The International Journal of Advanced Manufacturing Technology (2021) 116:1429–1435
https://doi.org/10.1007/s00170-021-07032-3

ORIGINAL ARTICLE

Multi-object optimization of EDM by Taguchi-DEAR method using AlCrNi coated electrode

Nguyen Huu Phan [1] · Pham Van Dong [2] · Hoang Tien Dung [1] · Nguyen Van Thien [1] · T. Muthuramalingam [3] · Shailesh Shirguppikar [4] · Nguyen Chi Tam [1] · Nguyen Trong Ly [1]

Received: 29 December 2020 / Accepted: 29 March 2021 / Published online: 16 April 2021

Abstract

In electrical discharge machining (EDM), the productivity and machined surface quality is directly influenced by the properties of the electrode surface material layer used. In the present study, a research attempt was made to find the optimal technological parameters in EDM process with AlCrNi coated electrode using Taguchi-Data Envelopment Analysis based Ranking (DEAR) based multi-response optimization approach. From the experimental investigation, the optimal technological parameter combination in EDM using AlCrNi coated electrode was found as peak current (40 A), voltage (55 V), and pulse-on-time (1000 μs) on machining Ti-6Al-4V titanium alloy. The current was found as more principal factor in EDM process with coated tool due to the electrical conductance of the tool coating. The better surface topography with lower surface roughness and micro cracks can be obtained on the machined specimens with proposed parameter combination.

Keywords Titanium alloy · EDM · Coating · Surface · Optimization

1 Introduction

The invention of newer electrode materials with improved mechanical and chemical properties can enhance the productivity, quality of machined surface, and accuracy machining in EDM. The utilization of coated electrodes in EDM process is still very interesting research area to overcome the limitations of this machining method. The micro-hardness (HV) of the machined surface has been enhanced by 163% compared to the base material layer [1]. As compared with uncoated electrode, the microscopic cracks formed on the machining surface in EDM using Cu-MWCNT coated electrode could be significantly reduced. Compared with the EDM using uncoated electrode, the use of a 5 μm coating with silver on the Cu in EDM electrode surface resulted in a significant increase in MRR of 26.8%, a sharp drop of TWR by 25%, dimensional accuracy, and surface quality is significantly improved [2]. Using electrodes with different coating materials, it will give very different machining efficiency in EDM. Compared to the nickel coated electrode, the TWR in EDM using diamond-nickel coated electrode has been significantly improved [3]. And the diameter size accuracy in EDM using coated electrode is higher than it with uncoated electrode. TiN and TiAlN were used to coat the surface of Cu electrode in EDM [4]. Compared with the uncoated Cu electrode, the machining efficiency of the coated electrode is better, and the TiN coated electrode is better than the TiAlN coated electrode. And EDM using TiN coated electrode is suitable for finishing. Coating material has been found on the machined surface layer, which is capable of improving the surface layer after EDM using coated electrodes [5]. The use of coated electrodes has resulted in a drop in the cost of the electrode, and this will contribute to improving the economics of the EDM machining process [6]. Electrodes coated in EDM are a new technology solution, which requires further research in this area including optimization of technological parameters, the types of coating

✉ Nguyen Huu Phan
phanktcn@gmail.com; nguyenhuuphan@haui.edu.vn

1 Faculty of Mechanical Engineering, Hanoi University of Industry, Hanoi, Vietnam

2 Faculty of Information Technology, Hanoi University of Industry, Hanoi, Vietnam

3 Department of Mechatronics Engineering, SRM Institute of Science and Technology, SRM Nagar, Kattankulathur-603203, Kanchipuram, Chennai, TN, India

4 Department of Mechanical Engineering, K.E. Society's Rajarambapu Institute of Technology Rajaramnagar, Islampur, Sangli, Maharashtra 415414, India

materials used, coating thickness on electrode surface, etc. [7]. The material is used to coat the surface of the electrode; it alters the properties of mechanical and physical chemistry of the material layer of electrode surface. It can affect the process of spark formation in the discharge gap. It will affect the selection of technology parameters to enhance the machining process in EDM. Hence, it is essential to determine optimal technological factors for each new material coated on the electrode surface for improving machining efficiency in EDM.

Since the machining mechanism is affected by many noise factors in EDM process, it is essential to choose and derive the optimal factors Taguchi is a commonly used solution to design experimental matrix and solve the optimal problem in EDM [8]. Nevertheless, it is only appropriate for solving single-target problems. It is very complicated on solving multi-target decision problems. The result of the multi-target decision problem can bring better technical economic efficiency than single-objective problem [9]. There have been many published research results on combining Taguchi method with other techniques for multi-goal decision making in EDM [10, 11].

Taguchi-Utility has been used to determine multiple targets simultaneously in EDM for AA6061/10% Al2O3 AMMC [12]. The productivity and surface quality at optimal conditions have been significantly improved by optimization approaches. The material-removal-rate (MRR) and surface-roughness (R_a) for machining EN31 material have been optimized simultaneously by the BBO algorithm and PSO method using EDM process [13]. The results showed that machining cost owing to the BBO algorithm is smaller than PSO. Hence, multi-target optimization using the BBO algorithm was assumed as better one. The quality indicators (MRR, tool-wear-rate (TWR), and overcut (OC)) for 304 steel at the optimum condition were significantly improved [14]. The grey relational approach (GRA) was used to simultaneously decide goals, and the GRG coefficient was improved by approximately 10.9%. The quality properties of nickel super alloy (white layer thickness (WLT), SR, and cracks) in EDM have been significantly improved at the optimum conditions [15].

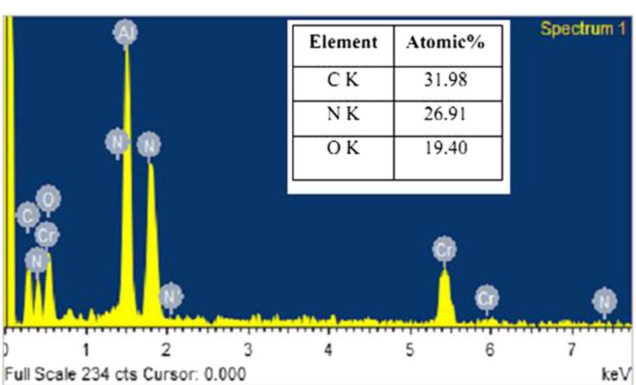

Fig. 1 EDX of aluminum chromium nickel thin film coating

Fig. 2 Thin film coating of aluminum chromium nickel

The weights of quality indicators are determined by PCA method in Taguchi-GRA method [16]. However, the weights of MRR, TWR, and OC were selected experimentally to enhance the scientific significance of the optimal result for obtaining lower recast layer thickness in EDM process [17]. The machining efficiency at the optimum conditions was improved by 44.23% under Taguchi–GRA, since it could significantly reduce the cost and time of the experimental process [18–21]. The optimum efficiency determined by the S/N analysis of GRG was increased by 24.3% in EDM process [22].

It is highly tedious in choosing the optimal and common decision-making method for machining engineering materials using EDM process in practice. The artificial neural network (ANN) was used for optimal technological parameters in EDM [23]. It was found that the accuracy of the optimal result in EDM by ANN method is higher than response surface methodology (RSM) owing the ability of producing lower prediction of 8% [24]. The RSM-Fuzzy-Topsis has been incorporated for obtaining maximum target optimization in EDM on machining titanium (Ti-6Al-4V) alloy to achieve lower TWR, taper angle (TA), and overcut with higher MRR as the quality indicators [25]. Although the productivity, machining accuracy, and surface quality at optimal conditions have been significantly improved, the number of experiments to experiment with RSM and ANN is high [26–28]. The number of experiments in the multi-target optimization study in EDM green using the Taguchi-Topsis combination technique has been significantly reduced [29]. However, the weight of 5 quality indicators (machining time, pulse energy, REWR, concentration, and dielectric consumption) was determined by the Fuzzy method efficiently [30]. The Topsis method was used to obtain better quality targets in the multi-target decision in EDM process with better surface quality and improved efficiency of 14.3% [31]. The adhesion particle size

Table 1 Input process parameters and their levels

Parameters	Symbol	Levels
Peak current (A)	I	10, 20, 30, 40
Gap voltage (V)	V_g	40, 45, 50, 55
Pulse-on-time (μs)	T_{on}	100, 500, 1000, 1500

was observed as uniform with lower number of adhesion particles and microscopic cracks [32]. Taguchi-Fuzzy is a technical solution for better target optimization problem in EDM [33]. However, the process of setting up the optimization problem by this method is very complicated. An effort was made to combine Taguchi with TGR for multi-purpose optimization for many non-traditional machining methods [34–38]. The optimal results were observed with good accuracy. This method for optimal problem is very simple with lower steps. Therefore, it can be applied in practice very easily. It can significantly contribute on reducing the experimentation cost and optimal problem solving time to improve productivity and lower product costs.

From the detailed literature survey, it was inferred that few research works were performed to apply optimization problems in coated electrode employed EDM. It was also observed that number of studies aimed on determining the optimal technology parameter in EDM for machining titanium alloy specimens using DEAR approach was very little. Hence, an attempt has been made to introduce Taguchi-DEAR based multi-target decision approach on machining titanium specimens with AlCrNi coated electrode in EDM process.

2 Experiments and methods

The experiments were performed on CNC type Electro Discharge Machine manufactured by Electronics India Private Limited. A die sinking ZNC type EDM was used for Ti-6Al-4V alloy. Two types of electrodes were used such as uncoated electrode and thin film AlCrNi coated aluminum electrode for machining purpose and comparative study were carried out to observed influence of AlCrNi coating on machining performance (Figs. 1 and 2). Thin film coating of AlCrNi on aluminum tool electrodes was performed at Oerlikon Balzers Coating India Pvt. Ltd., Pune by physical vapor deposition (PVD) process. Average diameter of uncoated aluminum tool electrode was 9.95 cm, and uniform layers of AlCrNi coating of 500 microns were achieved using PVD process. Coating thickness of AlCrNi was measured by surface rugosity meter available at Oerlikon Balzers Coating India Pvt. Ltd. The process variables were chosen based on low, medium, and high level of process parameter available at machine. All experiments were systematically planed with four level Taguchi method. The levels of process parameters in this study are described in Table 1. Since the work deals with three factors and four levels, orthogonal array (L_{16}) was selected in the present study.

The assessment of MRR and TWR was conducted on weight basis using high precision weight balance Contech available in Indian Chemical Technology (ICT), Mumbai. The surface roughness (R_a) of machined workpiece surface was measured by contact type surface roughness tester (Taylor Hobson machine, Surtronic S-100 Series Surface Roughness Tester) with the cutoff length of 0.8 mm. Assessment was performed on surface of workpiece machine (four directions; outside to inside). Each surface was assessed four times and then noted average value of surface roughness. Prob tip radius was 5 μm, and

Table 2 Results of the experiment in EDM

Exp. no.	Input factors			Response criteria		
	I	V_g	T_{on}	MRR (g/min)	TWR (g/min)	R_a (μm)
1.	10	40	100	0.004	0.0001	6.111
2.	10	45	500	0.0093	0.0002	6.162
3.	10	50	1000	0.0086	0.0002	6.251
4.	10	55	1500	0.0065	0.0003	6.294
5.	20	45	100	0.0053	0.0014	6.874
6.	20	40	500	0.0107	0.0022	6.976
7.	20	55	1000	0.0089	0.0011	7.648
8.	20	50	1500	0.0148	0.0022	7.669
9.	30	50	100	0.0077	0.0031	8.045
10.	30	55	500	0.0106	0.0041	8.338
11.	30	40	1000	0.0098	0.0037	8.768
12.	30	45	1500	0.0099	0.0046	8.946
13.	40	55	100	0.0133	0.0074	9.013
14.	40	50	500	0.0125	0.0081	9.112
15.	40	45	1000	0.0139	0.0089	9.313
16.	40	40	100	0.0121	0.0095	9.623

Table 3 Weights and MRPI

Trial	Weights			MRPI
	MRR	TWR	R_a	
1	0.025332	0.365015	0.078042	0.000212
2	0.058898	0.182507	0.077396	0.001148
3	0.054465	0.182507	0.076294	0.000982
4	0.041165	0.121672	0.075773	0.000561
5	0.033566	0.026072	0.06938	0.000373
6	0.067764	0.016592	0.068365	0.00152
7	0.056365	0.033183	0.062358	0.001052
8	0.09373	0.016592	0.062187	0.002908
9	0.048765	0.011775	0.059281	0.000787
10	0.067131	0.008903	0.057198	0.001492
11	0.062065	0.009865	0.054393	0.001275
12	0.062698	0.007935	0.05331	0.001301
13	0.084231	0.004933	0.052914	0.002349
14	0.079164	0.004506	0.052339	0.002075
15	0.08803	0.004101	0.05121	0.002566
16	0.076631	0.003842	0.04956	0.001944

Table 4 Calculation of optimal process parameters

Parameters	L1	L2	L3	L4	High–Min
I	0.00072599	0.00146337	0.00121397	0.00223328	0.00150729
V_g	0.00093038	0.00155884	0.00146865	0.00167875	0.00074837
T_{on}	0.00123801	0.00134709	0.0016881	0.001363387	0.00045009

sampling length was 2.5 mm. In the present study, MRR, TWR, and R_a have been selected as quality measures under DEAR Methodology mentioned as follows.

1. Determine the weights (w) for each response under designed parameters. Weight of response is the ration between response at any trial to the summation of responses
2. Transform the response date into weighted data
3. Divide the larger the better data with smaller the better data
4. Treat this value as multi-response performance index (MRPI) as per following Eqs. 1–7

$$\text{MRPI} = \frac{A}{B+C} \quad (1)$$

$$A = \text{MRR} \times W_{\text{MRR}} \quad (2)$$

$$B = R_a \times W_{R_a} \quad (3)$$

$$C = \text{TWR} \times W_{\text{TWR}} \quad (4)$$

$$\boldsymbol{W}_{\text{MRR}} = \frac{\text{MRR}}{\sum \text{MRR}} \quad (5)$$

$$W_{R_a} = \frac{1/R_a}{\sum 1/R_a} \quad (6)$$

$$W_{\text{TWR}} = \frac{1/\text{TWR}}{\sum 1/\text{TWR}} \quad (7)$$

3 Results and discussion

3.1 Optimal technological parameter combination

The experimental observations are described in Table 2. The values of the weight and MRPI for each experimental result were computed based proposed approach and tabulated as shown in Table 3, and MRPI of this problem is described in Table 4. The values were computed by including values of MRPI for corresponding level of each technological parameters.

Due to larger value of MRPI of each technological parameters indicates the value of the optimal technology parameter, I (Level 4), V_g (Level 4), and T_{on} (Level 3) can create better quality measures as shown in Table 4, and the combination is formed by the optimal combination of the process parameters in this optimization problem (Table 5).

3.2 Confirmation experiment

The experimental results at the optimal conditions show that the deviation of the MRPI of the quality indicators at the optimal conditions is 2.6% compared with the maximum mean value. This value is lower than the acceptable tolerance value which is 5% [25–28]. Hence, the prediction accuracy of the present approach was observed as acceptable limit.

3.3 Significant technological parameter in EDM process

The highest Max–Min value has shown that the more significant influence on the determination of the quality parameters in the machining processes. The current is more principal factor in EDM process with coated tool due to the electrical conductance of the tool coating. Since the electrical conductivity of spark column produces across the machining zone in EDM, the conductivity of the tool coating can modify the crater size and discharge energy. Due to its optimal energy, MRR and surface quality have been significantly improved in AlCrNi coated tool electrode employed EDM.

3.4 Analysis of machined surface under optimal process parameter combination

The SEM analysis of surface of Ti-6Al-4V workpiece after EDM is observed at Fig. 3. The roughness profile

Table 5 Optimal process parameter combination

Factors	Parameter values
I	40 A
V_g	55 V
T_{on}	1000 µs

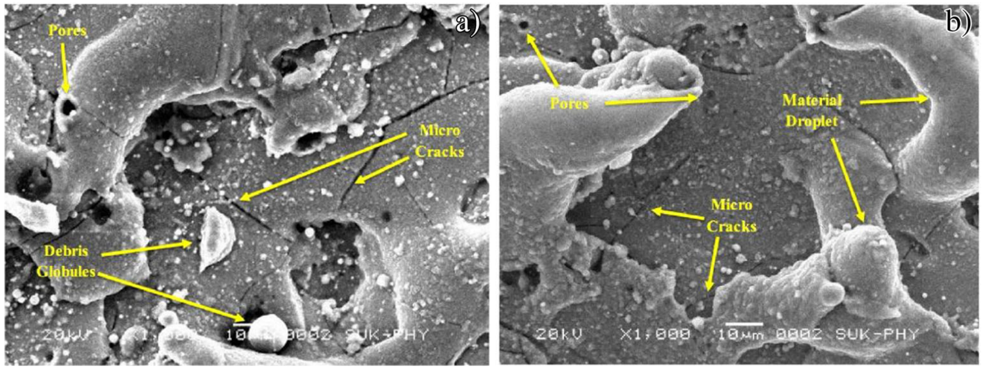

Fig. 3 Machined surface topography with AlCrNi coated electrode

obtained is directly dependent on amount of material to be removed. This could be controlled by the spark plasma column. This plasma is characterized by the discharge current flow. The current is modified by coating owing to the electrical conductivity of the tool coating. The craters, globules of debris, micro-cracks, etc. are covered on the machined surface. The lower machining power and craters with a small depth and diameter are formed. The increase in the size and length of the micro-crack is influenced by enhancing pulse energy. This is caused by an increase in heat transferred to the workpiece surface for producing more molten material. Therefore, the thermal stress generated at the machining surface layer is larger, so the size of the micro-crack is larger.

The EDX characterization was conducted on Ti-6Al-4V using AlCrNi coated tool, as in Fig. 4. It is clearly observed that presence of Al, Cr, and N on machined surface; hence, it can be concluded that thin film coating material gets dispersed on surface due to high temperature at pulse on time [39]. The appearance of Al, Cr, and Ni elements in machined surface layer and it can give the coating with good mechanical properties [40, 41]. And it could be the new solution to replace other expensive surface spray methods such as PVD, PVC, etc. The results of surface layer analysis of Ti-6Al-4V after EDM with AlCrNi coated electrode, it will be the basis to open the way to improve surface quality of materials with simple and low cost implementation.

4 Conclusion

In the present study, Taguchi-DEAR assisted multi-target decision was utilized to obtain optimal technological parameters on machining titanium alloy specimens in AlCrNi coated tool electrode employed EDM. The research results have shown the following conclusions.

- The optimal technology parameter has been selected on the basis of input technology parameters including I (40 A), V_g (55 V), and T_{on} (1000 μs).
- The current is the most influence factor among the input parameters in EDM with coated electrode due to its relationship with the electrical conductivity of the electrode coating.
- The topography of machined surface at the optimum condition combination has been significantly improved

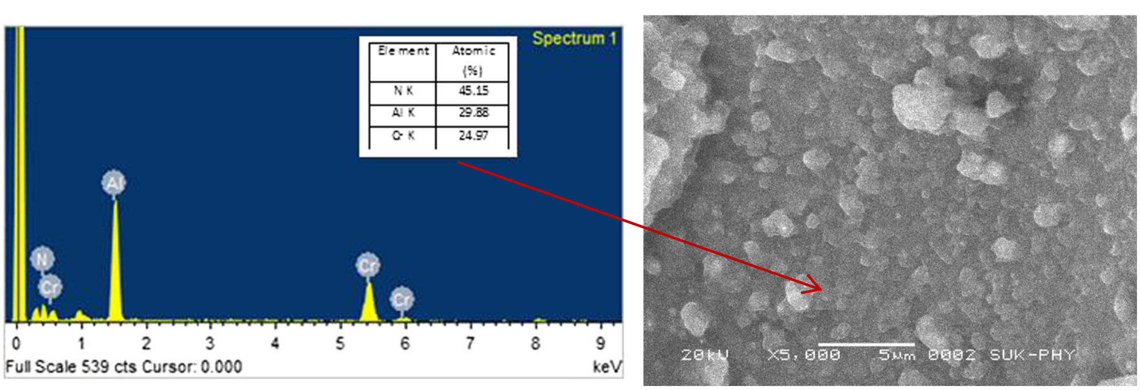

Fig. 4 EDX of coating layer with AlCrNi coated electrode

including the lower value of R_a, and the number and size of microscopic cracks are smaller.

Author contribution N.H. Phan: experiments and funding; P.V. Dong: analysis; H.T. Dung: design; N.V. Thien: surface morphology; T. Muthuramalingam: optimization; S. Shirguppikar: experiments; N.C. Tam: analysis; N.T. Ly: experiments.

Data availability There is no need to mention the availability of data and materials in the present study.

Declarations

Ethics approval There is no ethical approval needed in the present study.

Consent to participate There is no consent to participate needed in the present study.

Consent for publication There is no consent to publish needed in the present study.

Competing interests The authors declare no competing interests.

References

1. Mandal P, Mondal SC (2019) Surface characteristics of mild steel using EDM with Cu-MWCNT composite electrode. Mater Manuf Process 34(12):1326–1332. https://doi.org/10.1080/10426914.2019.1605179
2. Jothimurug R, Amirthagad KS, Daniel J (2012) Performance of silver coated copper tool with kerosene-servotherm dielectric in EDM of monel 400TM. J Appl Sci 12(10):999–1005. https://doi.org/10.3923/jas.2012.999.1005
3. Liu Y, Wang W, Zhang W, Ma F, Yang D, Sha Z, Zhang S (2019) Experimental study on electrode wear of diamond-nickel coated electrode in EDM small hole machining. Adv Mater Sci Eng 2019:1–10. https://doi.org/10.1155/2019/7181237
4. Panchal DL, Biradar SK, Gosavi VY (2016) Analysis of EDM process parameters by using coated electrodes. Int J Eng Trends Technol 41(4):181–185
5. Rashid A, Bilal A, Liu C, Jahan MP, Talamona D, Perveen A (2019) Effect of conductive coatings on micro-electro-discharge machinability of aluminum nitride ceramic using on-machine-fabricated microelectrodes. Materials 12(20):3316. https://doi.org/10.3390/ma12203316
6. Ablyaz TR, Shlykov ES, Kremlev SS (2017) Copper-coated electrodes for electrical discharge machining of 38X2H2MA steel. Russ Eng Res 37(10):910–911 https://link.springer.com/article/10.3103/S1068798X17100033
7. Uhlmann E, Langmack M, Garn R, Oberschmidt D, Fecher J, Rosiwal S M, Singer R F (2011) Using diamond coated tool-electrodes for drilling micro holes with EDM, 11th International Conference of the European Society for Precision Engineering and Nanotechnology 2011. Proceedings. Vol.2: May 23rd - 26th 2011, Como, Italy; conference proceedings
8. Khan F, Soota T (2020) Optimization of EDM process parameter for stainless steel D3. Mater Today Proc 25:635–638. https://doi.org/10.1016/j.matpr.2019.07.529
9. Bhardwaj B, Sharma V, Kumar S, Dutt S (2021) Multiresponse optimization of EDM machining parameters using Taguchi methodology with grey relational analysis. In: Optimization Methods in Engineering. Springer, Singapore, pp 349–357 https://link.springer.com/chapter/10.1007/978-981-15-4550-4_21
10. Meena VK (2006) Optimization of EDM machining parameters using DMLS electrode. Rapid Prototyp J 12(4):222–228. https://doi.org/10.1108/13552540610682732
11. Majumder H, Maity K (2017) Optimization of machining condition in WEDM for titanium grade 6 using MOORA coupled with PCA—a multivariate hybrid approach. J Adv Manuf Syst 16(02):81–99. https://doi.org/10.1142/S0219686717500068
12. Kandpal BC, Kumar J, Singh H (2017) Optimization and characterization of EDM of AA 6061/10% Al2O3 AMMC using Taguchi's approach and utility concept. Prod Manuf Res 5(1):351–370. https://doi.org/10.1080/21693277.2017.1389315
13. Faisal N, Kumar K (2018) Optimization of machine process parameters in EDM for EN 31 using evolutionary optimization techniques. Technologies 6(2):54. https://doi.org/10.3390/technologies6020054
14. Natarajan N, Arunachalam RM (2011) Optimization of micro-EDM with multiple performance characteristics using Taguchi method and Grey relational analysis. J Sci Ind Res 70:500–505 http://nopr.niscair.res.in/handle/123456789/12065
15. Balraj US, Krishna AG (2014) Multi-objective optimization of EDM process parameters using Taguchi method, principal component analysis and grey relational analysis. Int J Manuf Mater Mech Eng 4(2):29–46. https://doi.org/10.4018/ijmmme.2014040103
16. MeenaV K, Azad MS, Singh S, Singh N (2017) Micro-EDM multiple parameter optimization for Cp titanium. Int J Adv Manuf Technol 89(1-4):897–904 https://link.springer.com/article/10.1007%2Fs00170-016-9130-2
17. Pragadish N, Kumar MP (2016) Optimization of dry EDM process parameters using grey relational analysis. Arab J Sci Eng 41(11):4383–4390 https://link.springer.com/article/10.1007/s13369-016-2130-6
18. Bhaumik M, Maity K (2020) Multi-response optimization of EDM parameters using grey relational analysis (GRA) for Ti-5Al-2.5 Sn titanium alloy. World J Eng. https://doi.org/10.1108/WJE-06-2020-0210
19. Golshan A, Ghodsiyeh D, Izman S (2015) Multi-objective optimization of wire electrical discharge machining process using evolutionary computation method: effect of cutting variation. Proc IMechE Part B:J Eng Manuf 229(1):75–85. https://doi.org/10.1177/0954405414523593
20. Kumar SD, Ravichandran M (2018) Synthesis, Characterization and Wire Electric Erosion Behaviour of AA7178-10 wt.% ZrB 2 Composite. Silicon 10(6):2653–2662. https://doi.org/10.1007/s12633-018-9802-7
21. Durairaj M, Sudharsun D, Swamynathan N (2013) Analysis of process parameters in wire EDM with stainless steel using single objective Taguchi method and multi objective grey relational grade. Procedia Eng 64:868–877. https://doi.org/10.1016/j.proeng.2013.09.163
22. Khanna R, Kumar A, Garg MP, Singh A, Sharma N (2015) Multiple performance characteristics optimization for Al 7075 on electric discharge drilling by Taguchi grey relational theory. J Ind Eng Int 11(4):459–472 https://link.springer.com/article/10.1007/s40092-015-0112-z
23. Yusoff Y, Zain AM, Ngadiman MS (2016) Computational approach for multi performances optimization of EDM. MATEC Web Conf EDP Sci 78(1):01014–01020. https://doi.org/10.1051/matecconf/20167801014
24. Soni H, Narendranath S, Ramesh MR (2018) ANN and RSM modeling methods for predicting material removal rate and surface roughness during WEDM of Ti50Ni40Co10 shape memory alloy.

AMSE J IIETA Adv A 54(3):435–443. https://doi.org/10.18280/ama_a.540304
25. Tiwary AP, Pradhan BB, Bhattacharyya B (2014) Application of multi-criteria decision making methods for selection of micro-EDM process parameters. Adv Manuf 2(3):251–258 https://link.springer.com/content/pdf/10.1007/s40436-013-0050-1
26. Hanif M, Ahmad W, Hussain S, Jahanzaib M, Shah AH (2019) Investigating the effects of electric discharge machining parameters on material removal rate and surface roughness on AISI D2 steel using RSM-GRA integrated approach. Int J Adv Manuf Technol 101(5):1255–1265 https://link.springer.com/article/10.1007/s00170-018-3019-1
27. Pradhan MK (2013) Estimating the effect of process parameters on MRR, TWR and radial overcut of EDMed AISI D2 tool steel by RSM and GRA coupled with PCA. Int J Adv Manuf Technol 68(1-4):591–605 https://link.springer.com/article/10.1007%2Fs00170-013-4780-9
28. Sivapirakasam SP, Mathew J, Surianarayanan M (2011) Multi-attribute decision making for green electrical discharge machining. Expert Syst Appl 38(7):8370–8374. https://doi.org/10.1016/j.eswa.2011.01.026
29. Manivannan R, Kumar MP (2016) Multi-response optimization of micro-EDM process parameters on AISI304 steel using TOPSIS. J Mech Sci Technol 30(1):137–144 https://link.springer.com/article/10.1007%2Fs12206-015-1217-4
30. Manivannan R, Kumar MP (2017) Multi-attribute decision-making of cryogenically cooled micro-EDM drilling process parameters using TOPSIS method. Mater Manuf Process 32(2):209–215. https://doi.org/10.1080/10426914.2016.1176182
31. Raj SON, Prabhu S (2017) Analysis of multi objective optimisation using TOPSIS method in EDM process with CNT infused copper electrode. Int J Mach Mach Mater 19(1):76–94. https://doi.org/10.1504/IJMMM.2017.081190
32. Payal H, Maheshwari S, Bharti PS, Sharma SK (2019) Multi-objective optimisation of electrical discharge machining for Inconel 825 using Taguchi-fuzzy approach. Int J Inf Technol 11(1):97–105. https://doi.org/10.1007/s41870-018-0102-7
33. Anitha J, Dasa R, Pradhan MK (2016) Multi-objective optimization of electrical discharge machining processes using artificial neural network. Jordan J Mech Ind Eng 10(1)
34. Manoj M, Jinu GR, Muthuramalingam T (2018) Multi response optimization of AWJM process parameters on machining TiB 2 particles reinforced Al7075 composite using Taguchi-DEAR methodology. Silicon 10(5):2287–2293 https://link.springer.com/article/10.1007/s12633-018-9763-x
35. Muthuramalingam T, Vasanth S, Vinothkumar P, Geethapriyan T, Rabik MM (2018) Multi criteria decision making of abrasive flow oriented process parameters in abrasive water jet machining using Taguchi–DEAR methodology. Silicon 10(5):2015–2021. https://doi.org/10.1007/s12633-017-9715-x
36. Thangaraj M, Loganathan G B, Atif A, Palanisamy S (2019) Multi response optimization on machining titanium alloy using Taguchi-DEAR analysis in abrasive water jet cutting (No. 2019-28-0070). SAE Technical Paper. https://www.sae.org/publications/technical-papers/content/2019-28-0070/
37. Nguyen PH, Banh TL, Mashood KA, Tran DQ, Muthuramalingam T, Nguyen DT (2020) Application of TGRA-based optimisation for machinability of high-chromium tool steel in the EDM process. Arab J Sci Eng 45(7):5555–5562. https://doi.org/10.1007/s13369-020-04456-z
38. Phan NH, Muthuramalingam T (2020) Multi criteria decision making of vibration assisted EDM process parameters on machining silicon steel using Taguchi-DEAR methodology. Silicon:1–7. https://doi.org/10.1007/s12633-020-00573-4
39. Muthuramalingam T (2019) Measuring the influence of discharge energy on white layer thickness in electrical discharge machining process. Measurement 131:694–700. https://doi.org/10.1016/j.measurement.2018.09.038
40. Warcholinski B, Gilewicz A, Myslinski P, Dobruchowska E, Murzynski D (2020) Structure and properties of AlCrN coatings deposited using cathodic arc evaporation. Coatings 10(8):793. https://doi.org/10.3390/coatings10080793
41. Kumar S, Singh R, Singh TP, Sethi BL (2009) Surface modification by electrical discharge machining: a review. J Mater Process Technol 209(8):3675–3687. https://doi.org/10.1016/j.jmatprotec.2008.09.032