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Optimization of Material Removal Rate, Surface Roughness and Kerf Width in Wire-ED Machining of Ti-6Al-4V Using RSM and Grey Relation

D. Doreswamy[a], D. S. Shreyas[a], S. K. Bhat*[b]

[a] Department of Mechatronics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India
[b] Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India

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ABSTRACT

Wire-Electric Discharge (WED) Machining is one of the most suitable machining techniques for machining hard-to-cut materials such as Titanium, with precision. It is of utmost importance to optimize the control parameters to achieve the desired levels of machining performance characteristics. Considering this goal, this research investigates the effects of current, pulse on time (T_{on}) and pulse off time (T_{off}) on the material removal rate, surface roughness and kerf width of WED machined Ti-6Al-4V. The results of optimization showed that, current – 5.19 A, T_{on} – 20 µs, T_{off} – 30 µs, is the optimized settings for machining of Ti-6Al-4V alloy using molybdenum electrode for the best machining performance. Based on the analysis of grey relational grades, the order of influence of the control parameter is ranked as: T_{on} – I, T_{off} – II and Current – III. The efficacy of GRA based approach was evaluated through confirmation experiments wherein the theoretical predictions showed errors < 3%.

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1. INTRODUCTION

Ti-6Al-4V is one of the Titanium alloys which holds immense potential in diverse engineering domains including aerospace, automotive, marine and biomedical engineering because of its superior mechanical, thermal and chemical properties, as well as sustenance of these properties at high temperatures [1]. However, these very advantageous properties cause excessive machining forces, tool wear-rate, thermal as well as vibration related problems in case of the traditional machining of these alloys [2,3]. Therefore, non-traditional machining processes are preferred for their machining such as, Laser Beam Machining, Electro Chemical Machining, Abrasive Water Jet Machining, etc. But these techniques pose their own unique hurdles for obtaining the required machining characteristics due to their negative impact on the environment and their cost-effectiveness to achieve desirable properties on machined component [1,4]. Among the non-conventional machining techniques, Wire Electro Discharge Machining (WEDM) has risen as a technique of appropriate choice over other competing techniques for the task of machining of Titanium alloys [5-8].

The principle of operation of WEDM is basically a utilization of concentrated thermal energy through the application of repetitive and controlled amounts of sparks to achieve the erosion or evaporation of the work material, the thermal energy being from conversion of the electrical source energy to operate the machine [9]. The electrical sparks are applied on the work material by the means of an electrode in the shape of a wire, hence the name "wire"-electric discharge machining. These concentrated sparks of current generate extremely high temperatures around 10 000^{o}C, which are more than sufficient to evaporate or erode the target material around the region of application of the sparks. The eroded material is flushed away by dielectric fluid medium,

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*Corresponding Author Institutional Email: sk.bhat@manipal.edu (S. K. Bhat)

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which is constantly supplied during machining [9]. Numerous control parameters such as, pulse on time (T_{on}), pulse off time (T_{off}), discharge current, voltage, speed, feed and tension of wire, and flow rate of the dielectric fluid influence the obtained output characteristics of WEDM up to different extents [10]. T_{on} is the time duration of discharge during which current is supplied and T_{off} is the duration without discharge in between periods of successive T_{on}. Discharge current and voltage are measures of the total power supply required for machining. Wire speed, feed rate, and tension pertain to the mechanical arrangements of the electrode wire.

To achieve the required wire-ED machining performance, various optimization techniques [11-18] such as, Grey Relational Analysis (GRA), Principal Component Analysis, Taguchi method, Response Surface Methodology (RSM), etc., have been employed. Design of experiments approach has also been utilized to analyze the effects of process parameters on the machining characteristics of Titanium alloys [19,20]. Among these techniques, GRA is a normalization based statistical analysis technique, and is one of the most popular and effective techniques for multi-objective or multi-performance optimization of the process parameters, which can carry out minimization of certain parameters while simultaneously maximizing the others [11,17-18]. GRA is especially suitable when the system under consideration consists of a complex interplay of various factors and their overall effect in combination needs to be quantitatively analyzed.

In terms of the control parameters, current, pulse-on time and pulse-off time pivotal for controlling the machining performance of WEDM [11-20]. Therefore, these parameters were chosen for investigation in the present study. Among the response characteristics of Wire EDM, slot width or kerf width (KW), material removal rate (MRR), and surface roughness (SR) have been studied prominently [11-20], which are chosen in the present study. For the wire electrode in the WEDM of titanium alloys, various material combinations have been investigated [21,22]. However, molybdenum electrode wires have garnered comparatively lesser attention [23,24]. For the dielectric fluid media, oil and water are the key candidates, and water has been observed to be superior to oil in terms of its chemical stability and electrode wear rate [25]. In the present study, the electrode is made up of molybdenum and deionized water is used as the dielectric fluid.

GRA based multi-objective optimization of WED machining of Ti-6Al-4V has been conducted by other researchers by reviewing the effects of different process parameters on machining performance characteristics. However, most of the studies have utilized copper or brass as the electrode materials [11,26-30]. Using copper electrodes, the effects of current, T_{on} and T_{off} on MRR, SR and tool wear rate have been investigated [26,27,30]. Brass electrodes have been extensively used in the investigation of effects of current, T_{on} and T_{off} on MRR, SR and KW [11,28,29]. Further, using molybdenum wire electrodes, the effects of current, T_{on} and T_{off} on MRR and power consumption were studied [30]. However, as per the best knowledge of the authors, the simultaneous optimization of MRR, SR and KW has not been attempted for WEDM of Ti-6Al-4V in the literature. In the same vein, an important contribution of this paper is the investigation of the operating control settings, i.e., current, T_{on} and T_{off} with a wider range of values than that employed in literature [30]. Particularly, use of low current settings (2 A – 6 A) is a uniqueness of the present study. These are the lacunae in the research which is being bridged by the present study. The multi-response optimization of the WEDM can also improve the resistance of the finished product under impact and cyclic loadings due to the optimal surface roughness and microstructure of the processed titanium Ti-6Al-4V [31].

Among WED machining studies of Ti-6Al-4V in the literature, there still exists research gaps which need to be filled for improving the understanding of the effects of various control parameters on the machining performance characteristics. Therefore, the present study analyzes the optimum settings of peak current, T_{on} and T_{off} for obtaining the best possible machining performance characteristics, viz., MRR, SR and KW, using the Grey Relational Analysis, in conjunction with ANOVA and Response Surface Methodology during the use of molybdenum wire as the electrodes and deionized water as the dielectric fluid medium. In this paper, the multi-responses of Wire-ED machined Titanium alloy Ti-6Al-4V are optimized with respect to the process parameters. Moreover, the optimized machining responses obtained from GRA is compared with that obtained using the conventional RSM approach through confirmation experiments to verify the efficacy of the technique implemented in the present paper.

2. MATERIALS AND METHODS

2. 1. Experimental Setup and Design of Experiments The CNC Wire-EDM machine – Versa Cut 01 DK7732 (Make: Concord United Products Pvt. Ltd., Bengaluru, India) was used in this study having table dimensions of 320 mm × 400 mm (Figure 1). The work samples for the present study, the Ti-6Al-4V plate, is cut into a slab of 150 mm × 50 mm × 2 mm. Subsequently, machining experiments are performed on the samples by varying the control parameters as per the design of experiments for a length of 10 mm for each trial. Fifteen pieces are then removed and marked from the test sample for measuring the MRR, SR and KW along each side. Molybdenum wires of 0.18 mm diameter are used as the electrodes for machining and the dielectric

Figure 1. Experimental setup

fluid medium consists of demineralized/deionized water with cleanser gel during the Wire-EDM of the samples. The compositional information of test samples was obtained from tests conducted at Varsha Bullion Elemental Analab, Mumbai, India (Table 1). Based on previous studies on different materials using the current experimental setup [32-34], three imperative control factors T_{on}, T_{off} and peak current are chosen for the present work. Remaining control parameters were kept constant throughout the experiments (Table 2). The experimental levels (Table 3) are designed using the central composite design of RSM.

2. 2. Measurement of Machining Responses

The machining responses chosen for optimization are MRR, SR and KW. MRR is principally a measure of the material volume removed in a unit time interval of machining (expressed in mm^3/min). The machining time for individual slot is obtained from the WED machine. The quantity of removed material is determined by computing the weight reduction of the test sample after machining. SR (R_a) of machined cut surfaces were measured utilizing the Surtronic® Surface Roughness Tester (Made by Taylor Hobson). The stylus probe of the tester was made to move along the surface for a sampling length of 2.5 mm for each measurement. For each sample, the readings were recorded at four different locations and its average R_a is obtained. The slot/kerf width is measured using the IM7000 Series Mitutoyo Inverted Metallurgical Optical Microscope (Made by Meiji Techno). KW was measured at three different locations along the length and the average of the measurements is considered during the analysis. Table 4 presents the experimental plan and the measured response data.

TABLE 1. The composition of Ti-6Al-4V test samples used in the present study [31]

Material composition	Ti	Al	V	Fe	C	Cr	Cu
%	89.54	5.60	4.50	0.23	0.01	0.03	0.09

TABLE 2. Control parameters kept constant during the present work

Parameters	Values with units
Wire speed	4.4 m/s
Wire tension	8 kg-f
Dielectric fluid	Deionized water + cleanser gel
Fluid pressure	40 dm^3/minute
Servo Voltage	90 V

TABLE 3. The range of wire-EDM variable control parameters chosen in the present study

Control parameters	Level 1	Level 2	Level 3
Current (A)	2	4	6
T_{on} (μs)	20	35	50
T_{off} (μs)	10	20	30

2. 3. Grey Relational Analysis

Taguchi technique is useful for optimizing the control parameters for a single response characteristic. However, the present work comprises of optimization of three machining responses namely, MRR, R_a and KW. MRR is demands the “higher-the-better” characteristics, whereas R_a and KW demand the “lower-the-better” response characteristics. Such scenarios can be tackled using the Grey Relational Analysis (GRA) wherein “Grey” indicates the situation wherein the available information is between black-and-

TABLE 4. Experimental design with correspondingly obtained machining response data

Sl. No.	Current (A)	T_{on} (μs)	T_{off} (μs)	MRR (mm^3/min)	R_a (μm)	KW (mm)
1	2	20	20	0.931	6.32	0.100
2	4	35	20	1.675	7.35	0.112
3	2	50	20	1.071	8.36	0.115
4	6	35	10	3.027	8.34	0.123
5	4	20	30	1.118	5.59	0.098
6	6	20	20	2.040	8.37	0.113
7	4	50	30	1.115	7.04	0.117
8	2	35	30	0.722	6.93	0.105
9	4	50	20	1.704	9.63	0.118
10	6	50	20	1.930	9.88	0.123
11	4	35	20	1.680	7.54	0.117
12	2	35	10	1.600	7.50	0.107
13	6	35	30	1.360	6.56	0.108
14	4	50	10	2.388	7.75	0.108
15	4	20	10	2.124	7.98	0.098

white [35]. Here, black signifies no information condition, whereas white indicates the availability of complete information regarding the responses. The methodology of analysis involved in GRA is schematically presented in Figure 2.

3. RESULTS AND DISCUSSION

3. 1. Computation of Grey Relation Grey relation is computed by the linear normalization of the measured experimental results, viz., the machining performances (MRR, R_a and KW), between zero to one. During this computation, the input data is dispersed uniformly and scaled to a proportionate range for subsequent analysis. For R_a and KW, the normalization is carried out using "smaller-the-better" performance characteristics using Equation (1), whereas for MRR is normalized using the "higher-the-better" characteristic using Equation (2). Table 5 shows the original and linearly normalized responses.

$$X_{ijk}* = \frac{Max(X_{ijk}) - X_{ijk}}{Max(X_{ijk}) - Min(X_{ijk})} \text{ for j} = 1,2\ldots,15 \qquad (1)$$

$$X_{ijk}* = \frac{X_{ijk} - Min(X_{ijk})}{Max(X_{ijk}) - Min(X_{ijk})} \text{ for j} = 1,2,\ldots,15 \qquad (2)$$

3. 2. Computation of Grey Relational Coefficient Grey relational coefficient (ξ) establishes the association between the theoretical and normalized experimental results, which are computed using Equations (3) to (5). Since the machining performance characteristic responses chosen in this study are considered to be of identical importance, the characteristic coefficient which distinguishes between the response, $\xi \in (0,1)$ is taken as 1/3. Table 5 summarized the grey relational coefficients (GRC) computed with respect to the normalized responses.

$$R = Max(X*_{ijk}) = 1 \qquad (3)$$

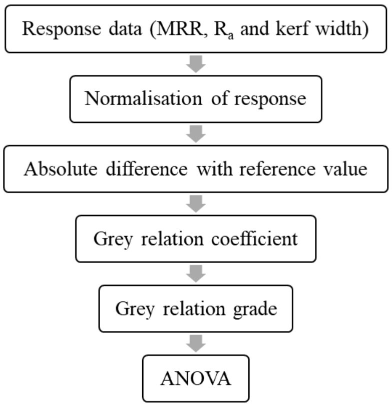


Figure 2. Steps involved in grey relational analysis

$$\Delta_{ijk} = |X*_{ijk} - R| \qquad (4)$$

$$\xi_{ijk} = \frac{Min(\Delta_{ijk}) + \xi Max(\Delta_{ijk})}{\left(\Delta_{ijk} + \xi Max(\Delta_{ijk})\right)} \qquad (5)$$

3. 3. Computation of Grey Relational Grade The grey relational grade (GRG) represents (Table 5) the degree of composite relationship among the output responses [36]. The grades for each experimental setting are computed by obtaining the mean value of the respective grey relational coefficients using Equation (6), where m is the number of response or performance characteristics being analysed ($m = 3$).

TABLE 5. Grey relational computated values

Trial No.	Normalized Response			GRC			GRG
	MRR	R_a	KW	MRR	R_a	KW	
1	0.091	0.830	0.920	0.266	0.660	0.805	0.577
2	0.413	0.590	0.440	0.360	0.446	0.371	0.392
3	0.151	0.354	0.320	0.280	0.338	0.327	0.315
4	1.000	0.359	0.000	1.000	0.340	0.248	0.529
5	0.172	1.000	1.000	0.285	1.000	1.000	0.762
6	0.572	0.352	0.400	0.435	0.337	0.355	0.376
7	0.170	0.662	0.240	0.285	0.494	0.303	0.360
8	0.000	0.688	0.720	0.248	0.514	0.541	0.434
9	0.426	0.058	0.200	0.365	0.259	0.292	0.306
10	0.524	0.000	0.000	0.409	0.248	0.248	0.302
11	0.416	0.545	0.240	0.361	0.421	0.303	0.361
12	0.381	0.555	0.640	0.348	0.426	0.478	0.417
13	0.277	0.774	0.600	0.313	0.593	0.452	0.453
14	0.723	0.497	0.600	0.543	0.396	0.452	0.464
15	0.608	0.443	1.000	0.457	0.372	1.000	0.610

$$GRG = \gamma_i = \frac{1}{m}\sum_{i=1}^{m} \xi_{ik} \qquad (6)$$

3. 4. Analysis of Grey Relational Grade Figure 3 presents the main effects plot with respect to GRG. The corresponding output response, i.e., GRG is observed to increase with rise of peak current until 4 A starting from 2 A, but further increase reduces the mean response of GRG. This is due to the fact that small current settings cause lesser amounts of MRR and higher surface unevenness, whereas the maximum current setting can lead to larger kerf widths because of excessive generation of the spark discharge energy. Therefore, current settings close to 4 A gives the best response for an overall

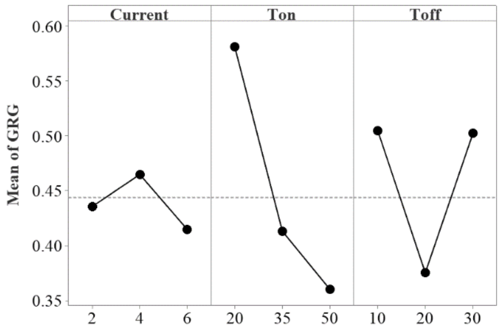


Figure 3. Main effects plot of grey relational grade

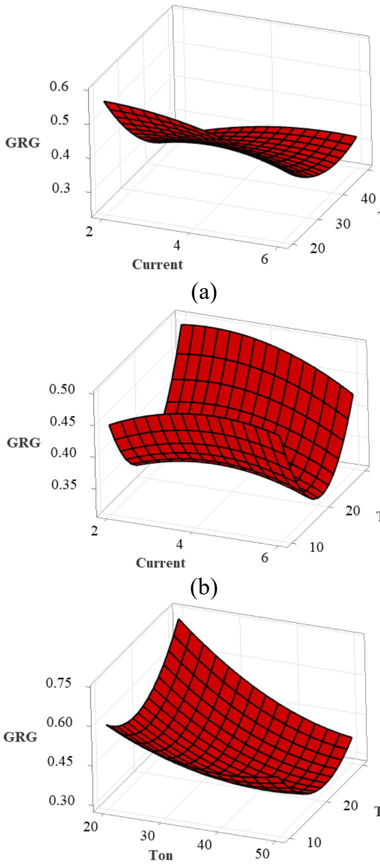
optimized response. Further, it is observed that the smallest duration of T_{on} (20 µs) generates the best GRG, whereas maximum T_{on} (50 µs) gives the least response. This is because, as T_{on} increases, because of the continuous material removal, both MRR and KW tends to increase, and it also leads to excessive surface unevenness because of inadequate time intervals for the dielectric fluid medium to flush away the molten or evaporated work material. Therefore, T_{on} duration of 20 µs gives the best GRG response. In case of T_{off}, both extremes of the range of values gives the best response of grey relational grade, but T_{off} duration of 20 µs gives the least response.

The GRG is them examined through the analysis of variance (ANOVA) to evaluate the simultaneous effects of the individual control parameters on MRR, R_a and KW at 95% confidence interval. From the standard Fisher's table, critical *F*-statistic is found to be 2.90 (error degree of freedom (DF) – 5). Input parameters having *F*-statistic greater than the critical *F*-statistic implies that the respective parameter possesses a statistically significant influence on the output response. Table 6 demonstrates that the individual effect of T_{on} has a significant influence on the response, while other two parameters are observed to be statistically insignificant. The second-order terms of individual parameters T_{on} and T_{off}, and interaction effect between T_{on} and T_{off} are found to be statistically significant. Lack-of-fit is observed to be statistically insignificant, indicating the effectiveness of the prediction of GRG in terms of the statistically significant terms.

Figure 4 shows the response surfaces of the interaction effects between the control parameters chosen in the present work. From Figure 4(a), it is observed that both current and T_{on} have significant effect on each other's individual effects on the responses. At the minimum value of T_{on} (10 µs), the current tends to reduce the output response, whereas at its maximum value (30 µs) current tends to increase the response GRG. The interaction between Current and T_{off} (Figure 4(b)) shows a similar conclusion as shown in the main effect plots with respect to the nature of influence of T_{off} and Current. The interaction between T_{on} and T_{off} (Figure 4(c)) shows that at minimum T_{on} (10 µs) the effect of T_{off} is much larger and as T_{on} increases its impact on output response reduces.

TABLE 6. ANOVA of GRG for MRR, R_a and KW

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Current	1	0.000871	0.000871	0.17	0.698
T_{on}	1	0.097469	0.097469	18.91	0.007
T_{off}	1	0.000015	0.000015	0.00	0.960
Current*Current	1	0.002411	0.002411	0.47	0.524
T_{on}*T_{on}	1	0.015563	0.015563	3.02	0.143
T_{off}*T_{off}	1	0.063301	0.063301	12.28	0.017
Current*T_{on}	1	0.008842	0.008842	1.72	0.247
Current*T_{off}	1	0.002183	0.002183	0.42	0.544
T_{on}*T_{off}	1	0.016289	0.016289	3.16	0.136
Lack-of-Fit	3	0.021906	0.007302	3.78	0.216



(a)

(b)

(c)

Figure 4. Interaction effects of (a) Current and T_{on} at constant T_{off} = 20 µs, (b) Current and T_{off} at constant T_{on} = 35 µs, and (c) T_{on} and T_{off} at constant Current = 4 A

3. 5. Simultaneous Multi-response Optimization

The mean GRG computed for process parameters at each control parameter settings is presented in Table 7. The maximum mean GRG (highlighted in bold text in Table 7) is observed at the settings, Current – 4 A, T_{on} – 20 µs, T_{off} – 10 µs.

Hence A2B1C1 is the optimum combination of settings for the best performance of MRR, R_a and KW. Using Equation (7) the projected GRG is obtained as 0.6081 at the optimized set of control parameter settings. Confirmation experiments were carried out at the corresponding control parameter combination of A2B1C1, and the MRR, R_a and KW obtained ranged 2.186 ± 0.131 mm^3/min, 7.60 ± 0.74 µm and 0.102 ± 0.018 mm. Further, based on the maximum GRG values in Table 7 for each process parameters, the order of significance of their influence on the response is ranked as, T_{on} – I, T_{off} – II and Current – III.

$$GRG_{optimum} = f(A_2 + B_1 + C_1) - 2\sum_{i=1}^{15} GRG_i/15 \qquad (7)$$

Figure 5 shows the optimized Current, T_{on} and T_{off} settings and the corresponding output responses of MRR, R_a and KW. Composite desirability is a statistical measure which indicates an overall optimal performance. In this study, a composite desirability of 0.664 is obtained, which is close to the mean value reported in a GRA based study on WEDM of Ti-6Al-4V [36]. It is observed from the optimization of individual parameters that maximum desirability and maximum GRG is attempted to be obtained such that the individual parameter's optimization goals are being satisfied to the best possible extent within the allowable parameter space.

The Pareto chart (Figure 6) lists the control parameters in the order of their influence from the highest to the smallest, along with a reference line which represents a statistical threshold. Parameters which cross the reference line representing this statistical threshold are considered to have statistically significant influence on the simultaneous response, i.e., GRG. The Pareto distribution shows that individual effect on T_{on} and second-order effect of T_{off} have the significant influence on the overall response, followed by other combinations.

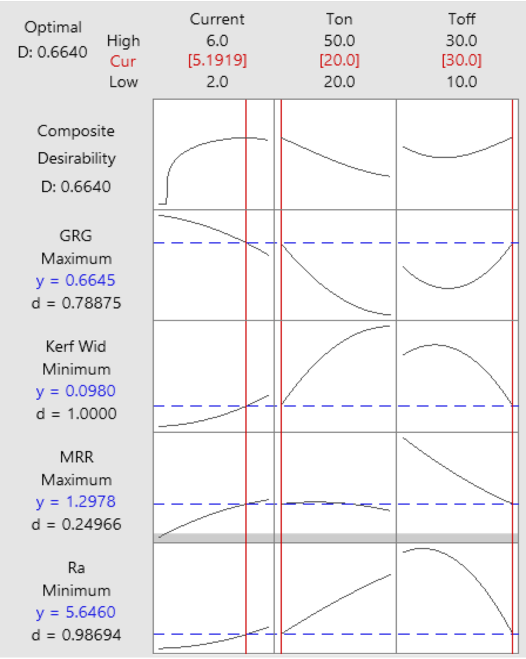


Figure 5. Response surface plots of composite desirability, GRG, MRR, R_a, KW as a function of control parameters

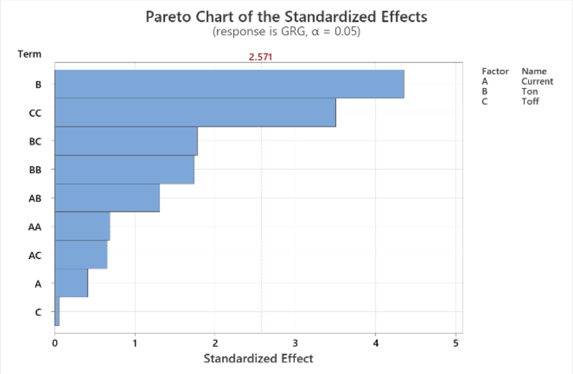


Figure 6. Pareto chart of the standardized effects of control parameters on GRG

3. 6. Comparison of GRA Based Multi-response Optimization with RSM

To validate the results obtained using GRA, it is compared with that from conventional single-response optimization using RSM. The optimal parameters and the corresponding machining responses from RSM based single-response

TABLE 7. Mean grey relational grades at each levels of the control parametric

Level	Current (A)	T_{on} (µs)	T_{off} (µs)
1	0.4359	**0.5259**	**0.5050**
2	**0.4650**	0.4312	0.3756
3	0.4150	0.3603	0.5023

TABLE 8. Errors of GRA and RSM response predictions along with experimental responses

Trial No.	GRA – Error (%)			RSM – Error (%)		
	MRR	R_a	KW	MRR	R_a	KW
1	1.6	4.3	1.0	2.7	3.2	7.0
2	3.0	1.4	3.9	3.8	4.0	5.9
3	2.4	0.9	3.0	3.9	7.0	8.0
4	2.4	0.7	1.0	9.9	9.5	13.4
5	3.7	0.9	1.0	7.2	4.0	1.6

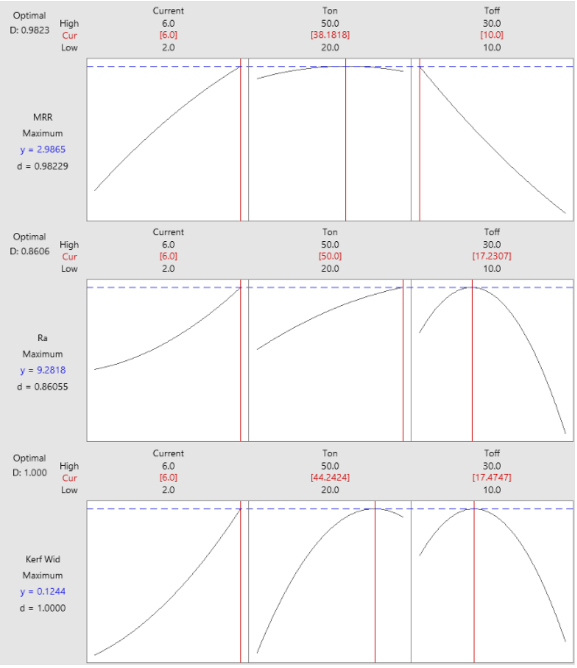


Figure 7. The effects of Current, T_{on} and T_{off} on individual responses – MRR, Ra and KW

optimization are presented in Figure 7. Five confirmation experiments were conducted using the optimal parameters obtained from the two methods and the experimental responses are compared with theoretical predictions, expressed as absolute % errors (Table 8). The mean error for GRA is < 3% and for RSM it is > 5%.

4. CONCLUSIONS

The following conclusions were drawn from the present study of GRA based multi-response optimization for the WED machining of Ti-6Al-4V using molybdenum wire electrode, through a comprehensive analysis of the effects of peak current, T_{on}, and T_{off} on the machining responses, i.e., MRR, R_a and KW:

- Main effects analysis of the individual control parameters revealed that intermediate level of current (4 A), minimum T_{on} (20 µs) and either minimum or maximum T_{off} (10 µs), gives the best output response.
- ANOVA of GRG indicated that the linear and quadratic term of T_{on} and the quadratic term of T_{off} have significant impact on the machining responses, whereas current was statistically insignificant. Further, the interaction effect of T_{off} on T_{off} is found to be significant whereas other interaction effects are statistically insignificant.
- Analysis of the Grey Relational Grades showed that within the experimental range, Current – 4 A, T_{on} – 20 µs, T_{off} – 10 µs, provided the best machining performance. The order of influence of the control parameter was ranked as: T_{on} – I, T_{off} – II and Current – III.
- The multi-response optimization considering the composite desirability showed that, current – 5.19 A, Ton – 20 µs, Toff – 30 µs, gave the optimal response of MRR, R_a and KW.
- The comparison of GRA and RSM results with those from confirmation experiments showed that GRA had errors < 3%, demonstrating the efficacy of the optimization method.

5. REFERENCES

1. Qosim, N., Supriadi, S., Puspitasari, P., Kreshanti, P. "Mechanical Surface Treatments of Ti-6Al-4V Miniplate Implant Manufactured by Electrical Discharge Machining", ***International Journal of Engineering, Transactions A: Basics***, Vol. 31, No. 7, (2018), 1103-1108, doi: 10.5829/ije.2018.31.07a.14
2. Gupta, K., Laubscher, R. "Sustainable machining of titanium alloys: A critical review", ***Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture***, Vol. 231, No. 14, (2016), 2543-2560, doi: 10.1177/0954405416634278
3. Pramanik, A. "Problems and solutions in machining of titanium alloys", ***The International Journal of Advanced Manufacturing Technology***, Vol. 70, (2014), 919-928, doi: 10.1007/s00170-013-5326-x
4. Oke, S.R., Ogunwande, G.S., Onifade, M., Aikulola, E., Adewale, E.D., Olawale, O.E. "An overview of conventional and non-conventional techniques for machining of titanium alloys", ***Manufacturing Review***, Vol. 7, No. 34, (2020). 24, doi: 10.1051/mfreview/2020029
5. Nishanth, B.S., Kulkarni, V.N., Gaitonde V.N. "A review on conventional and nonconventional machining of titanium and nickel-based alloys", ***AIP Conference Proceedings***, Vol. 2200, No. 020091, (2019), doi: 10.1063/1.5141261
6. Davim, J.P., Machining: Fundamentals and Recent Advances. London: Springer, 2008. ISBN: 978-1-84800-213-5
7. Davim, J.P., Nontraditional Machining Processes. London: Springer, 2013. ISBN: 978-1-4471-5179-1
8. Davim, J.P., Machining of Titanium alloys. Heidelberg: Springer Berlin, 2014. ISBN: 978-3-662-43902-9
9. Qudeiri, J.A.E., Mourad, A.H.I., Ziout, A. "Electric discharge machining of titanium and its alloys: review", ***The International Journal of Advanced Manufacturing Technology***, Vol. 96, (2018), 1319-1339, doi: 10.1007/s00170-018-1574-0
10. Patel, S.S., Prajapati, J.M. "Experimental Investigation of Surface Roughness and Kerf Width During Machining of Blanking Die Material on Wire Electric Discharge Machine", ***International Journal of Engineering, Transactions A: Basics***, Vol. 31, No. 10, (2018), 1760-1766, doi: 10.5829/ije.2018.31.10a.19
11. Saedon, J.B., Jaafar, N., Yahaya, M.A., Saad, N., Kasim, M.S. "Multi-objective Optimization of Titanium Alloy through Orthogonal Array and Grey Relational Analysis in WEDM", ***Procedia Technology***, Vol. 15, (2014), 832-840, doi: 10.1016/j.protcy.2014.09.057
12. Raj, S.O.N., Prabhu, S. "Modeling and analysis of titanium alloy in wire cut EDM using Grey relation coupled with principle component analysis", ***Australian Journal of Mechanical***

Engineering, Vol. 15, No. 3, (2017), 198-209, doi: 10.1080/14484846.2016.1251077

13. Mohamed, M.F., Lenin, K. "Optimization of Wire EDM process parameters using Taguchi technique", ***Materials Today: Proceedings***, Vol. 21, (2020), 527-530, doi: 10.1016/j.matpr.2019.06.662
14. Nourbakhsh, F., Rajurkar, K.P., Malshe, A.P., Cao, J. "Wire Electro-Discharge Machining of Titanium Alloy", ***Procedia CIRP,*** Vol. 5, (2013), 13-18, doi: 10.1016/j.procir.2013.01.003
15. Golshan, A., Ghodsiyeh, D, Izman, S. "Multi-objective optimization of wire electrical discharge machining process using evolutionary computation method: Effect of cutting variation", ***Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture***, Vol. 229, No. 1, (2015), 75-85, doi: 10.1177/0954405414523593
16. Arikatla, S.P., Mannan, K.T., Krishnaiah, A. "Parametric Optimization in Wire Electrical Discharge Machining of Titanium Alloy Using Response Surface Methodology", ***Materials Today: Proceedings***, Vol. 4, (2017), 1434-1441, doi: 10.1016/j.matpr.2017.01.165
17. Chaudhari, R., Vora, J., Parikh, D.M., Wankhede, V., Khanna, S. "Multi-response Optimization of WEDM Parameters Using an Integrated Approach of RSM–GRA Analysis for Pure Titanium", ***Journal of The Institution of Engineers (India): Series D***, Vol. 101, No. 1, (2020, 117-126, doi: 10.1007/s40033-020-00204-7
18. Saindane, U.V., Soni, S., Menghani, J.V. "Friction and Wear Performance of Brake Pad and Optimization of Manufacturing Parameters using Grey Relational Analysis", ***International Journal of Engineering, Transactions C: Aspects***, Vol. 35, No. 03, (2022), 552-559, doi: 10.5829/ije.2022.35.03c.07
19. Khanna, N., Davim, J.P. "Design-of-experiments application in machining titanium alloys for aerospace structural components", ***Measurement***, Vol. 61, (2015), 280-290, doi: 10.1016/j.measurement.2014.10.059
20. Lauro, C.H., Filho, S.L.M.R., Brandao, L.C., Davim, J.P. "Analysis of behaviour biocompatible titanium alloy (Ti-6Al-7Nb) in the micro-cutting", ***Measurement***, Vol. 93, (2016), 529-540, doi: 10.1016/j.measurement.2016.07.059
21. Hascalik, A., Caydas, U. "Electrical discharge machining of titanium alloy (Ti–6Al–4V)", ***Applied Surface Science***, Vol. 253, No. 22, (2007), 9007-9016, doi: 10.1016/j.apsusc.2007.05.031
22. Phan, N.H., Dong, P.V., Muthuramalingam, T., Thien, N.V., Dung, H.T., Hung, T.Q., Duc, N.V., Ly, N.T. "Experimental Investigation of Uncoated Electrode and PVD AlCrNi Coating on Surface Roughness in Electrical Discharge Machining of Ti-6Al-4V", ***International Journal of Engineering, Transactions A: Basics***, Vol. 34, No. 04, (2021), 928-934, doi: 10.5829/ije.2021.34.04a.19
23. Chaudhari, R., Vora, J.J., Patel, V., Lacalle, L.N.Ld., Parikh, D.M. "Effect of WEDM Process Parameters on Surface Morphology of Nitinol Shape Memory Alloy", ***Materials***, Vol. 13, No. 21, (2020), 4943, doi: 10.3390/ma13214943
24. Devarasiddappa, D., Chandrasekaran, M., Arunachalam, R. "Experimental investigation and parametric optimization for minimizing surface roughness during WEDM of Ti6Al4V alloy using modified TLBO algorithm", ***Journal of the Brazilian Society of Mechanical Sciences and Engineering***, Vol. 42, (2020), 128. doi: 10.1007/s40430-020-2224-7
25. Chakraborty, S., Mitra, S., Bose, D. "Performance Analysis on Eco-friendly Machining of Ti6Al4V using Powder Mixed with Different Dielectrics in WEDM", ***International Journal of Automotive and Mechanical Engineering***, Vol. 17, No. 2, (2020), 8128-8139, doi: 10.15282/ijame.17.3.2020.06.0610
26. Kao, J.Y., Tsao, C.C., Wang, S.S., Hsu. C.Y. "Optimization of the EDM parameters on machining Ti–6Al–4V with multiple quality characteristics", ***The International Journal of Advanced Manufacturing Technology***, Vol. 47, (2010), 395-402, doi: 10.1007/s00170-009-2208-3
27. Kumar, S., Dhanabalan, S., Narayanan, C.S. "Application of ANFIS and GRA for multi-objective optimization of optimal wire-EDM parameters while machining Ti–6Al–4V alloy", ***SN Applied Sciences***, Vol. 1, (2019), 298, doi: 10.1007/s42452-019-0195-z
28. Sharma, N., Khanna, R., Sharma, Y.K., Gupta, R.D. "Multi-quality characteristics optimisation on WEDM for Ti-6Al-4V using Taguchi-grey relational theory", ***International Journal of Machining and Machinability of Materials***, Vol. 21, No. 1/2, (2019), 66-81, doi: 10.1504/IJMMM.2019.098067
29. Sonawane, S.A., Ronge, B.P., Pawar, P.M. "Multi-characteristic optimization of WEDM for Ti-6Al-4V by applying grey relational investigation during profile machining", ***Journal of Mechanical Engineering and Sciences***, Vol. 13, No. 4, (2019), 6059-6087, doi: 10.15282/jmes.13.4.2019.22.0478
30. Gugulothu, B., Rao, G.K.M., Bezabih, M. "Grey relational analysis for multi-response optimization of process parameters in green electrical discharge machining of Ti-6Al-4V alloy", ***Materials Today: Proceedings***, Vol. 46, No. 1, (2021), 89-98, doi: 10.1016/j.matpr.2020.06.135
31. Maruschak, P.O., Chausov, M.G., Konovalenko, I.V, Yasnii, O.P., Panin, S.V., Vlasov, I.V. "Effect of Shock and Vibration Loading on the Fracture Mechanisms of a VT23 Titanium Alloy", ***Strength of Materials***, Vol. 52 (2020), 252-261, doi: 10.1007/s11223-020-00172-z
32. Deepak, D., Shreyas, D.S., Bhat, S.K., Rao, R.N. "Optimization of material removal rate and surface characterization of wire electric discharge machined Ti-6Al-4V alloy by response surface method", ***Manufacturing Review***, Vol. 9, No. 15, (2022), 11, doi: 10.1051/mfreview/2022016
33. Doreswamy, D., Javeri, J. "Effect of Process Parameters in EDM of D2 Steel and Estimation of coefficient for Predicting Surface Roughness", ***International Journal of Machining and Machinability of Materials***, Vol. 20, (2018), 101-117, doi: 10.1504/IJMMM.2018.090542
34. Deepak, D., Shrinivas, P., Hemant, G., Iasy, R. "Optimisation of Current and Pulse Duration in Electric Discharge Drilling of D2 Steel Using Graphite Electrode", ***International Journal of Automotive and Mechanical Engineering***, Vol. 15, (2018), 5914-5926, doi: 10.15282/ijame.15.4.2018.14.0451
35. Devarajaiah, D., Muthumari, C. "Evaluation of power consumption and MRR in WEDM of Ti–6Al–4V alloy and its simultaneous optimization for sustainable production", ***Journal of the Brazilian Society of Mechanical Sciences and Engineering***, Vol. 40, (2018), 400, doi: 10.1007/s40430-018-1318-y
36. Deepak, D., Davim, J.P. "Multi-Response Optimization of Process Parameters in AWJ Machining of Hybrid GFRP Composite by Grey Relational Method", ***Procedia Manufacturing***, Vol. 35, (2019), 1211-1221, doi: 10.1016/j.promfg.2019.07.021

Persian Abstract

چکیده

ماشین کاری با تخلیه الکتریکی سیمی (WED) یکی از مناسب ترین تکنیک های ماشین کاری برای ماشین کاری مواد برش سخت مانند تیتانیوم با دقت بالا است. بهینه سازی پارامترهای کنترل برای دستیابی به سطوح مطلوب از ویژگی های عملکرد ماشین کاری بسیار مهم است. با در نظر گرفتن این هدف، این تحقیق به بررسی تاثیر جریان، زمان پالس در زمان (Ton) و زمان خاموش شدن پالس (Toff) بر میزان حذف مواد، زبری سطح و عرض کرف Ti-6Al-4V ماشین‌کاری WED می‌پردازد. نتایج بهینه‌سازی نشان داد که جریان – ۵.۱۹ A، تن – ۲۰ µs، Toff - 30 µs، تنظیمات بهینه برای ماشین‌کاری آلیاژ Ti-6Al-4V با استفاده از الکترود مولیبدن برای بهترین عملکرد ماشین‌کاری است. بر اساس تجزیه و تحلیل گریدهای رابطه خاکستری، ترتیب تأثیر پارامتر کنترل به صورت تن – I، تاف – II و جریان – III رتبه‌بندی می‌شود. اثربخشی رویکرد مبتنی بر GRA از طریق آزمایش‌های تاییدی مورد ارزیابی قرار گرفت که در آن پیش‌بینی‌های نظری خطاهای کمتر از ۳٪ را نشان دادند.