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IMPROVEMENT OF SURFACE QUALITY OF Ti-6Al-4V ALLOY BY POWDER MIXED ELECTRICAL DISCHARGE MACHINING USING COPPER POWDER

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Abstract. *Electrical Discharge Machining (EDM) is one of the most popular non-conventional machining processes that are being used in many high precision manufacturing industries. To increase the EDM performance, a hybrid technique, namely, powder mixed electrical discharge machining (PMEDM) is generally used for getting more precise requirements. In this study, an experimental investigation is carried out in order to explore the machining performance of the PMEDM process on Ti-6Al-4V alloy using copper (Cu) powder in the EDM oil dielectric. Taguchi's L_{18} orthogonal array design has been utilized for design of experiments and the analysis of variance (ANOVA) has been performed with the help of Minitab-19 software. The optimal parametric setting of Cu powder mixed EDM has been found utilizing the Taguchi - Grey Relational Analysis (GRA) integrated approach and also validation of optimal parametric setting is done through experimentation. It is a novel approach for machining Ti-6Al-4V alloy by this PMEDM technique in which the surface quality has been improved significantly with the addition of suitable amount of Cu powder into the dielectric medium.*

Key Words: *PMEDM, Ti-6Al-4V Alloy, Cu Powder, Taguchi Analysis, Grey Relational Analysis (GRA), Surface Roughness (SR)*

1. INTRODUCTION

As one of the dominant non-conventional machining processes, electrical discharge machining (EDM) is widely used in manufacturing industry. In EDM ([1], the voltage is applied between the tool and the job material which are electrical conductors in nature. The EDM process improvement may be further enhanced by incorporating the convenient modifications like mixing the electrically conductive powder materials in the dielectric fluid medium which is called powder mixed EDM (PMEDM). Generally, PMEDM

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exhibits better performance in terms of various response parameters like material removal rate (MRR), tool wear rate (TWR), surface roughness (SR), etc. Here below, Fig. 1 shows the schematic diagram of a PMEDM process.

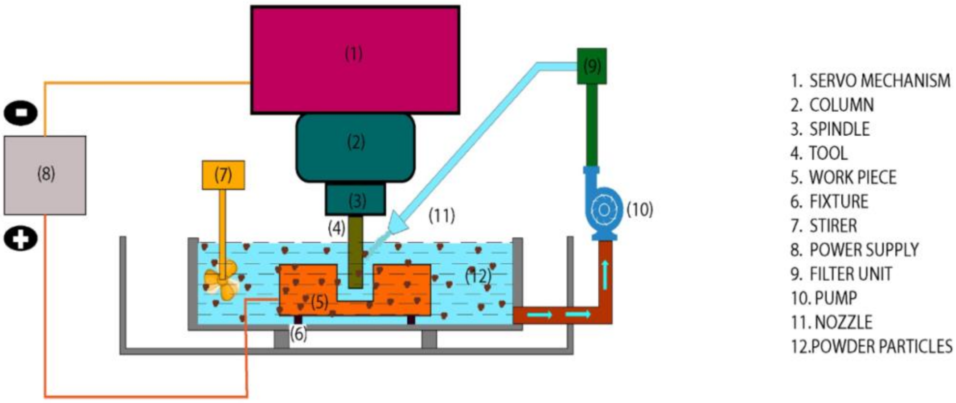

Fig. 1 Schematic view of PMEDM process

In last few decades, numbers of research studies have been carried out by several researchers in the domain of PMEDM and they showed the enhancement of different response parameters to achieve the better performance in this machining process. The effect of mixing fine graphite powder in PMEDM on tool steels with the improvement of 60% in MRR and decrement of 28% wear ratio has been carried out by Jeswani [2]. Mohri et al. [3] carried out their research to achieve a better surface finish by mixing of silicon powder into the dielectric medium on H-13 die steel. Chow et al. [4] proposed their work by mixing of SiC and aluminum powders on the EDM machining of titanium alloy by showing the increment of material removal depth, SR and TWR. Kibria et al. [5] carried out experimental study on the performance during micro-hole machining of Ti-6Al-4V alloy by using different dielectrics for micro-EDM. In their analysis they have shown that there is a significant influence of adding powder additives in improving machining performance criteria in PMEDM on Ti-6Al-4V alloy. Ojha et al. [6] carried out their research work on the area of improvement of surface roughness by PMEDM of EN8 steel. Here, to analyze the experiments, the response surface methodology has been adapted. The study of parametric optimization on performance characteristics of PMEDM on EN-8 steel has been analyzed by Garg and Ojha [7]. In their study, they observed various effects of some important process parameters on the performance measures. Bhattacharya et al. [8] carried out their work on PMEDM of die steels with the addition of silicon, graphite and tungsten powder. They observed that there is a better surface finish by EDM oil compared to kerosene dielectric. Also, micro-hardness of the machined surface has been significantly affected by various process parameters. Unses and Cogun [9] experimented on Ti-6Al-4V alloy by using graphite powder into the kerosene dielectric medium to enhance better performance of MRR, TWR, texture properties, etc. Long et al. [10] carried out their research on the machining of SKD61, SKD11 and SKT4 die steels adding titanium powder in PMEDM process by incorporating Taguchi analysis. Sugunakar et al. [11] showed that there is a reduction of recasting the layer thickness (RLT) by impinging the powder materials into the dielectric.

They also revealed that there is an increment of crater depth and diameter with the increase of powder from surface topography analysis. In PMEDM, the maximum MRR by using Al powder with copper tool and least radial over cut (ROC) by using Al_2O_3 powder with tungsten tool have been shown by Ramesh et al. [12]. B. K. Paul et al. [13] analyzed the performance of PMEDM process in terms of material removal efficiency, SR, surface crack density and white layer thickness during the machining of Inconel 718. Lamichhane et al. [14] carried out their research work on PMEDM on 316L stainless steel by adding Hydroxyapatite (HAp) nano-powder showing improvement of surface quality. Singh [15] revealed his research on PMEDM by using of high-speed steel T1 grade. Here, GRA has been introduced to optimize the input process parameters for getting a better output response in terms of TWR, MRR and SR, respectively. Within the selected process parameters, the comparative study of span-20 surfactant and micro-nano chromium mixed PMEDM by Hosni and Lajis [16] stated that for machining AISI-D2 hardened steel, span-20 surfactant and nano chromium powder showed better machining performance in terms of MRR and SR. Rajavel et al. [17] investigated the machinability condition of a metal matrix composite by PMEDM experimentation through Taguchi based GRA technique.

From the above studies it has been observed that there is no work carried out in PMEDM on Ti-6Al-4V alloy using Cu powder so far. Hence in this work, mixing of Cu powder in PMEDM process on Ti-6Al-4V alloy material using EDM oil as dielectric has been introduced for better enhancement of MRR, TWR and SR. Titanium alloy (Ti-6Al-4V) has been chosen as the workpiece material in our experiment because of its high strength, low weight ratio, high corrosion resistance, high temperature resistance and low-density element and abundant in nature. Also, it has a wide range of applications in the field of medical science, aerospace, automotive, chemical plant, pressure vessels, power generation, etc. In our experimentation, Cu is chosen as a powder material because of its high electrical conductivity which is a very important property in EDM process. It is also reported that the GRA technique has been incorporated with this proposed work to find out the optimal settings of process parameters.

2. Experimental Methodology

All the experiments have been conducted in the EDM machine (Make: EXCETEK TECHNOLOGIES, Model No.: ED-30). Throughout the experiment, the EDM oil is used as dielectric medium. Table 1 shows the properties of the EDM oil. As the chamber of conventional EDM machine is very large, it is difficult to do homogeneous mixing of the powder particles during the machining. Hence, to perform the experiment properly and to realize homogeneous mixing of the powder particles within the dielectric medium, it is important to introduce a newly designed and developed smaller chamber (carrying capacity of 15-20 liters of dielectric fluid) into the larger chamber. All the machining operations have been carried out in a newly developed experimental setup as shown in Fig. 2.

Table 1 EDM Oil properties

Color	Colorless
Kinematic Viscosity at 40°C, cSt	3.0 – 4.0
DI-electric Strength, KVA	45
Flash Point, PMCC, °C, Min.	108

Fig. 2 Newly developed PMEDM experimental set-up

In this new set-up, a separate bucket is kept outside the main chamber along with a centrifugal pump having capacity of 0.25 hp which has been attached for pumping operation from the bucket to the smaller chamber. Also, to achieve uniform distribution of the powder particles within the dielectric medium and to avoid settling of the powder particles at the bottom of the machining tank a motorized stirring mechanism has been incorporated in our experimentation. Due to the sharing of 40% and 25% of total discharge energy by anode and cathode, respectively, in the EDM process (Xia et al.) [18], the whole experimentation has been performed using straight polarity, i.e. job is kept as positive and the tool electrode is negative in this study. In our experimentation, Ti-6Al-4V alloy is taken as job material. Tables 2 and 3 show the chemical composition and physical properties of the job material, respectively. Cu powder is used in the proposed experiment as powder material whose properties are shown in Table 4. Table 5 shows the physical properties of tungsten electrode (7.5mm diameter) which is used as tool material.

Table 2 Chemical compositions of Ti-6Al-4V alloy material

Elements	Wt.%
Al	5.48
C	0.369
Fe	0.112
Sn	0.0625
Zr	0.0028
Mo	0.005
Cr	0.0099
Si	0.0222
V	4.22
Ni	<0.001
Cu	<0.02
Nb	0.0386
Ti	90

Table 3 Physical and mechanical properties of Ti-6Al-4V alloy material

Properties	Typical Value
Density (g/cm^3)	4.42
Melting range (°C±15°C)	1649
Specific heat (J/Kg °C)	560
Thermal conductivity (W/m K)	7.2
Tensile strength (MPa)	1000
Elastic modulus (GPa)	114
Hardness (Rockwell C)	36

Table 4 Properties of copper (Cu) powder material

Item	Description
Melting point	1083^{0}C
Boiling point	2562^{0}C
Density	8.96 g/cm^3
Heat of fusion	13.26 KJ.mol^{-1}
Specific heat	0.39 KJ/Kg K
Thermal conductivity	401 W. m^{-1}.K^{-1}
Thermal expansion	(25^{0}C) 16.5 µm.m^{-1}.K^{-1}
Electrical resistivity	1.673 µΩ-cm @20^{0}C

Table 5 Physical and mechanical properties of Tungsten tool material

Item	Description
Tensile strength	1725 MPa
Yield strength	750 MPa
Modulus of elasticity	400 GPa
Atomic weight	183.84
Melting point	3422^{0}C
Density	19.3 gm/cm^3

While analyzing several past references, it has been observed that the researcher tried to increase the performance of the EDM process by applying various techniques during machining. In this proposed study, the authors carried out some preliminary investigation and after analyzing the output characteristics it is identified that the main influencing parameters which played dominancy over the performance characteristics of PMEDM are peak current (I_p), pulse on time (T_{on}), pulse off time (T_{off}) and powder concentration (C_p). So, these parameters have been chosen as variable parameters to investigate the effects on performance measures, namely, MRR, TWR and SR. The other process parameters are kept constant throughout the experimentation. As there are only four variables, for performing the experiments, the Taguchi's L_{18} orthogonal array design has been adapted for design of experiments [19] having three variables with three levels each and the remaining variable with six levels (Table 6). While selecting levels of parameters, the authors have chosen the maximum range where stable machining was carried out during preliminary investigations.

Table 6 Process parameters and their levels during PMEDM technique

Parameters	Symbol	Level	Units
Peak Current	I_p	4,7,10	A
Pulse-on-Time	T_{on}	10,15,20	µs
Pulse-off-Time	T_{off}	30,40,50	µs
Powder Concentration	C_p	0,4,8,12,16,20	g/l

Each experiment was run for 3 times and the average value of the three was calculated for measuring MRR, TWR and SR. The weight of the work piece and tool material was taken before and after the machining processes to measure MRR and TWR by using an electronic weighing balance (Make: ACZET PVT. LTD., Vasai (E); Model: CY1003C). Surface roughness in terms of center-line average value or simply CLA value (R_a) of the machined work piece surfaces have been measured by using a portable surface roughness profilometer (Make: Mitutoyo, Japan, Model:SJ-410, Courtesy: Jadavpur University). The important process parameters which affect the performance of the PMEDM process have been identified by applying the ANOVA technique with the help of Minitab-19 software.

3. RESULTS AND DISCUSSION

Table 7 shows overall experimental results that have been carried out based on the Taguchi's experimental design (L_{18}) by which the significant performance parameters, i.e. MRR, TWR and SR (R_a) were calculated. Further, two important outcomes namely, MRR and SR, are recognized conflicting in nature. So, it is necessary to make a trade-off between these two conflicting response parameters for any manufacturing products or parts. This trade off can be made by any multi-objective optimization method. In this research study, the GRA technique is introduced as a multi-objective optimization technique.

Table 7 Experimental Results

Exp. No.	I_p (A)	T_{on} (μs)	T_{off} (μs)	C_p (g/l)	MRR (gm/min)	TWR (gm/min)	SR (μm)
1.	4	10	30	0	0.0014	0.0024	3.006
2.	7	15	40	0	0.0021	0.0043	3.457
3.	10	20	50	0	0.0029	0.0065	4.157
4.	7	10	30	4	0.0024	0.0043	2.776
5.	10	15	40	4	0.0033	0.0071	2.889
6.	4	20	50	4	0.0009	0.0015	2.938
7.	4	10	40	8	0.0009	0.0018	3.253
8.	7	15	50	8	0.0017	0.0038	3.611
9.	10	20	30	8	0.0033	0.0062	3.422
10.	10	10	50	12	0.0021	0.0057	4.156
11.	4	15	30	12	0.0013	0.0022	3.383
12.	7	20	40	12	0.0020	0.0043	3.653
13.	10	10	40	16	0.0023	0.0061	4.058
14.	4	15	50	16	0.0009	0.0016	3.547
15.	7	20	30	16	0.0026	0.0045	3.845
16.	7	10	50	20	0.0013	0.0030	5.145
17.	10	15	30	20	0.0035	0.0080	4.615
18.	4	20	40	20	0.0014	0.0019	3.643

3.1. Material Removal Rate (MRR)

MRR is defined as the weight of the material removed from the workpiece for a specified period. So, the unit of MRR is taken to be gm/min. The influence of the process parameters on the mean MRR is presented in Fig. 3 and the corresponding ANOVA analysis is drawn in Table 8. It has been noticed from the response graph (Fig. 3) that with the increase of peak current values from 4 to 10 A, MRR significantly increased. The available discharge energy in the inter electrode gap (IEG) is directly affected by the peak current. At a higher peak current, MRR increases significantly because of the higher current density caused by increasing spark energy with the current increase which causes overheating of the job material. At low current, the amount of energy utilized in melting and vaporizing the electrodes is not so intense due to the generation of a small quantity of heat at electrodes and its major area is absorbed by the surroundings. Likewise, it is evident from the ANOVA results that the peak current played a major role in material removing.

From Fig. 3 and ANOVA results of MRR (Table 8), it is clearly understood that the pulse off time is one of the influencing parameters in the case of MRR. MRR decreases with the increase of pulse off time. It happens due to the fact that with the increase in pulse off time the machining idle time increases, so no machining is happening. It is clear from the figure that MRR is inversely proportional to the pulse off time. Pulse on time is another important parameter in material removing process. From Fig. 3, it is noticed that MRR increases to a smaller extent with the increasing effect of pulse on time from 10 μs to 20 μs; this happens due to the supplement of energy per cycle resulting in more material melting and evaporating. Further on, it is also seen that there is not such an impact of adding copper powder in material removal. It is also noticed that by adding Cu powder concentration up to 8 g/l, MRR decreases and marginally increases thereafter.

This may be due to the fact that the additional powder accumulates in the gap and minimizes the discharge transitivity and as a result the MRR is reduced.

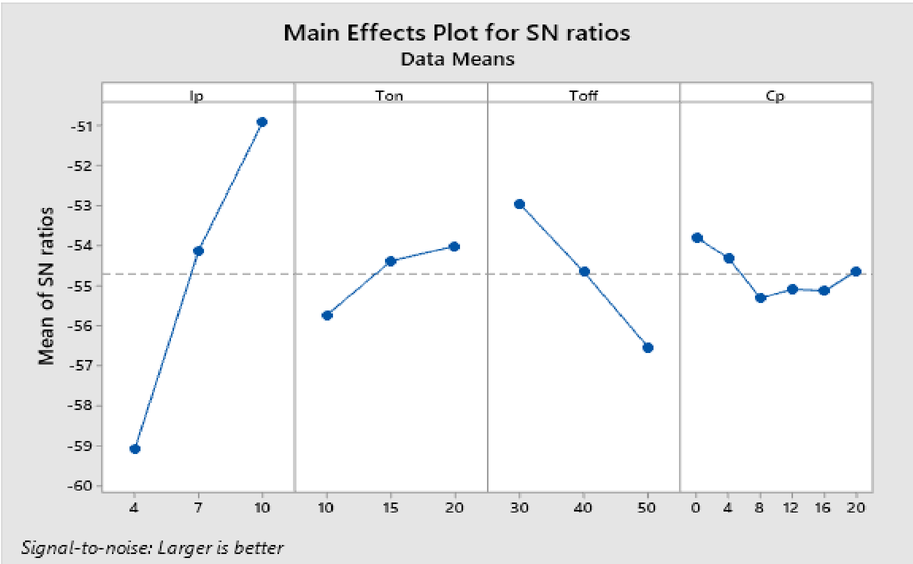

Fig. 3 Effect of process parameters on MRR

Table 8 Detail of ANOVA analysis of MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Ip	2	0.000009	0.000009	0.000005	122.13	0.000
Ton	2	0.000001	0.000001	0.000000	9.52	0.014
Toff	2	0.000002	0.000002	0.000001	24.04	0.001
Cp	5	0.000000	0.000000	0.000000	1.66	0.276
Error	6	0.000000	0.000000	0.000000		
Total	17	0.000012				

Model Summary

S	R-sq	R-sq(adj)
0.0001958	98.16%	94.78%

3.2. Tool Wear Rate (TWR)

TWR is defined as the amount of weight loss of tool material per unit time (usually minute) during machining. So, its unit is gm/min. The effect of process parameters on mean of TWR is presented in Fig. 4 and corresponding ANOVA analysis is drawn in Table 9. From the response graph (Fig. 4) as well as from ANOVA analysis (Table 9), it is very clear that the peak current is the major significant process parameter on TWR. The figure shows that with the increment of the peak current, tool wear is rapidly increased. During the current flows through the plasma column, the electrons collide with the dielectric particle due to the in which positive ions are produced and these produced positive ions flow towards the negative electrode (tool) resulting in melting and vaporizing of tool material. Thus, tool wear takes place.

It is also noticed that with the increment of pulse on time from 10 µs to 15 µs tool wear increases and marginally decreases thereafter. Also, tool wears decreases with the increase of pulse-off time as no machining takes place during that pulse off period. When powder is added up to 8 g/l, TWR decreases a little bit and then it increases with the increase of powder concentration from 8 g/l to 12 g/l and marginally decreases thereafter. It is due to the fact that with increase of powder concentration, sparking energy decreases which lowers the tool wear rate.

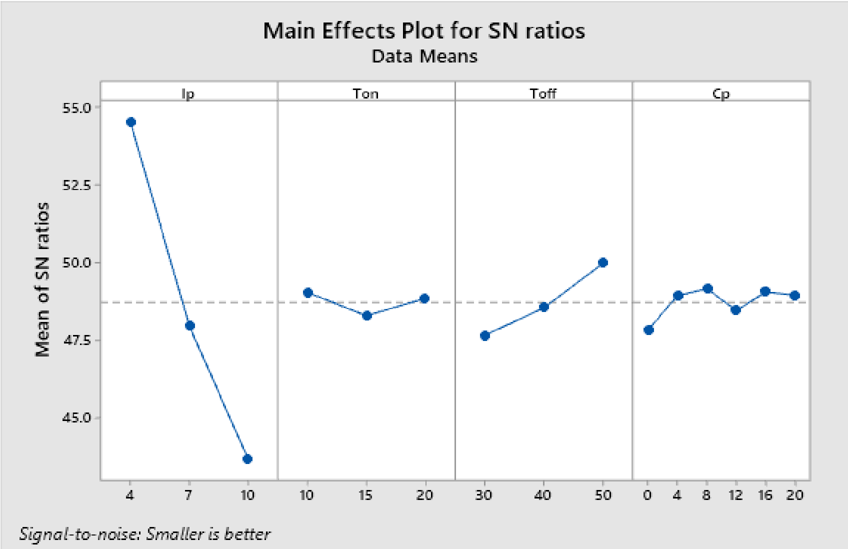

Fig. 4 Effect of process parameters on TWR

Table 9 Detail of ANOVA analysis of TWR

Source	DF	Seq SS	Adj SS	Adj MS	F	P			
Ip	2	0.000066	0.000066	0.000033	143.78	0.000			
Ton	2	0.000001	0.000001	0.000001	2.48	0.164			
Toff	2	0.000003	0.000003	0.000001	5.56	0.043			
Cp	5	0.000000	0.000000	0.000000	0.42	0.817	Model Summary		
Error	6	0.000001	0.000001	0.000000			S	R-sq	R-sq(adj)
Total	17	0.000072					0.0004807	98.08%	94.55%

3.3. Surface Roughness (SR) (R_a)

Superior surface finish is a major requirement for all machine components. Simply, surface roughness (SR) can be defined as the evaluation of the surface texture in terms of surface irregularities, waviness and flaws. Surface roughness most commonly refers to the variations in the height of the surface relative to a reference plane. It is measured either along a single line profile or along a set of parallel line profiles (surface maps). It is usually characterized by: (a) R_a (Centre-line average, CLA) value, (b) R_q (Root mean square, RMS) value and (c) R_z (Average peak-to-valley height) value. In our study, we have taken R_a value of surface roughness which is the most universally used roughness parameter. It is defined as the average absolute deviation of the roughness irregularities from the mean line sampling length. Mathematically, it is written by the application of the following equation:

$$R_a = \frac{1}{L}\int_0^L |z(x)|dx \tag{1}$$

where *'L'* is the sampling length, *'z'* is height of peaks and valleys of roughness profile and *'x'* is the profile direction. The effect of process parameters on surface roughness is presented in Fig. 5. Powder concentration is the most crucial factor which is seen from the figure and its ANOVA study. The ANOVA results are shown in Table 10. From the Fig. 5, it is seen that with the increment of the peak current, surface roughness increases. This is because of the formation of deeper and larger craters takes place due to increase in the spark energy with the increase in the peak current.

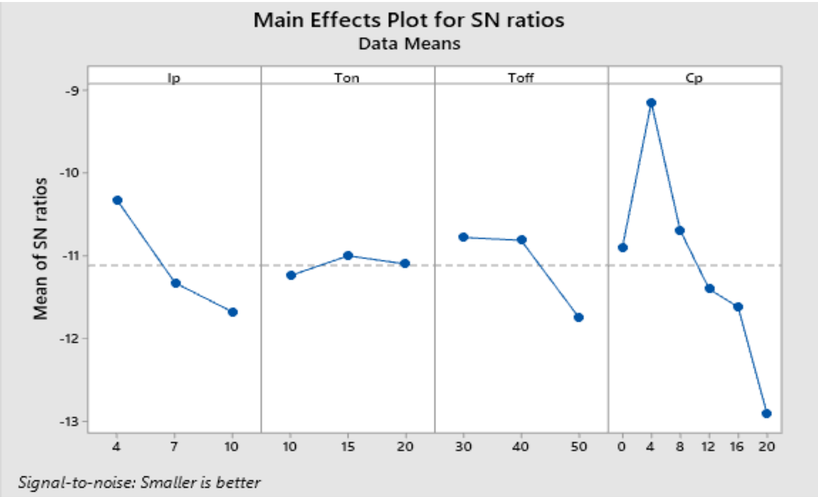

Fig. 5 Effect of process parameters on SR

Table 10 Detail of ANOVA analysis of SR (R_a)

Source	DF	Seq SS	Adj SS	Adj MS	F	P			
Ip	2	1.13766	1.13766	0.56883	8.28	0.019			
Ton	2	0.07565	0.07565	0.03782	0.55	0.603			
Toff	2	0.72550	0.72550	0.36275	5.28	0.048			
Cp	5	4.12681	4.12681	0.82536	12.02	0.004	Model Summary		
Error	6	0.41201	0.41201	0.06867			S	R-sq	R-sq(adj)
Total	17	6.47764					0.262047	93.64%	81.98%

It is also seen that when the pulse on time increases from 10 μs to 15 μs, R_a value marginally decreases and thereafter increases slightly with further increment of pulse on time. From the analysis of pulse off time, it is noticed that the surface roughness increases significantly with the increment of pulse-off time. This is due to the fact that with the increased pulse off time, the debris in the machining zone is properly washed away and cleaned by the flushing of dielectric fluid. So when the next sparking takes place on the cleaned surface, the waste of the spark energy is less and full energy is utilized to create a larger and deeper crater. As a result, the surface roughness increases. It is noticed that the surface quality gets improved with the addition of a suitable amount of the powder up to 4 g/l. With the addition of conductive powder materials, the gap between the electrodes becomes wide due to the decrement of insulating strength of the EDM oil causing stable discharge. As a result, due to the reduction of electrical density, shallow craters develop on the machining surface which leads to better surface finish. Oppositely, surface roughness increases with further addition of powder (up to 20 g/l) due to the fact that after removing a good amount of material results, deeper and larger craters during machining and arc formation over the workpiece takes place. This helps to generate higher surface roughness.

3.4. Multi-objective optimization using the Grey Relational Analysis (GRA)

It has been observed that direct application of the Taguchi methodology fails in optimizing multi-response characteristics. Generally, single response characteristic is optimized by the designing of Taguchi. Hence other methods are required with the combination of the Taguchi method in order to optimize multi-response characteristics involved in the analysis. In 1982, Deng proposed the grey system theory. It is being widely used for analyzing any system in which control parameters have complex characteristics. The complicated interrelationships among multiple response parameters are efficiently solved by the application of this theory. Investigation of a system by means of relational coefficient, relational grade and decision may be carried out based on this grey theory. Consequently, the grey relational grade will be evaluated by using GRA to evaluate the multiple response parameters for getting the optimal values.

Several researchers like Tosun and Pihtili [20], Kuo et al. [21], Tosun [22] have done multi-objective optimization of several machining processes by applying this technique. Lin and Lin [23] first reported the application of GRA technique for multi-objective optimization in the field of EDM. Later several other researchers like Singh et al. [24], Lin and Lee [25] applied this multi-objective optimization technique to get the optimal value of the process parameters in the area of EDM and WEDM processes. The multi-objective optimization by using this Taguchi - GRA integrated methodology has been performed in the following steps:

a. The experimental results have been normalized first.
b. Grey relational coefficients have been calculated by performing grey relational generation.
c. Grey relational grades have been evaluated by averaging the grey relational coefficients.
d. The optimal level of process parameters is selected.

In this research work by considering four input parameters and three output parameters, the GRA methodology is performed. The output parameters are the MRR, TWR and SR. The main objective of this multi response optimization is to increase productivity while maintaining desired surface finish and geometrical accuracy.

3.4.1. Normalization of the experimental results

In this methodology, firstly the original data sequence has been transferred to a comparable sequence in a scale range between zero and one which is called normalization. Indicating a higher value for better performance, i.e. MRR in our case, it can be normalized by the following expression:

$$x_{ij} = \frac{y_{ij} - Min[y_{ij}, i = 1,2,...n, j = 1,2,...., m]}{Max[y_{ij}, i = 1,2,...n, j = 1,2,...., m] - Min[y_{ij}, i = 1,2,...n, j = 1,2,...., m]} \tag{2}$$

where, x_{ij} is the normalized value of y_{ij} of experiment i (i=1,2,…..n) for response j (j = 1,2,….m).

And, TWR and SR whose lower value indicates better performance can be expressed in equation as follows:

$$x_{ij} = \frac{Max[y_{ij}, i = 1,2,...n, j = 1,2,...., m] - y_{ij}}{Max[y_{ij}, i = 1,2,...n, j = 1,2,...., m] - Min[y_{ij}, i = 1,2,...n, j = 1,2,...., m]} \tag{3}$$

If any response parameter requires achieving a particular value, then it can be normalized by using the following equation:

$$x_{ij} = 1 - \frac{\left| y_{ij}[y_{ij}, i = 1,2,...n, j = 1,2,...., m] - x_0 \right|}{Max[y_{ij}, i = 1,2,...n, j = 1,2,...., m] - x_0} \tag{4}$$

Here, x_0 is the desired value of the response parameter.

3.4.2. Calculation of the Grey Relational Coefficient

The closeness of x_{ij} to x_{0j} is determined by the calculation of the grey relational coefficient. The closeness of x_{ij} to x_{0j} is indicated by a higher value of the grey relational coefficient. Grey relational coefficients have been calculated by using the following equation:

$$z(x_{0j,} x_{ij}) = \frac{\delta_{Min} + \xi\delta_{Max}}{\delta_{ij} + \xi\delta_{Max}}, [i = 1,2,...., n \ \& \ j = 1,2,...., m] \tag{5}$$

where:

$$\delta_{ij} = \left| x_{0j} - x_{ij} \right| \tag{6}$$

$$\delta_{Min} = Min[\delta_{ij}, i = 1,2,...., n \ \& \ j = 1,2,...., m] \tag{7}$$

$$\delta_{Max} = Max[\delta_{ij}, i = 1,2,...., n \ \& \ j = 1,2,...., m] \tag{8}$$

and ξ is the distinguishing coefficient, $\xi \in (0,1)$.

Generally, fitting the practical requirements is done by adjusting the distinguishing coefficient and it is usually set at 0.5.

3.4.3. Calculation of the Grey Relational Grade

The grey relational grade is defined as the average of the grey relational coefficients by considering a weight parameter for a particular experiment and it is calculated by using the following equation:

$$\Gamma(x_{0,} x_i) = \frac{1}{m} \sum_{j=1}^{m} w_j z(x_{0j,} x_{ij}) \tag{9}$$

where w_j is the weight of jth factor.

By using Eq. (9), the grey relational grade for all the 18 experiments has been calculated. Now, the experiment which shows the highest grey relational grade is providing the optimal level of different parameters. In other words, the experiment having the maximum grey relational grade is the best choice for getting the optimal response parameter setting among all the response parameter settings considered.

3.4.4 Optimization using the GRA

In this research study, a conventional gray relation analysis has been proposed. The experimental data based on the Taguchi's (L_{18}) orthogonal array design is taken for optimization.

Here the optimization problem is formulated as:

$$\text{Maximize, MRR} = f(I_p, T_{on}, T_{off}, C_p)$$

$$\text{Subject to tool wear rate} \leq \alpha \text{ and surface roughness} \leq \beta$$

where α is the maximum allowable TWR and β is the maximum allowable surface roughness (R_a). As per Table 7, the range of α is within 0.0015 gm/min to 0.0080 gm/min and for β is within 2.776 μm to 5.145 μm. The desired value of the tool wear rate is taken as 0.0045 gm/min and the surface roughness of the workpiece is taken as 2.8 μm. The normalized value for MRR is computed by using the Eq. (2). And by using the Eq. (4), the normalized value for TWR and surface roughness (R_a) with their desired values have been calculated. All the normalized values are shown in Table 11. Then from those normalized values of each of the responses, the grey relational coefficient and grade are calculated by using the Eq. (5) and Eq. (9), respectively, for all eighteen experiments. All these results are summarized in Table 12.

It is seen from the Table 12 that due to the highest grey relational grade of experiment no. 4 after giving the equal weight to all the three responses, the parametric combinations corresponding to this experiment give the best multiple performance characteristics of all 18 experiments. It is found that this combination gives MRR = 0.0024 gm/min, TWR = 0.0043 gm/min and SR (R_a) = 2.776 μm.

Table 11 Normalized decision matrix for MRR, TWR and SR (Ra)

Exp. No.	MRR	TWR	SR
1.	0.192307692	0.4	0.912153518
2.	0.461538462	0.942857143	0.719829424
3.	0.769230769	0.428571429	0.421321962
4.	0.576923077	0.942857143	0.989765458
5.	0.923076923	0.257142857	0.962046908
6.	0	0.142857143	0.941151386
7.	0	0.228571429	0.806823028
8.	0.307692308	0.8	0.654157783
9.	0.923076923	0.514285714	0.734754797
10.	0.461538462	0.657142857	0.421748401
11.	0.153846154	0.342857143	0.751385928
12.	0.423076923	0.942857143	0.636247335
13.	0.538461538	0.542857143	0.463539446
14.	0	0.171428571	0.681449893
15.	0.653846154	1	0.554371002
16.	0.153846154	0.571428571	0
17.	1	0	0.226012793
18.	0.192307692	0.257142857	0.640511727

Table 12 Grey relation coefficient, Grade and Rank matrix for MRR, TWR and SR

Exp. No.	Grey relation coefficient			Grey Relation	Rank
	MRR	TWR	SR	Grade	
1.	0.382352941	0.454545455	0.855320596	0.564072997	9
2.	0.481481481	0.897435897	0.644470861	0.674462747	5
3.	0.684210526	0.466666667	0.466123519	0.539000237	10
4.	0.541666667	0.897435897	0.985423687	0.808175417	1
5.	0.866666667	0.402298851	0.934648784	0.7345381	2
6.	0.333333333	0.368421053	0.899701977	0.533818788	11
7.	0.333333333	0.393258427	0.725351855	0.483981205	15
8.	0.419354839	0.714285714	0.594433799	0.576024784	7
9.	0.866666667	0.507246377	0.657040647	0.676984563	4
10.	0.481481481	0.593220339	0.466307867	0.513669896	12
11.	0.371428571	0.432098765	0.671637392	0.491721576	14
12.	0.464285714	0.897435897	0.582107845	0.647943152	6
13.	0.52	0.52238806	0.48510983	0.509165963	13
14.	0.333333333	0.376344086	0.614253421	0.44131028	17
15.	0.590909091	1	0.531706625	0.707538572	3
16.	0.371428571	0.538461538	0.335198135	0.415029415	18
17.	1	0.333333333	0.394664248	0.575999194	8
18.	0.382352941	0.402298851	0.584996002	0.456549264	16

Here, it is clearly observed that for this optimal MRR the corresponding TWR and SR (R_a) are within the desired limit. Hence, this experimental set up gives the optimal result. So, based on the above discussions, the optimal machining parameter combinations would be as follows: Peak Current (I_p) = 7 A, Pulse on Time (T_{on}) = 10 µs, Pulse off Time (T_{off}) = 30 µs and Powder Concentration (C_p) = 4 g/l.

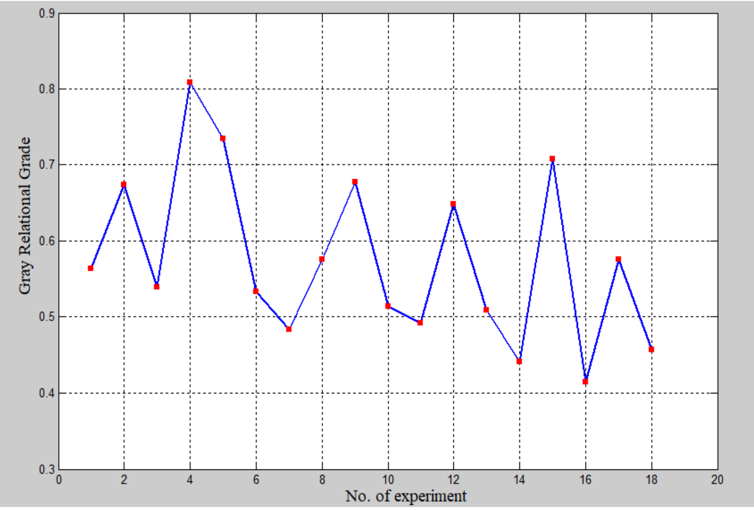

Fig. 6 Plot of grey relational grade values on experiment numbers

Fig. 6 shows the plot of grey relational grade values on experiment numbers. From this plotting, it is revealed that the experiment number 4, i.e. the multi-objective parametric combinations setting of peak current of 7 A, pulse on time of 10 µs, pulse off time of 30 µs and powder concentration of 4 g/l gives the least surface roughness (R_a) value i.e. 2.776 µm among all the experiments.

3.5. Surface Topography Analysis

Fig. 7(a) and (b) shows the 3D surface topography of the best (R_a = 2.776 µm) and worst (R_a = 5.145 µm) surface, respectively, using CCI (Make: Taylor & Hobson) of the machined surface. From the figures, it is observed that at a higher powder concentration, the crater produced in the second case (Fig. 7(b)) is larger and deeper, and more high peaks are developed due to more arcing which promotes higher surface roughness.

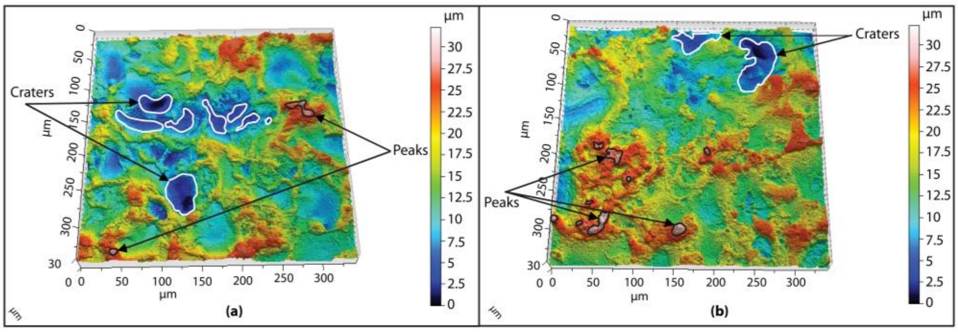

Fig. 7 3D surface stereogram of Ti-6Al-4V alloy after machining at (a) I_p= 7 A, T_{on} = 10 µs, T_{off} = 30 µs and C_p= 4 g/l and (b) I_p= 7 A, T_{on} = 10 µs, T_{off} = 50 µs and C_p= 20 g/l

4. Conclusions

In this work, the performance parameters namely MRR, TWR and SR by PMEDM of Ti-6Al-4V alloy material with Cu powder are investigated. As there are response parameters of conflicting nature, the multi-objective optimization of process parameters was done by the Taguchi based Grey Relational Analysis method. This is the novel approach by using copper powder within the EDM oil dielectric fluid in EDM process to enhance the surface quality of Ti-6Al-4V alloy material. Based on the experimentation and analyzing the results, the following conclusions can be drawn:

(a) It has been observed that the copper powder concentration is the most significant factor in analyzing the surface quality. It is noticed that surface quality gets improved with the addition of suitable amount powder from 0 g/l to 4 g/l and thus decreases with further addition of powder up to 20 g/l.

(b) The main factors which affect the MRR are peak current and pulse off time. The removal of material increases rapidly with the increase in peak current. The reverse effect observed in the case of pulse off time. There is not so severe effect of powder concentration in material removing. MRR decreases with the increase in powder.

(c) The response parameter peak current has the main role in affecting the TWR. With the increase in current, TWR increases significantly. There is no such noticeable effect of other process parameters on TWR.

(d) The combination of Taguchi Methodology and GRA technique have been very rightly and satisfactorily chosen to analyze the multi-objective optimization parametric combinations setting and results of responses during PMEDM of Ti-6Al-4V alloy material.

(e) The optimal value of machining process parameters of peak current (I_p), pulse on time (T_{on}), pulse off time (T_{off}) and powder concentration (C_p) are 7 A, 10 µs, 30 µs and 4 g/l, respectively, for this copper powder mixed electrical discharge machining process.

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