to the dielectric fluid with (0/3/6 gms per litre) concentrations and the micro structural analysis can be done after machining of selected samples was carried out using EDS and SEM with different magnifications. MRR is calculated by dividing the weight difference before and after each machining operation of the work piece material by the time duration of one complete experiment.

$$\mathbf{MRR}\left(\frac{\mathrm{mm}^3}{\mathrm{min}}\right)=\frac{\text{workpiecewt. beforemachining} - \text{workpiecewt. aftermachining}}{\text{machiningtime}} \tag{1}$$

TWR is calculated by dividing the difference of weight of electrode before and after each experiment to the time elapsed during machining.

$$\mathbf{TWR}\left(\frac{\mathrm{mm}^3}{\mathrm{min}}\right)=\frac{\text{electrodewt. beforemachining} - \text{electrodewt. aftermachining}}{\text{machiningtime}} \tag{2}$$

After completion of each experiment, the Workpiece material and tool electrode was properly cleaned to ensure that no debris and dielectrics were present. A CY-220 Precision Balance was used to measure the weight of the Workpiece and tool electrode. The surface roughness of each experiment may be calculated by using eq. 3. It can be represented by Ra.

$$\mathbf{R_a}=\frac{1}{l}\int_0^l \left|\mathbf{H(x)dx}\right| \tag{3}$$

Where, H(x): value of roughness profile and l: evaluation length

A Mitutoyo-Surftest SJ-400 used for measurements of surface roughness. Three values of Ra were taken at different angles for each machined surface to find the average value of Ra.

Powder Metallurgy Electrode:

CuTi1(90%:10%by weight) & CuTi2 (80%:20% by weight)

1. Preparation of metal powder (a) Mechanical pulverization (b) Atomization (c) Reduction of metal oxide (d) Electric deposition
2. Mixing or blending of powder
3. Compacting the powder
4. Sintering

3. TOPSIS Technique

The two artificial alternatives are supposed in this technique:

Ideal alternative: The most beneficial level for all attributes considered. Negative ideal alternative: the worst attribute values may be considered. This technique chooses the alternative that is the nearest to the ideal solution and utmost from negative ideal alternative. The technique assumes m alternatives and n criteria's and we have the score of each option with respect to each criterion. Let X = xij (m×n matrix). Let J be the set of benefit attributes or criteria "higher is better". Let J' be the set of negative criteria that "less is better".

3.1 Procedure for TOPSIS

Construct normalized decision matrix which transforms various attribute dimensions into non- dimensional attributes and allows comparisons across criteria. Normalize data is given as follows.

$$r_{ij} = \frac{x_{ij}}{(\Sigma(x^2_{ij}))} \text{ for } i=1,\ldots,m;\ j=1,\ldots,n \tag{4}$$

Construct the weighted normalized decision matrix. Assume we have a set of weights for each criteria, wj for j=1,…., n. Multiply each column of the normalized decision matrix by its associated weight. An element of the new matrix is given by equation (5)

$$v_{ij} = w_j r_{ij} \tag{5}$$

Equation for Ideal solution calculation is

Table 1. Design of Experiments

Expt. No.	A	B	C	D	E	F	Expt. No.	A	B	C	D	E	F
1	-ve	Cu	0	4	40	0.7	19	+ve	Cu	3	4	60	0.9
2	-ve	CuTi1	3	7	50	0.8	20	+ve	CuTi1	6	7	40	0.7
3	-ve	CuTi2	6	10	60	0.9	21	+ve	CuTi2	0	10	50	0.8
4	-ve	Cu	0	4	40	0.8	22	+ve	Cu	3	7	60	0.9
5	-ve	CuTi1	3	7	50	0.9	23	+ve	CuTi1	6	10	40	0.7
6	-ve	CuTi2	6	10	60	0.7	24	+ve	CuTi2	0	4	50	0.8
7	-ve	Cu	0	7	60	0.7	25	+ve	Cu	6	7	40	0.8
8	-ve	CuTi1	3	10	40	0.8	26	+ve	CuTi1	0	10	50	0.9
9	-ve	CuTi2	6	4	50	0.9	27	+ve	CuTi2	3	4	60	0.7
10	-ve	Cu	0	10	50	0.7	28	+ve	Cu	6	7	50	0.8
11	-ve	CuTi1	3	4	60	0.8	29	+ve	CuTi1	0	10	60	0.9
12	-ve	CuTi2	6	7	40	0.9	30	+ve	CuTi2	3	4	40	0.7
13	-ve	Cu	3	10	40	0.9	31	+ve	Cu	6	10	60	0.8
14	-ve	CuTi1	6	4	50	0.7	32	+ve	CuTi1	0	4	40	0.9
15	-ve	CuTi2	0	7	60	0.8	33	+ve	CuTi2	3	7	50	0.7
16	-ve	Cu	3	10	50	0.7	34	+ve	Cu	6	4	50	0.9
17	-ve	CuTi1	6	4	60	0.8	35	+ve	CuTi1	0	7	60	0.7
18	-ve	CuTi2	0	7	40	0.9	36	+ve	CuTi2	3	10	40	0.8

$A^* = \{v_1^*, \ldots \ldots, v_n^*\}$, where $v_j^* = \{\max(v_{ij})$ if $j \in J$; $\min(v_{ij}$ if $j \in J'\}$

Equation for Negative Ideal solution calculation is

$A' = \{v_1', \ldots \ldots, v_n'\}$, where $v' = \{\min(v_{ij})$ if $j \in J$; $\max(v_{ij})$ if $j \in J'\}$

Calculate the separation measures for each alternative. The separation from ideal alternative is:

$$S_i^* = \left[\sum_j \left((v_j^* - v_{ij})\right)^2\right]^{\frac{1}{2}} \quad \text{for } i = 1, \ldots\ldots, m \qquad (6)$$

Similarly, the separation from the negative ideal alternative is:

$$S'_i = \left[\sum_j \left((v'_j - v_{ij})\right)\right]^{\frac{1}{2}} \quad \text{for } i = 1, \ldots\ldots, m \qquad (7)$$

Calculate the relative closeness to the ideal solution Ci*

$$C_i^* = \frac{S'_i}{(S_i^* + S'_i)}, \quad 0 < Ci^* < 1 \qquad (8)$$

The best alternative selected was highly close to the ideal solution on the basis of higher rank of the Ci* in Table 2.

4. Results and Discussion

The machining efficiency is directly related to greater material removal rate with lower tool wear rate and the surface roughness produced during machining without the creation of crater, dispersion of recast layer on the work piece surface. The main aim for the tool wear rate and surface roughness is to minimize it so the criteria selected using the Minitab 17 statistical software is "Smaller is better" and for MRR "Higher is better". As per main effect plot for means in MRR, the material removal rate increases continuously when aluminium abrasive powder is added with maximum current and voltage in average duty cycle values for copper electrode tool using straight polarity. From the plots it is observed that the levels of the parameter are the best levels for maximum material removal rate (A2B1C3D3E3F2) shown in Figure 1. The main effect plot for means-TWR as per Figure 2 the best tool wear rate produced when aluminium abrasive

Table 2. Results of responses and Ci* -Ideal Solution with Rank

Expt. No.	MRR	TWR	SR	Ci*	Rank	Expt. No.	MRR	TWR	SR	Ci*	Rank
1	0.000132	0.000022	0.15	0.428798	34	19	0.001227	0.000068	0.11	0.4596	29
2	0.000943	0.000013	1.71	0.475799	24	20	0.004117	0.000017	0.59	0.4799	21
3	0.001333	0.000615	0.55	0.48572	17	21	0.006	0.000065	1.24	0.4917	11
4	0.00002	0.000009	0.51	0.428139	36	22	0.007083	0.001	1.36	0.4920	10
5	0.001077	0.000215	0.6	0.475881	23	23	0.003773	0.000205	1.91	0.4938	9
6	0.000971	0.000157	2.16	0.486652	14	24	0.000455	0.001	0.27	0.4865	16
7	0.000176	0.000033	0.16	0.43602	33	25	0.010556	0.001667	1.19	0.5176	3
8	0.001	0.000383	2.96	0.502862	4	26	0.003795	0.000564	1.59	0.4971	7
9	0.000767	0.000533	0.78	0.483594	18	27	0.002244	0.000044	0.09	0.4645	28
10	0.000582	0.000036	0.11	0.445984	32	28	0.007647	0	0.11	0.4821	19
11	0.0007	0.000146	0.79	0.465429	27	29	0.003667	0.000697	1.7	0.4992	5
12	0.000717	0.000633	2.66	0.499227	6	30	0.003	0.000478	0.66	0.4889	13
13	0.000899	0.00003	0.92	0.468976	26	31	0.016167	0.001	0.94	0.5284	2
14	0.00036	0.00006	1.75	0.474993	25	32	0.00091	0.000449	2.56	0.4958	8
15	0.000549	0.00022	2.21	0.486606	15	33	0.001105	0.000447	0.51	0.4811	20
16	0.00006	0.000007	0.35	0.428649	35	34	0.004545	0.000091	0.15	0.4797	22
17	0.000516	0.000156	0.06	0.451706	31	35	0.001167	0.000071	0.08	0.4573	30
18	0.000695	0.000419	2.13	0.4908	12	36	0.004833	0.00131	0.75	0.5295	1

powder is added with maximum current and minimum voltage with average duty cycle values for powder metallurgy (CuTi2) electrode tool on straight polarity. The best levels for TWR are (A2B3C3D3E1F2). When electrical power increased in machining the discharge channel supply more thermal energy for stable and uniform electric sparks to improve the machining rate and surface quality of M2 tool steel. The addition of aluminium abrasive powder is also showing its contribution towards improvements in MRR and TWR.

It is clear from Figure 3. main effects plots for means-SR that it is minimum when using CuTi1 powder metallurgy tool electrode with maximum value of concentration of the abrasive powder, current, duty cycle and minimum value of voltage. From the plot it is observed that the levels of the parameter are the best levels for minimum Ra and the factors are (A1B2C3D3E1F3).

From experiment results shown in Table 2., it is observed that more smooth surfaces produced during machining on M2 tool steel with powder metallurgy tool electrode (CuTi1) with composition 90%Cu and 10%Ti by weight as compare to surfaces machined by using conventional copper (99% Cu) tool electrode. It is initially decreases with the increase in gap voltage. But at higher gap voltage values, rougher surface produced. It is due to the availability of more energy per spark at higher gap voltage values. The addition of aluminium abrasive powder to the dielectric, the surface quality improves and the roughness values are reduced with little range continuously during machining. The range of all responses with use of electrode type is shown in Table 3.

Table 3. Highest and Lowest value of responses

Electrode type		MRR	TWR	SR
Cu Conventional Copper	Highest Value	0.016167	0.001667	1.36
	Lowest Value	0.00002	0	0.11
CuTi1 (by weight) Cu=10%, Ti=90%	Highest Value	0.004117	0.000697	2.96
	Lowest Value	0.00036	0.000013	0.06
CuTi2 (by weight) Cu=20%, Ti=80%	Highest Value	0.006	0.00131	2.66
	Lowest Value	0.000455	0.000044	0.09

Table 4. ANOVA for Ideal Solution Ci*

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Polarity	1	1.5450	1.5450	1.54502	20.13	0.000
Electrode Type	2	0.9012	0.9012	0.45059	5.87	0.008
Conc. of Abrasive Powder	2	0.8553	0.8553	0.42766	5.57	0.010
Current	2	0.8026	0.8026	0.40132	5.23	0.013
Voltage	2	0.2103	0.2103	0.10513	1.37	0.273
Duty Cycle	2	1.3522	1.3522	0.67609	8.81	0.001
Residual Error	24	1.8420	1.8420	0.07675		
Total	35	7.5086				

Table 5. Response Table for Ideal Solution Ci*

Level	Polarity	E-Type	COA-Powder	Current	Voltage	Duty Cycle
1	0.4675	0.4680	0.4703	0.4673	0.4851	0.4639
2	0.4901	0.4808	0.4759	0.4829	0.4753	0.4869
3		0.4876	0.4903	0.4863	0.4761	0.4857
Delta	0.0226	0.0196	0.0200	0.0190	0.0098	0.0230
Rank	2	4	3	5	6	1

TOPSIS

The optimization of machining without abrasive powder and with addition of abrasive powder the multiple attributes like MRR, TWR and SR was performed using "TOPSIS" and having equal role during machining on ideal condition. The results found after the experimentation combined with calculated relative closeness values to the ideal solution by highest rank order shown in Table 2 after calculation by using equations 4 to 8. The multi-attribute optimization is thus converted into single objective optimization by using a united approach of Taguchi's design and TOPSIS. The experiment no. 36 attains the maximum closeness to the ideal value and getting highest rank with optimal setting of levels is A2B3C2D3E1F2.ANOVA with 95% confidence interval used to determine the influence of the process variables on the performance characteristics as shown in Table 4, 'higher-the-better' prevision by use of MINITAB 17 statistical software. Table 5, _bookmark13response for Ideal Solution Ci*, shows that the parameters duty cycle, polarity, concentration of abrasive powder, electrode type and current having more significant contribution than voltage towards finding the ideal solution.

Table 6. Confirmation test with predicted result as per model

Output parameter	Actual	Predicted	Errors %
MRR (mm3/min.)	0.024369	0.025449	4.24
TWR (mm3/min.)	0.001099	0.001202	8.56
SR (μm)	2.19	2.28	3.94
TOPSIS			
Initial Level 0.424798	highest rank Ci* 0.529562	10.47% Improvement	

Main effects plot for Means-Ideal Sol. Ci* as per Figure 4, shows that powder metallurgy tool electrode with minimum titanium CuTi2 is best when parameters setting at maximum value of current and concentration of aluminium abrasive powder, average duty cycle and minimum applied voltage used during machining.It is observed from Table 6, the error is below 10% which is satisfactory for the research work. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) find the ideal value with highest rank Ci* (0.529562) and the value 0.424798 is produced when all parameters are at initial level and found 10.47% improvement.

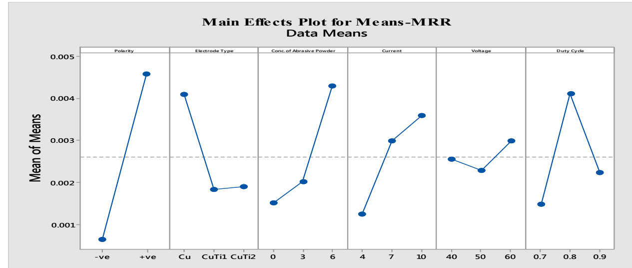

Figure 1. Main effects plot for Means-MRR.

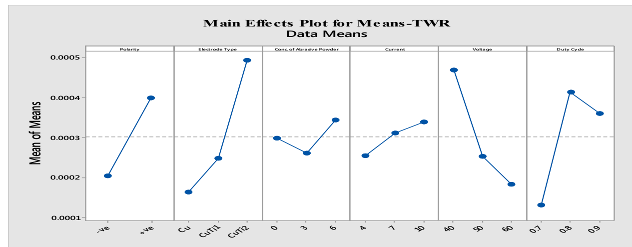

Figure 2. Main effects plot for Means-TWR.

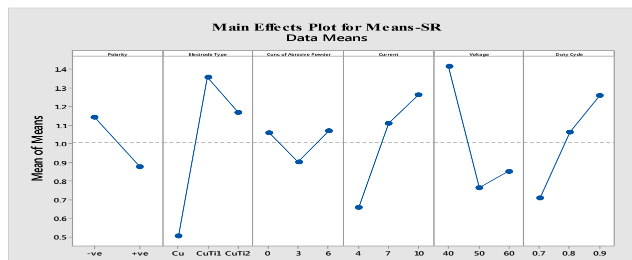

Figure 3. Main effects plot for Means-SR.

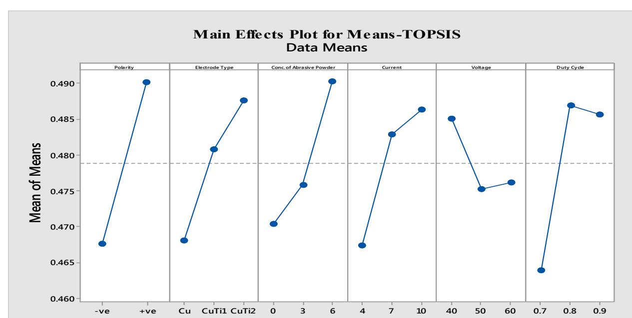

Figure 4. Main effects plot for Means-Ideal Sol. Ci*.

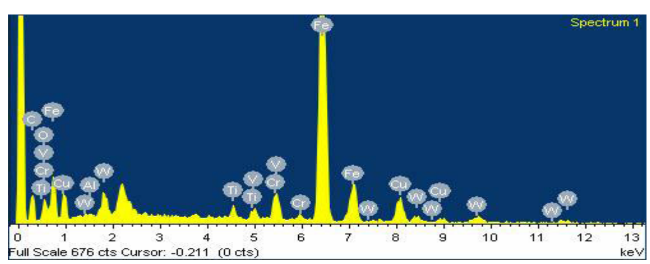

Figure 5. EDS-CuTi2 electrodes.

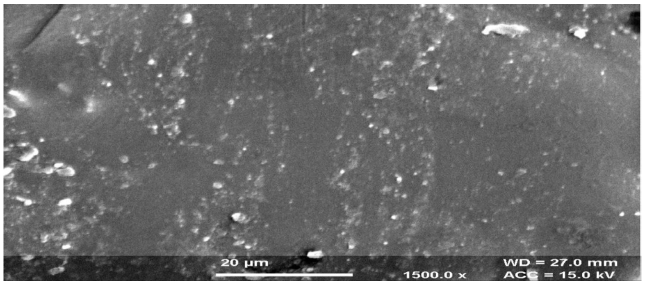

Figure 6. SEM-CuTi2 (80%:20% by weight) electrodes.

4.1 Microstructure analysis through EDS and SEM

As per Figure 5 and Figure 6, EDS and SEM analysis for best optimal parameters confirms that downfall of titanium from powder metallurgy tool electrode (CuTi) and deposition of aluminium material from powder mixed EDM shown between the scale 1-2 in Figure 5 and Figure 6 shows the melioration in surface quality significantly.

5. Conclusion

The research investigates with the objectives of improving the productiveness and surface quality by EDMing on M2 tool steel with and without the add-on aluminum abrasive powder to increasing the MRR and decreasing the TWR and SR by using Taguchi's Technique and TOPSIS, the multi-attribute optimization to find out the most significant process parameters. First of all it improves the surface quality by mixing the abrasive powder in standard dielectric fluid with powder metallurgy tool electrodes by reducing the defects creates during machining. The range of the responses for machined surface varies from 0.11μm to 1.36μm in standard dielectric fluid and with the addition of aluminum abrasive powder its range varies with 2.96 μm that is better for reducing surface roughness results. To find out the significance of machining parameters towards improvement ANOVA was used which decleared that voltage is insignificant. The satisfactory confirmatory test of TOPSIS find the most appropriate solution for input process parameters with most optimal set levels A2B3C2D3E1F2 shows 10% improvement with initial parameters set and with all responses improvement is varies within 10%.

The consequence of this research work contributes for better surface quality to the cutting tool industries by using PMEDM with powder metallurgy tool electrodes.

6. Acknowledgements

The authors would like to acknowledge the support of department of Mechanical Engineering, Beant College of Engineering and Technology, Gurdaspur, Punjab, India for providing the Machines required for the successful completion of this project and Panjab University and Thapar University for SEM, EDS analysis.

7. References

1. Sarikaya M, Yılmaz V. Optimization and predictive modeling using S/N, RSM, RA and ANNs for micro-electrical discharge drilling of AISI 304 stainless steel. Neural Computing and Application. 2016 Dec; 1–15. Crossref
2. Azhiri RB, Teimouri R. Application of Taguchi, ANFIS and grey relational analysis for studying, modeling and optimization of wire EDM process while using gaseous media. International Journal of Advance Manufacturing Technology. 2014; 71(1-4):279–95. Crossref
3. Chandrasekaran SKTNNM. Optimization of EDM process in machining micro holes for improvement of hole quality. Journal of the Brazilian Society of Mechanical Sciences and Engineering. Springer Berlin Heidelberg. 2016.
4. Hourmand M, Farahany S. Investigating the electrical discharge machining (EDM) parameter effects on Al-Mg 2 Si metal matrix composite (MMC) for high material removal rate (MRR) and less EWR–RSM approach. International Journal of Advance Manufacturing Technology. 2015; 77(5–8):831–8. Crossref
5. Kumar A, Kumar V, Kumar J. Semi-empirical model on MRR and overcut in WEDM process of pure titanium using multi-objective desirability approach. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2015; 37(2):689–721. Crossref
6. Kumar NPMP. Optimization of Dry EDM Process Parameters Using Grey Relational Analysis. Arabian Journal for Science and Engineering. 2016; 41(11):4383–90. Crossref
7. Kuriachen B, Somashekhar KP, Mathew J. Multiresponse optimization of micro-wire electrical discharge machining process. The International Journal of Advanced Manufacturing Technology. 2015; 76(1):91–104. Crossref
8. Long BT, Phan NH, Cuong N, Jatti VS. Optimization of PMEDM process parameter for maximizing material removal rate by Taguchi's method. International Journal of Advanced Manufacturing Technology. 2016; 87(5-8). Crossref
9. Manivannan R, Kumar MP. Multi-response optimization of Micro-EDM process parameters on AISI304 steel using TOPSIS. Journal of Mechanical Science and Technology. 2016; 30(1):137–44. Crossref

10. Meena VK, Azad MS, Singh S, Singh N. Micro-EDM multiple parameter optimization for Cp titanium. The International Journal of Advanced Manufacturing Technology. 2017; 89(1):897–904. Crossref
11. Mohanty CP, Sankar S. A particle swarm approach for multi-objective optimization of electrical discharge machining process. Journal of Intelligent Manufacturing. 2016; 27(6):1171–90. Crossref
12. Ray JA. Multi-Objective Optimization of Green EDM : An Integrated Theory. Journal of the Institution of Engineers (India): Series C. 2015; 96(1):41–7. Crossref
13. Si N, Selvarajan L, Manohar M, Udhaya A, Dhinakaran P. Modelling and experimental investigation of process parameters in parameters in EDM of Si3N4-TiN composites using GRA-RSM. Journal of Mechanical Science and Technology. 2017; 31(1):111–22. Crossref
14. Zhang Z, Ming W, Huang H, Chen Z, Xu Z, Huang Y. Optimization of process parameters on surface integrity in wire electrical discharge machining of tungsten tool YG15. The International Journal of Advanced Manufacturing Technology. 2015; 81(5):1303–17. Crossref