Int J Adv Manuf Technol (2014) 70:469–475
DOI 10.1007/s00170-013-5274-5

ORIGINAL ARTICLE

Experimental study on green electrical discharge machining in tap water of Ti–6Al–4V and parameters optimization

L. Tang · Y. T. Du

Received: 17 December 2012 / Accepted: 25 August 2013 / Published online: 15 September 2013

Abstract Ti–6Al–4V is widely used in the aerospace, automobile, and biomedical fields, but is a difficult-to-machine material. Electrical discharge machining (EDM) is regarded as one of the most effective approaches to machining Ti–6Al–4V alloy, since it is a non-contact electro-thermal machining method, and it is independent from the mechanical properties of the processed material. This paper aims to combine grey relational analysis and Taguchi methods to solve the problem of EDM parameters optimization. From the viewpoint of health and environment, tap water as working fluid has good working environment, since it does not release harmful gas. The process parameters include discharge current, gap voltage, lifting height, negative polarity and pulse duty factor. The electrode wear ratio (EWR), material removal rate (MRR) and surface roughness (SR) as objective parameters are chosen to evaluate the whole machining effects. Experiments were carried out based on Taguchi $L9$ orthogonal array and grey relational analysis, and then verified the results through a confirmation experiment. Compared the machining parameters $A_1B_1C_3D_2$ with $A_1B_2C_2D_2$, MRR increased from 1.28 mm^3/min to 2.38 mm^3/min, EWR decreased from 0.14 to 0.10 mm^3/min and SR decreased from Ra 2.37 μm to Ra 1.93 μm. The process parameters sequenced in order of relative importance are: the ratio of pulse width to pulse interval, discharge current, lifting height and gap voltage. The results showed that using tap water machining Ti–6Al–4V material can obtain high MRR, decrease the machining cost and have no harmful to the operators and the environment.

Keywords EDM · Ti–6Al–4V alloy · Material removal rate · Electrode wear rate · Surface roughness · Orthogonal experiment · Grey relational analysis

1 Introduction

Ti–6Al–4V alloy has exceptional merits such as high strength–weight ratio, good temperature stability and prominent corrosion resistance, which makes it widely used in aerospace, automobile, chemical and biomedical fields [1, 2]. However, it is a hard-to-cut material with its high melting and low thermal conductivity and it not suitable for traditional machining. Therefore, non-traditional machining methods such as electrical discharge machining (EDM) have been used to process this alloy. EDM is a non-traditional machining method, which is extensively used in machining hard, high-strength, complex geometry shape and temperature-resistant materials in a contactless manner. The material is melted and evaporated by the heat between electrode tool and work piece [3–9]. Recently, EDM technology made it widely used in machining the key parts such as aerospace and aeronautical components. Much research has been conducted in an attempt to improve the EDM material removal rate (MRR), surface roughness (SR), reduce the electrode wear rate (EWR) and seek optimal machining parameters.

Brass and bronze were used as electrode materials to machining D2 tool steel in tap water and deionized water, and the results showed that by using 75 % tap water and 25 % deionized water mixture, the dielectric can obtain the maximum MRR and the minimum EWR [10]. In order to obtain surface integrity of Ti–6Al–4V, graphite, electrolytic copper, aluminium and copper–tungsten material were researched as EDM electrodes [11–14]. EDM dielectric-water-in-oil, kerosene and

L. Tang (✉)
School of Mechatronics Engineering, Xi'an Technological University, Xi'an 710032, China
e-mail: tang_lin168@yahoo.com

Y. T. Du
School of Mechatronics Engineering, Weiyang Campus, Xi'an Technological University, 2 Xuefuzhonglu Avenue Weiyang College Park, Weiyang District, Box 41, Xi'an 710021, Shaanxi Province, People's Republic of China
e-mail: steven791025@126.com

Table 1 Chemical composition of Ti–6Al–4V alloy

Element	Ti	Al	V	Fe	O	C	N	H
wt.%	89.464	6.08	4.02	0.22s	0.18	0.02	0.01	0.0053

deionized water were studied to get high MRR and low EWR [15–18]. Powder-mixed EDM is one of the methods for improving the capabilities of EDM, which can reduce the gap between the tool and work piece, and make the machining more stable and improve the MRR [19–22]. Cryogenic cooling and treatment method can reduce EWR in Ti–6Al–4V and Ti 6246 alloy EDM [23, 24]. Ultrasonic, vibratory, rotary and magnetic field can also improve MRR in EDM [25–30]. The residual stresses and white layer have a great relationship with the type of the EDM dielectric [31, 32]. Machining performance in the EDM process can be improved effectively through optimal machining parameters [33–39]. Using kerosene as dielectric will discharge large amounts of solid, liquid and gaseous wastes, which result in serious environmental problems. These toxic substances can enter the body through inhalation and skin contact [8, 9].

Green manufacturing aims at improving the efficiency and saving resources. Thus, optimization of process parameters is an essential requirement to achieve environmentally friendly EDM. The aim of this paper was to select optimum process parameters for Ti–6Al–4V alloy green EDM. The experiments were designed using a Taguchi L9 orthogonal array. Peak current, gap voltage, lifting height and pulse duty factor were the process parameters considered in this study. The experimental data of MRR, SR and EWR were transferred to grey relational grade and were assessed to determine the significant machining parameters. The goal of seeking high efficiency, high quality and no-pollution machining meets the modern industrial requirements.

2 Experiments research

The work piece material was Ti–6Al–4V alloy with the dimension of 50 × 50 × 8 mm. The sample was milled and ground to keep parallel before the experiments. The chemical composition of the alloy is shown in Table 1. In this study, the CNC ACTSPARK EDM machine is used and the experimental setup is shown in Fig. 1. A red copper rod with the diameter of 10 mm and the height of 100 mm was used as electrode in this study. In addition, tap water was employed as a dielectric fluid in this investigation.

However, there are several machining parameters to be considered in the EDM process. The process parameters such as discharge current, gap voltage, the ratio of pulse width to pulse interval and lifting height have a clear effect on the EDM performance of Ti–6Al–4V alloy. Table 2 presents the four process parameters and three levels of the machining parameters designed in the experiments. This experiments used a negative polarity electrode and the Taguchi experimental design of $L_9(3^4)$ orthogonal array with four columns and nine rows. The results of experiments were depicted in Table 3.

Each experiment was repeated three times with the average being taken. The MRR, EWR and SR of the machined surface are the performance characteristics to evaluate the machining quality in this study. The EWR (in cubic millimeter per minute) is defined by the volume of the electrode worn in the period of working time in minute. The MRR (in cubic millimeter per minute) uses the same measuring unit that accounts for the work piece removal volume under the working time. To measure the weight of the worn electrode and workpiece removal, a precision balance (NL5003, China) was used. In the experiments, the surface roughness of the machined work piece was measured by a surface roughness tester (Taylor Hobson, UK).

3 Optimal multi-objective EDM parameters

The relation between the objective parameters and the machining parameters can be determined through the grey relational analysis method. Based on this theory, the grey relational grade can be acquired to judge of multiple objective parameters, adopting discrete value to evaluate and find the relationship of these data. The sequences can be categorized into two types for our research.


Fig. 1 The EDM experimental setup

Table 2 Experimental levels of the machining parameters

Symbol	Control parameters	Level 1	Level 2	Level 3
A	Discharge current(A)	11	16	20
B	Pulse width/pulse interval (T_{on}/T_{off}) (μs)	30:70	50:50	70:30
C	Gap voltage (V)	20	25	30
D	Lifting height (mm)	3	6	9

For the higher-the-better MRR, data preprocessing is calculated by:

$$x_i^*(k) = \frac{x_i^{(0)}(k) - \min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (1)$$

For the lower-the-better EWR and SR, data preprocessing is calculated by:

$$x_i^*(k) = \frac{\max x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (2)$$

Where $x_i^*(k)$ is obtained from grey relational analysis; min $x_i^{(0)}(k)$ is the minimum value of sequence $x_i^{(0)}(k)$; max$x_i^{(0)}(k)$ is the maximum value of the sequence $x_i^{(0)}(k)$; $x^{(0)}$ is the expectation value. Table 4 shows the data preprocessing results.

The grey relational coefficient can be calculated as:

$$\gamma\left(x_0(k), x_i^*(k)\right) = \frac{\left|\min_i \min_j\right| \left|x_0(k) - x_j^*(k)\right| + \zeta \max_i \max_j \left|x_0(k) - x_j^*(k)\right|}{\left|x_0(k) - x_i^*(k)\right| + \zeta \max_i \max_j \left|x_0(k) - x_j^*(k)\right|} \quad (3)$$

Where $x_0(k)$ the ideal value:

$\Delta_{0i}(k) = |x_0(k) - x_i^*(k)|$ is the difference of the absolute value between $x_0(k)$ and $x_i^*(k)$;

$\Delta \min = \forall j^{\min} \in i \forall k^{\min} |x_0(k) - x_j^*(k)|$ is the smallest value of Δ_{0i};

$\Delta \max = \forall j^{\max} \in i \forall k^{\max} |x_0(k) - x_j^*(k)|$ is the largest value of Δ_{0i};

ζ is a coefficient that is defined in the range between 0 and 1.

$$\Delta_v = \frac{1}{nm} \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{1}{n} \left|x_0(k) - x_j^*(k)\right| = 0.4032 \quad (4)$$

$$\varepsilon_\Delta = \frac{\Delta_v}{\Delta_{\max}} = 0.4032 \quad (5)$$

$$\Delta_{\max} \le 3\Delta_v \quad (6)$$

$$1.5\varepsilon_\Delta < \zeta \le 2\varepsilon_\Delta \quad (7)$$

In this paper, through the calculations, we selected ζ as 0.75. The grey relation coefficients of each performance characteristic are calculated using Formula (3), the results and grey relational grade are shown in Table 5. No. 7 shows the highest grey relational grade, indicating the optimal process parameter set of $A_1B_2C_2D_2$ has the best multiple performance characteristics among the nine experiments.

Since the experimental design is orthogonal, it is possible to separate the effects of each process parameter at different levels. For example, the mean of grey relational grade for the discharge current at level 1, 2 and 3 can be calculated by taking the average of the grey relational grade for the experiments1–3, 4–6 and 7–9, respectively. The mean of the grey relational grade for each level of other machining parameters

Table 3 $L_9(3^4)$ orthogonal array, control parameters and observed values

No.	Control factors					Observed values	
	A	B	C	D	Ra (μm)	MRR (mm³/min)	EWR (mm³/min)
1	1	1	1	1	2.17	2.96	0.21
2	1	2	2	2	2.37	1.28	0.14
3	1	3	3	3	2.83	1.73	0.16
4	2	1	2	3	2.19	3.27	0.30
5	2	2	3	1	2.61	4.30	0.30
6	2	3	1	2	2.86	4.07	0.28
7	3	1	3	2	2.15	5.90	0.41
8	3	2	1	3	2.65	6.62	0.41
9	3	3	2	1	4.27	6.36	0.41

Table 4 Grey relational generating of MRR, EWR and SR

Number	MRR	EWR	SR
	Ideal sequence		
	1	1	1
1	0.32	0.75	0.96
2	0	1	0.89
3	0.09	0.93	0.68
4	0.37	0.41	0.98
5	0.56	0.40	0.78
6	0.52	0.47	0.66
7	0.86	0.03	1
8	1	0.03	0.76
9	0.95	0	0

Table 5 Grey relational coefficients and grades

Number	Grey relational coefficient			Grey relational grades	
	MRR	EWR	SR	Average value	Rank
1	0.42	0.67	0.93	0.68	3
2	0.33	1	0.82	0.72	1
3	0.35	0.88	0.61	0.61	6
4	0.44	0.46	0.96	0.62	5
5	0.53	0.45	0.70	0.56	7
6	0.51	0.49	0.60	0.53	8
7	0.79	0.34	1	0.71	2
8	1	0.34	0.68	0.67	4
9	0.91	0.33	0.33	0.53	9

can be computed in a similar method. Figure 2 shows the influence of process parameters on machining characteristics. Based on the grey relational analysis, the predicted optimal process parameters set is $A_1B_1C_3D_2$. The mean value of the grey relational grade is 0.63. The process parameters sequenced in order of relative importance are the following: discharge current, the ratio of pulse width to pulse interval, gap voltage, and lifting height.

4 Confirmation experiment research

Since the optimal EDM process parameter set is obtained, the confirmation tests are used to check the performance characteristics improvement. The data of the confirmation experiment are compared with the data obtained by orthogonal array and grey theory prediction. The experimental comparison results between $A_1B_2C_2D_2$ and $A_1B_1C_3D_2$ are shown in Table 6. We can see that the MRR increased from 1.28 mm^3/min to 2.38 mm^3/min, the EWR decreased from 0.14 to 0.10 mm^3/min and the SR decreased from 2.37 to 1.93 μm. The corresponding amelioration in MRR is 87.3 %, EWR reduced 25.7 % and surface roughness reduced 18.9 %, respectively.

The SEM micrograph of surface topography with the orthogonal array parameters ($A_1B_2C_2D_2$) is shown in Fig. 3a and the optimal grey relation analysis theory predicted design ($A_1B_1C_3D_2$) is shown in Fig. 3b. We can see that the latter cracks are smaller than the former. Surface defects such as globules debris and melted drops are unclear except for crater scattering in $A_1B_1C_3D_2$. Figure 3 also shows that many micro-voids existed on the surface of the sample machined.

In addition, energy-dispersive X-ray spectroscopy of Ti–6Al–4V alloy of $A_1B_1C_3D_2$ is shown in Fig. 4. It indicated that the oxide form of TiO occurs when Ti–6Al–4V alloy is machined using copper electrode with tap water dielectric fluid. As illustrated in Fig. 4, the working area was occupied by the tap water droplets which can be easily vaporized and subsequently reacted with the melted material. The melted Ti metal is oxidized by oxygen decomposed from water.

The sole crater machined by EDM with tap water is measured by Confocal laser scanning microscope (OLYMPUS OLS3000), we can see that the surface roughness of $A_1B_2C_2D_2$ machining parameters in Fig. 5a is worse than the optimal grey theory prediction design ($A_1B_1C_3D_2$) shown in Fig. 5b. From Fig. 6a, we can see the cross-

Fig. 2 Process parameters effects on grey relational grade

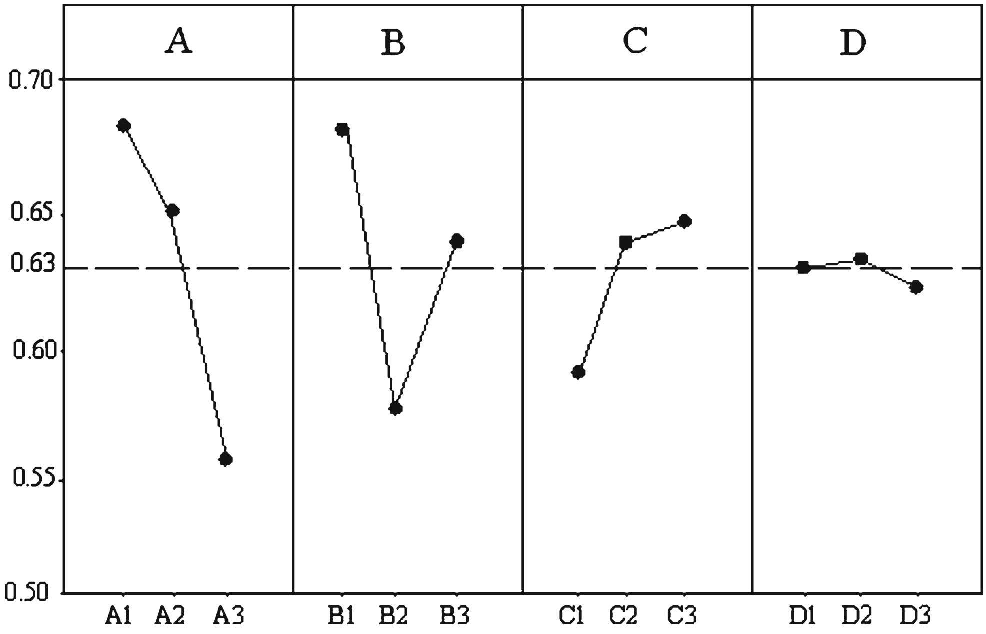
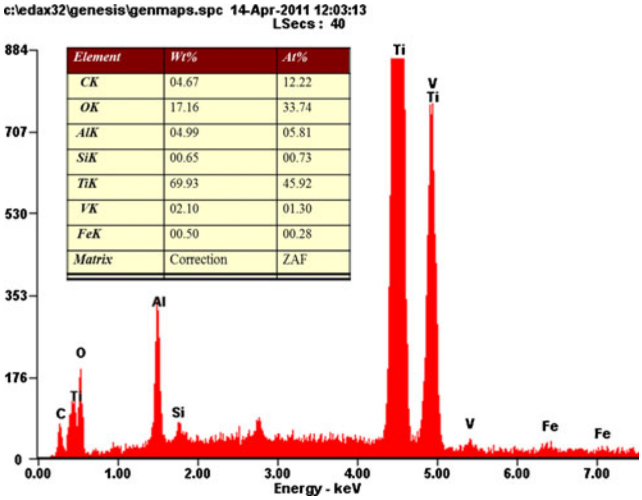


Table 6 Results of the confirmation experiments

Observer values	Orthogonal array	Optimal combination levels of machining parameters	
		Prediction	Experiment
Level	$A_3B_1C_3D_2$	$A_1B_1C_3D_2$	$A_1B_1C_3D_2$
MRR (mm^3/min)	5.90	–	6.02
EWR (mm^3/min)	0.41	–	0.17
SR (μm)	2.15	–	2.07
Grey relational grade	0.72	0.78	0.80



Element	Wt%	At%
CK	04.67	12.22
OK	17.16	33.74
AlK	04.99	05.81
SiK	00.65	00.73
TiK	69.93	45.92
VK	02.10	01.30
FeK	00.50	00.28
Matrix	Correction	ZAF

Fig. 4 Energy-dispersive X-ray spectroscopy of Ti–6Al–4V alloy $A_1B_1C_3D_2$

sectional side wall micrograph of samples machined with the orthogonal array parameters ($A_1B_2C_2D_2$) has much molten metal in the side wall, but in Fig. 6b, there is almost no molten metal in the side wall. So, the SR of $A_1B_1C_3D_2$ is better than $A_1B_2C_2D_2$. We found that using $A_1B_2C_2D_2$ parameters machined hole is larger than using $A_1B_1C_3D_2$ parameters. The results demonstrate that $A_1B_1C_3D_2$ parameters machined hole has better machining precision.

5 Conclusions

The manufacturing industry was considered as one of the main sources of environmental pollution. How to minimize the pollution is an important topic for manufacturers all over the world. The novel EDM Ti–6Al–4V with tap water was explored. The application of the Taguchi method and grey relational analysis to improve the multiple performance of the EWR, MRR and SR in the EDM has been reported in this paper. There are three conclusions gained as follows:

1. The optimal process parameters are 11 A discharge current, 30 V gap voltage, 3 mm lifting height, 30 μs pulse duration and 30 % duty factor.
2. The machining performance of the EWR decreased from 0.14 to 0.10 mm^3/min, the MRR increased from 1.28 to 2.38 mm^3/min, and the SR decreased from Ra 2.37 μm to Ra 1.93 μm, The corresponding improvement in MRR is 87.3 %, EWR reduced 25.7 %, and SR reduced 18.9 %, respectively.
3. It was indicated that the method of combining Taguchi and grey relational analysis was efficient and effective for multi-objective parameters optimization in green electrical discharge machining Ti–6Al–4V with tap water. Using tap water machining, Ti–6Al–4V alloy has high MRR, has no harm to operators and the environment, and also decreases the whole cost.

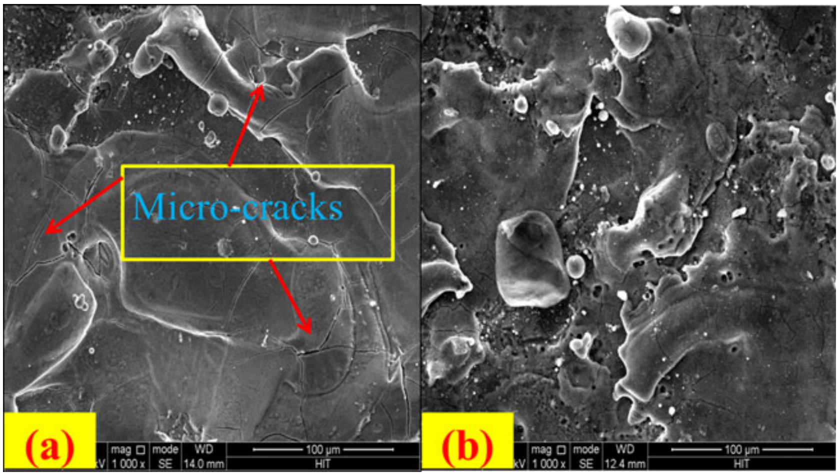


Fig. 3 SEM micrographs of the work piece. **a** $A_1B_2C_2D_2$, **b** $A_1B_1C_3D_2$

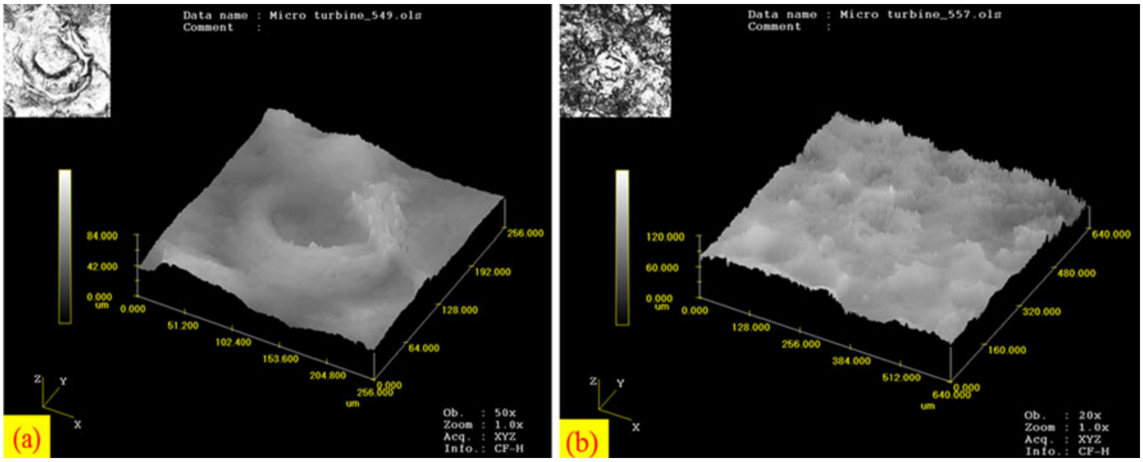
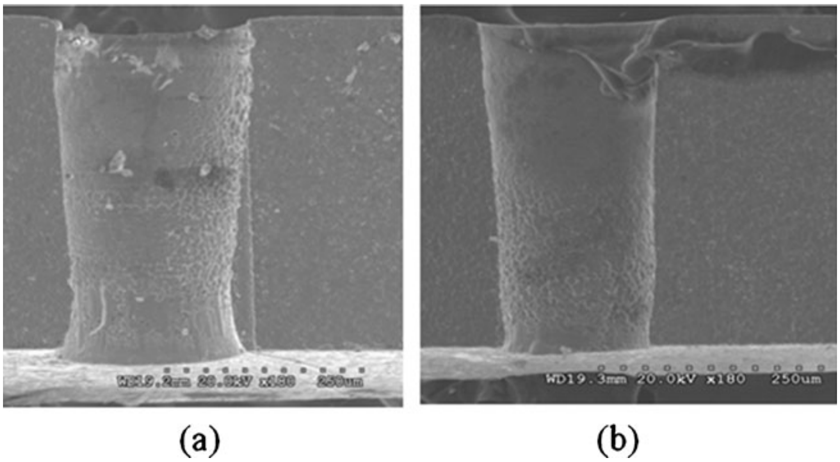


Fig. 5 The surface morphology of crater. **a** $A_1B_2C_2D_2$, **b** $A_1B_1C_3D_2$

Fig. 6 The side wall morphology of machined hole. **a** $A_1B_2C_2D_2$, **b** $A_1B_1C_3D_2$



Acknowledgments The work is partially supported by a grant from Shaanxi Provincial Department of Education Fund (Grant No. 2013JK1014). The authors would like to thank professor Fan of Xi'an technological university for her helpful suggestions, as well as thank Mr. Zhao for supplying the materials for the work pieces. We would also like to thank Dr Jia and Mr. Yang for their continuous support of this research.

References

1. Kao JY, Tsao CC, Wang SS, Hsu CY (2010) Optimization of the EDM parameters on machining Ti–6Al–4V with multiple quality characteristics. Int J Adv Manuf Technol 47(1–4):395–402
2. Lin YC, Yan BH, Chang YS (2000) Machining characteristics of titanium alloy (Ti–6Al–4V) using a combination process of EDM with USM. J Mater Process Technol 104:171–177
3. Pandey A, Singh S (2010) Current research trends in variants of electrical discharge machining: a review. Int J Eng Sci Technol 2(6):2172–2191
4. Leão FN, Pashby IR (2004) A review on the use of environmentally-friendly dielectric fluids in electrical discharge machining. J Mater Process Technol 149(1–3):341–346
5. Mohd Abbas N, Solomon DG, Fuad Bahari M (2007) A review on current research trends in electrical discharge machining (EDM). Int J Mach Tools Manuf 47(7–8):1214–1228
6. Singh S, Bhardwaj A (2011) Review to EDM by using water and powder-mixed dielectric fluid. J Min Mater Charact Eng 10(2):199–230
7. Abbas NM, Yusoff N (2012) Electrical discharge machining (EDM): practices in Malaysian industries and possible change towards green manufacturing. Procedia Eng 41:1684–1688
8. Sivapirakasam SP, Mathew J, Surianarayanan M (2011) Multi-attribute decision making for green electrical discharge machining. Expert Syst Appl 38(7):8370–8374
9. Klocke F, Zeis M, Klink A, Veselovac D (2012) Technological and economical comparison of roughing strategies via milling, EDM and ECM for titanium-and nickel-based blisks. Procedia CIRP 2(1):98–101
10. Medellin HI, De Lange DF, Morales J, Flores A (2009) Experimental study on electrodischarge machining in water of D2 tool steel using

two different electrode materials. Proc Inst Mech Eng, Part B: J Eng Manuf 223(11):1423–1430

11. Hasçalık A, Çaydaş U (2007) Electrical discharge machining of titanium alloy (Ti–6Al–4V). Appl Surf Sci 253:9007–9016
12. Singh GK, Yadava V, Kumar R (2010) Diamond face grinding of WC-Co composite with spark assistance: experimental study and parameter optimization. Int J Precis Eng Man 11(4):509–518
13. Lee HT, Hsu FC, Tai TY (2004) Study of surface integrity using the small area EDM process with a copper–tungsten electrode. Mater Sci Eng, A 364:346–356
14. Gu L, Li L, Zhao W, Rajurkar KP (2012) Electrical discharge machining of Ti6Al4V with a bundled electrode. Int J Mach Tools Manuf 53:100–106
15. Chen SL, Yan BH, Huang FY (1999) Influence of kerosene and distilled water as dielectrics on the electric discharge machining characteristics of Ti–6Al–4V. J Mater Process Technol 87:107–111
16. Zhang Y, Liu Y, Ji R, Cai B, Shen Y (2013) Sinking EDM in water-in-oil emulsion. Int J Adv Manuf Technol 65(5–8):705–716. doi:10.1007/s00170-012-4210-4
17. Yan BH, Tsai HC, Huang FY (2005) The effect in EDM of a dielectric of a urea solution in water on modifying the surface of titanium. Int J Mach Tools Manuf 45(2):194–200
18. Nguyen MD, Rahman M, Wong YS (2012) An experimental study on micro-EDM in low-resistivity deionized water using short voltage pulses. Int J Adv Manuf Technol 58(5–8):533–544
19. Fonda P, Wang Z, Yamazaki K, Akutsu Y (2008) A fundamental study on Ti–6Al–4V's thermal and electrical properties and their relation to EDM productivity. J Mater Process Technol 202(1–2):583–589
20. Kansal HK, Singh S, Kumar P (2007) Technology and research developments in powder mixed electric discharge machining (PMEDM). J Mater Process Technol 184:32–41
21. Kansal HK, Singh S, Kumar P (2008) Numerical simulation of powder mixed electric discharge machining (PMEDM) using finite element method. Math Comput Model 47:1217–1237
22. Wu KL, Yan BH, Lee JW, Ding CG (2009) Study on the characteristics of electrical discharge machining using dielectric with surfactant. J Mater Process Technol 209(8):3783–3789
23. Abdulkareem S, Khan AA, Konneh M (2009) Reducing electrode wear ratio using cryogenic cooling during electrical discharge machining. Int J Adv Manuf Technol 45:1146–1151
24. Gill SS, Singh J (2010) Effect of deep cryogenic treatment on machinability of titanium alloy (Ti-6246) in electric discharge drilling. Mater Manuf Process 25(6):378–385
25. Kumar J, Khamba JS (2010) Modeling the material removal rate in ultrasonic machining of titanium using dimensional analysis. Int J Adv Manuf Technol 48(1–4):103–119
26. Ghoreishi M, Atkinson J (2002) A comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary electro-discharge machining. J Mater Process Technol 120(1–3):374–384
27. Abdullah A, Shabgard MR (2008) Effect of ultrasonic vibration of tool on electrical discharge machining of cemented-tungsten carbide (WC-Co). Int J Adv Manuf Technol 38:1137–1147
28. Kibria G, Sarkar BR, Pradhan BB, Bhattacharyya B (2010) Comparative study of different dielectrics for micro-EDM performance during microhole machining of Ti–6Al–4V alloy. Int J Adv Manuf Technol 48(5–8):557–570
29. Teimouri R, Baseri H (2013) Experimental study of rotary magnetic field-assisted dry EDM with ultrasonic vibration of workpiece. Int J Adv Manuf Technol 67(5–8):1371–1384
30. Chattopadhyay KD, Satangi PS, Verma S, Sherma PC (2008) Analysis of rotary electrical discharge machining characteristics in reversal magnetic field for copper-en8 steel system. Int J Adv Manuf Technol 38:925–937
31. Ekmekci B (2007) Residual stresses and white layer in electric discharge machining (EDM). Appl Surf Sci 253:9234–9240
32. Zhang Y, Liu Y, Ji R, Cai B (2011) Study of the recast layer of a surface machined by sinking electrical discharge machining using water-in-oil emulsion as dielectric. Appl Surf Sci 257(14):5989–5997
33. Manivannan S, Devi SP, Arumugam R, Sudharsan NM (2011) Multi-objective optimization of flat plate heat sink using Taguchi-based grey relational analysis. Int J Adv Manuf Technol 52(5–8):739–749
34. Lin YC, Lee HS (2009) Optimization of machining parameters using magnetic-force-assisted EDM based on gray relational analysis. Int J Adv Manuf Technol 42(11–12):1052–1064
35. Lin JL, Lin CL (2002) The use of the orthogonal array with grey relational analysis to optimize the electrical discharge machining process with multiple performance characteristics. Int J Mach Tools Manuf 42(2):237–244
36. Tzeng CJ, Lin YH, Yang YK, Jeng MC (2009) Optimization of turning operations with multiple performance characteristics using the Taguchi method and grey relational analysis. J Mater Process Technol 209(6):2753–2759
37. Pan LK, Wang CC, Wei SL, Sher HF (2007) Optimizing multiple quality characteristics via Taguchi method-based grey analysis. J Mater Process Technol 182:107–116
38. Haq AN, Marimuthu P, Jeyapaul R (2008) Multi-response optimization of machining parameters of drilling Al/SiC metal matrix composite using grey relational analysis in the Taguchi method. Int J Adv Manuf Technol 37(3–4):250–255
39. Jung JH, Kwon WT (2010) Optimization of EDM process for multiple performance characteristics using Taguchi method and grey relational analysis. J Mech Sci Technol 24(5):1083–1090