Grey Relational Analysis of EDM of Ti6Al4V using TiC/Cu Composite Tool Electrode Made with Nano and Micron Sized Particles

Chundru Venkata Rao, Koona Ramji, Pujari Srinivasa Rao

Abstract: ***This paper covers the use of Taguchi based grey relational analysis in EDM process. The analysis is used to determine an optimum combination of process parameters, which involves individual and simultaneous improvement of surface roughness (SR) and the micro hardness (MH) of Ti6Al4V alloy in electric discharge machining (EDM). The tool used in the machining process is TiC/Cu powder metallurgy (P/M) electrode. Taguchi's L18 mixed orthogonal array is used to plan experimentations which includes the machine tool and electrode parameters as the study parameters. The analysis of variance (ANOVA) for grey relational grade showed that particle size EDM electrode was the most dominant factor (64.13%) followed by peak current (7.41%) in influencing surface quality of EDMed Ti6Al4V alloy. Whereas, peak current is the most influential parameter while evaluating the individual responses of SR and MH. Finally, the optimum combination of process parameters was validated by confirmation experiments that considerably improved the multiple quality characteristics simultaneously.***

Keywords: ***Ti6Al4V alloy, Surface roughness, Micro hardness, Taguchi method, Grey relational analysis, ANOVA.***

I. INTRODUCTION

Electric discharge machining (EDM) is one of the extensively used non-conventional machining processes for machining of difficult to cut materials through surface modification. The material removal is achieved by the electrical discharges generated between tool and workpiece which are separated by a dielectric fluid. The machining process involves a lot of heat generation between the workpiece and the tool electrode. The temperature generated melts the workpiece at the point of discharge and vaporizes the material. This phenomena helps the material to be removed from the workpiece and the electrode [1]. Resulting in deposition of electrode particles on the workpiece and leads to the surface modification of the workpiece, which is identified as one of the key manufacturing processes [2]. Due to the surface modification, some improvements occur in terms of resistance to wear, resistance to corrosion, hardness, fatigue resistance etc. Copper and its alloys, brass, zinc, tungsten and graphite are the commonly used EDM electrodes materials. The above conventional solid electrodes have their own advantages and disadvantages. Due to the unavailability of desirable properties in a single tool material, researchers have focused on developing a composite electrode by mixing of various materials and produce through powder metallurgy (P/M) method. Powder metallurgy (P/M) is one of the least expensive techniques to produce tool electrodes. This technique is used to manufacture tool electrodes which can be used for machining any type of electrical conductive materials. The materials included are the ones which cannot be machined using conventional machining process. One of the materials is alloys of Titanium. The low thermal conductivity and elastic modulus of Titanium alloys makes poor machinable characteristics, hence unsuitable for conventional machining processes [3-5]. Whereas, the same Titanium alloys can be efficiently machined with unconventional machining processes like electric discharge machining. However, machining of Titanium alloys with EDM process needs optimum control of machining parameters for obtaining good surface characteristics. The EDM process is currently being employed in machining of Titanium and its alloys. These alloys have significantly good properties which include high strength and corrosion resistance. Due to its different properties, titanium and its alloys are used in various fields including medical and chemical industries. They are also significantly used in aviation industries. But in all the above applications it necessitates the simultaneous improvement of performance measures like surface roughness, hardness, wear resistance, corrosion resistance etc. In view of that, the following researchers have attempted to improve the various performance measures simultaneously by optimizing the process parameters. Rajesh Khanna et al. [6] evaluated the multiple performance characteristics improvement for Al7075 through electric discharge drilling by Taguchi grey relative theory and obtained the optimum results for improvement of TWR and MRR. Machining of C-40 steel using W-Cu P/M tool electrode was analyzed by P.K. Patowari et al. [7] using EDM. The experimentation was carried out and output parameters like mass transfer rate and deposited layer thickness were analyzed. The surface roughness parameter was also studied. H. Payal [8] machined the Inconel 825 using EDM process and evaluated the performance measures using Taguchi-fuzzy approach. They obtained the optimal combination of machining parameters for improved MRR and SR. S. Singh [9] used EDM process for machining 6061Al/Al_2O_3p/20P composites.

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Machining characteristics were optimized using the technique grey relational analysis. The performance characteristics considered for the experimentation are MRR and TWR. Surface roughness was another quality characteristic considered for evaluation of the method.
Chinmaya P. Mohanty et al. [10] conducted the experiments on Inconel718 and machined with copper, graphite and brass electrodes. Various machining parameters like voltage and discharge current were considered. The other parameters considered are pulse-on-time and electrode material. The performance characteristics considered are MRR and TWR. Other characteristics considered are SR and radial overcut.

From the literature it is clear that, past decade some work has been done in this area in evaluating the optimal combination of machining parameters in machining of various materials using variety of tool electrodes. Most of the past research is concentrated in optimization of machining parameters, but tool parameters also plays an important role in obtaining better machining conditions hence it is under investigation now for the researchers working in this area. The particle size of P/M electrode is one of the important considerations in EDM electrode made with P/M route which influences the machining conditions. One of the basic requirements for liquid phase sintering is small particle size (fine particle) [11] and machining of EDMed surface for obtaining lower roughness. For process stability of the EDM, particle size of the P/M electrode is also important [12]. During the process of machining, a chance for short circuit increases with the increase in the particle size. This in turn reduces the process stability, in that way reducing the machining efficiency. To the best of the author's knowledge, the earlier period research was not fully focused on the property of particle size variation, especially when the particle size is reduced to nano level. Distinct from the tool parameters, the machining parameters setting was also proved to be important in getting better mechanical properties of EDMed surface as they are dependent on tool parameters. The present study focuses on setting of machining and tool parameters for simultaneous optimization of parameters during machining of Ti6Al4V alloy using TiC/Cu P/M electrode using Grey relational analysis (GRA) method.

II. EXPERMENTAL PROCEDURES

2.1 Parameters Selection

Experiments are designed as per Taguchi's L_{18} (2^1x3^7) mixed orthogonal array (OA) by considering six parameters as shown in Table 1, among the six parameters one parameter is of 2-level and remaining five parameters are of 3-level. In this study, the parameters selected consists of both tool and workpiece process parameters like, polarity, peak current, pulse on time, particle size, %TiC and compaction pressure. Chemical composition of as received workpiece samples of Ti6Al4V alloy is shown in Table 2.

Table 1. Process parameters with their levels

Parameters	Symbol	Level 1	Level 2	Level 3
polarity of Electrode	POL	Positive	Negative	---
Peak current (Amp)	IP	4	6	8
Pulse on time (µsec)	TON	4	5	6
Particle Size	PS	NP	NMP	MP
% wt of TiC in TiC/Cu tool electrode	%TiC	10	20	30
Compaction Pressure (MPa)	CP	250	350	450

Table 2. As received EDMed Ti6Al4V alloy workpiece chemical composition

Elem-ents	Ti	Cu	C	O_2	Al	V	Fe
	88.07	0.08	0.1	0.2	6.65	4.5	0.4

2.2 TiC/Cu Electrodes Fabrication

The Tool electrodes are fabricated with 99% purity raw materials which include electrolytic copper (Cu) and titanium carbide (TiC) powders. The combination are mixed at 3 different %weight proportions like (90:10, 80:20 and 70:30) . The particle sizes of the raw materials used vary from 20-40nm (nano size) and 30-50µm (micron size). The electrodes made with nano and micron powders are designated as "NP electrode" and "MP electrode" respectively. While, the electrode made with a mix of nano and micron powders (equal wt%) is referred to as "NMP electrode". For combining the powders Mortar and pestle technique is employed. In this process, the bonding agent is Liquid wax (1% of total weight) and the mixing process is carried out for 30 minutes. The powdered particles are then compacted at three different pressure settings, i.e., 250, 350 and 450 MPa in a cylindrical shape die with 15 mm diameter and 50 mm length punch using 200T universal compression testing machine (CTM). A vacuum furnace is used to sinter the produced green compacts. The sintering process involves the increase in temperature gradually from room temperature to 350^{0}C at a rate of 5^{0}C/min. The tool is held for 60 minutes at that temperature.
In the second phase, the temperature is raised up to 950^{0}C at the speed of 10^{0}C/min with a holding time of one hour. Argon (Ar) gas is provided as working environment during the sintering process.

In order to avoid cracking, the sintered components are furnace cooled. The rate of cooling is $5^{0}C/min$. This cooling process takes around 3½ hours. The sintered components are then used as EDM electrodes by fabricating a holding device and using an electrically conductive adhesive.

2.3 Experimental Setup

Electronica CNC EDM S50 model is used for conducting experiments. EDM 30, a standard dielectric is used during the process of experimentation. TiC/Cu as an electrode and Ti6Al4V alloy as workpiece, experimentations were conducted for which surface roughness (SR) and micro hardness (MH) were measured. The stylus type profilometer, Talysurf 10 with a cut off length of 0.8mm is employed for measurement of surface roughness. Readings have been recorded and the average of all the readings is considered. Vickers digital micro hardness tester, DHV-1000, with a load of 2.94 N (300 g) is used for measuring micro hardness value of the EDMed surface. MINITAB 14, statistical software is used for analyzing the obtained experimental results.

III. RESULTS AND DISCUSSION

3.1 Single Response Optimization: Taguchi's Analysis

Taguchi's technique is employed to conduct the analysis of Signal/Noise (S/N) ratio to find out the optimum parameter settings of Surface roughness (SR) and Micro hardness (MH). This may be measured as a logarithmic transformation of the loss function. The performance characteristics particularly for SR and MH are "Lower is better" and "Higher is better" as given in equations (1) and (2) respectively.

"Lower is better" characteristics of S/N ratio for Surface Roughness

$$\eta = -10\log\frac{1}{n}\sum_{i=1}^{n} y^2 \qquad (1)$$

"Higher is better" characteristics of S/N ratio for Micro-hardness

$$\eta = -10\log\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y^2}\right) \qquad (2)$$

Where

η = S/N ratio
y = individual measured response value
n = number of measurements.

In Table 3, the experimental values of SR and MH are given. Fig. 1 and Fig. 2 represent the mean calculated values at each level of S/N ratio for SR and MH respectively. The optimum level of the defined parameters is represented by higher S/N ratio. This optimum combination of machining parameters is obtained by selecting positive polarity (A1), lower level of peak current (B1), lower level of pulse on time (C1), NP electrode (D1), lower level of TiC% (E1) and higher level of compaction pressure (F3). This combination gives better surface finish. Reason for positive polarity to be selected as the particles produces the discharge spot at work surface instead of at tool surface. This is possible as the particles are held together by weakly bonded particles. This helps in the reduction of tool elements flowing towards the work surface. Migration and deposition of smaller particles (nano level) made the surface smoother when compared to machining with other electrodes, viz., NMP and MP electrodes. Values of roughness at its lower end are due to the lower levels of TON and IP. This results in low discharge energies, which leads to decreasing crater size. Other properties affecting surface roughness and which are related to the electrodes playing dominant role are electrical conductivity and density. NP electrodes have higher migration of particles compared to NMP and MP electrodes, this property is attributed to the fact that NP electrodes have higher thermal conductivity. The use of NP electrode makes the particle size smaller than the spark gap dimension. This leads to the reduction in arcing and short circuiting. This property reduces the surface roughness and process stability. Higher compaction pressure also leads to smoother surfaces.

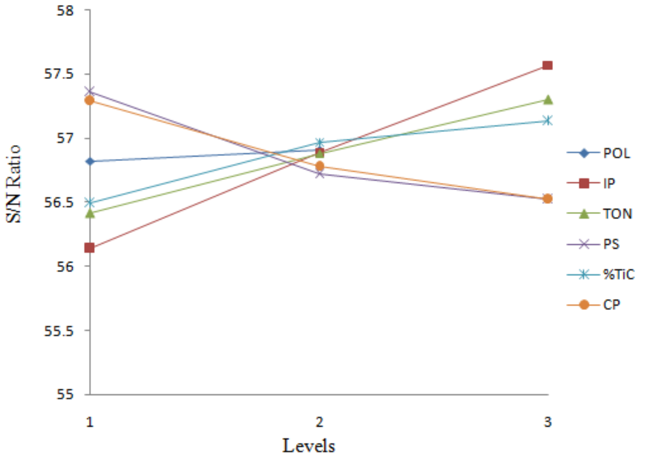

Fig. 1. Surface roughness mean S/N ratio at various levels of parameters

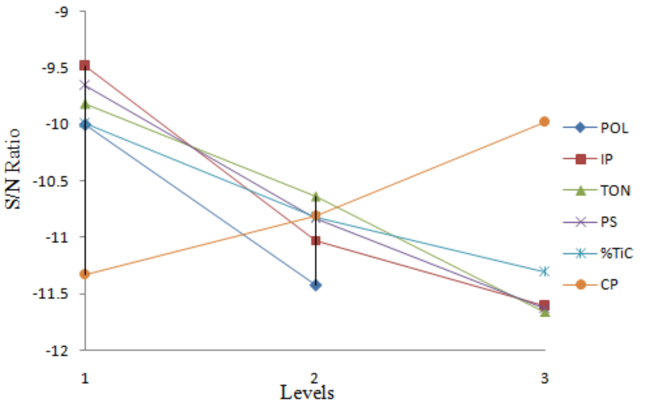

Fig. 2. Micro hardness mean S/N ratio at various levels of parameters

In order to obtain the best MH, some of the machining conditions to be considered are negative polarity of the tool (A2), higher levels of TON (B3) and IP (C3). The other parameters are NP electrode (D1) and higher wt% of TiC (E3). In order to obtain the best MH, lower level of compaction pressure (F1) is to be considered. As per the combinations, the optimal combination of the input parameters for good SR is A1B1C1D1E1F3 and for MH is A2B3C3D1E3F1. Analysis of variance (ANOVA) is used to find the influence of all the input parameters on SR and MH, in terms of percentage contribution, the results of which are depicted in Tables 4 and 5.

Table 3. L_{18} OA with experimental values of SR and MH

Exp. Run	Input Parameters						SR		MH	
	POL	IP	TON	PS	%TiC	CP	SR (μm)	S/N (dB)	MH (HV)	S/N (dB)
1	P	4	4	NP	10	250	1.901	-5.46	635	56.05
2	P	4	5	NMP	20	350	2.785	-8.89	624	55.90
3	P	4	6	MP	30	450	3.098	-9.82	625	55.91
4	P	6	4	NP	20	350	2.797	-8.93	701	56.91
5	P	6	5	NMP	30	450	3.158	-9.98	685	56.71
6	P	6	6	MP	10	250	4.449	-12.96	718	57.12
7	P	8	4	NMP	10	450	2.957	-9.41	672	56.54
8	P	8	5	MP	20	250	4.290	-12.64	759	57.60
9	P	8	6	NP	30	350	3.912	-11.84	850	58.58
10	N	4	4	MP	30	350	3.848	-11.70	620	55.84
11	N	4	5	NP	10	450	2.696	-8.61	619	55.83
12	N	4	6	NMP	20	250	4.180	-12.42	730	57.26
13	N	6	4	NMP	30	250	4.050	-12.14	681	56.66
14	N	6	5	MP	10	350	3.695	-11.35	645	56.19
15	N	6	6	NP	20	450	3.454	-10.76	768	57.70
16	N	8	4	MP	20	450	3.659	-11.26	662	56.41
17	N	8	5	NP	30	250	4.142	-12.34	895	59.03
18	N	8	6	NMP	10	350	4.047	-12.14	725	57.20

Table 4. Surface roughness ANOVA

Sources	Degree of freedom	Seq. Sum of squares	Sum of squares	Mean square	F-test	P-value	%Contribution
POL	1	1.0996	1.0996	1.0996	9.00	0.024	13.38
IP	2	1.7873	1.7873	0.8937	7.32	0.025	21.75
TON	2	1.3197	1.3197	0.6599	5.40	0.045	16.06
PS	2	1.4488	1.4488	0.7244	5.93	0.038	17.63
%TiC	2	0.5203	0.5203	0.2602	2.13	0.200	6.33
CP	2	1.3108	1.3108	0.6554	5.37	0.046	15.95
Error	6	0.7327	0.7327	0.1221			
Total	17	8.2194					

Table 5. Micro hardness ANOVA

Sources	Degree of freedom	Seq. Sum of squares	Sum of squares	Mean square	F-test	P-value	%Contribution
POL	1	320.9	320.9	320.9	0.39	0.555	0.31
IP	2	42019.4	42019.4	21009.7	25.52	0.001	40.08
TON	2	16626.8	16626.8	8313.4	10.10	0.012	15.86
PS	2	17981.4	17981.4	8990.7	10.92	0.010	17.16
%TiC	2	10133.8	10133.8	5066.9	6.16	0.035	9.67
CP	2	12874.1	12874.1	6437.1	7.82	0.021	12.28
Error	6	4938.7	4938.7	823.1			
Total	17	104895.1					

For the purpose of analysis, a confidence level of 95% ($\alpha = 0.05$) is considered, for which p-value of less than 0.05 is taken into consideration in order to statistically define its performance measure. It is observed that for SR, the peak current is the most vital parameter (21.75%) in defining its variation followed by the other parameters like particle size, pulse on time, compaction pressure and polarity. It is also observed that the %TiC does not show any considerable impact on the SR. Similar is the case for MH, where the peak current (40.08%) plays a dominating role. It is to be observed that polarity does not play a significant role on micro hardness. The common parameters which affect the quality of both SR and MH are IP, PS, TON and CP. The optimal combination of process parameters for simultaneous improvement of SR and MH is evaluated by using Grey relational analysis (GRA).

3.2 Multi response optimization: Grey relational analysis (GRA)

Taguchi technique utilized for the optimum setting of process parameters focuses simply on single response variable. Whereas, obtaining optimal combination of parameters for simultaneous improvement of more than one response is a difficult task.

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The present industrial requirements also have changed from improvement of single response to multi-response quality characteristics. So, the multiple quality characteristic optimizations are the task for the researchers working in EDM. GRA is a knowledgeable tool for multi-response analysis [13]. It computes the grey relational coefficients for each quality characteristics. This grey relational coefficient will represent the link between the actual and desired experimental results. Hence, the grey relational grade is simultaneously computed by averaging all the coefficients. The multiple performance characteristics of EDM of Ti6Al4V alloy is optimized by producing single grey relational grade from varied coefficients of performance characteristics. A higher grey relational grade corresponds to the best optimal setting of process parameters for multi responses. The utilization of Taguchi system with the Grey relational analysis is considerably improved the parametric optimization for varied quality characteristics and the same is also reported in others research work [14-15]. The methodology followed in the present work for performing GRA is depicted in Fig. 3 and has been utilized to optimize EDMed surface of Ti6Al4V alloy for multiple response, viz., surface roughness and micro hardness.

3.2.1 Data Pre-Processing

In data pre-processing stage all the experimental results were normalized within the vary between zero and one. Table 6 provides the normalized results, deviational sequence, grey relational coefficient, grey relational grade and rank for individual responses irrespective of quality characteristics and the corresponding equations are given in (3) and (4).

The smaller is the better

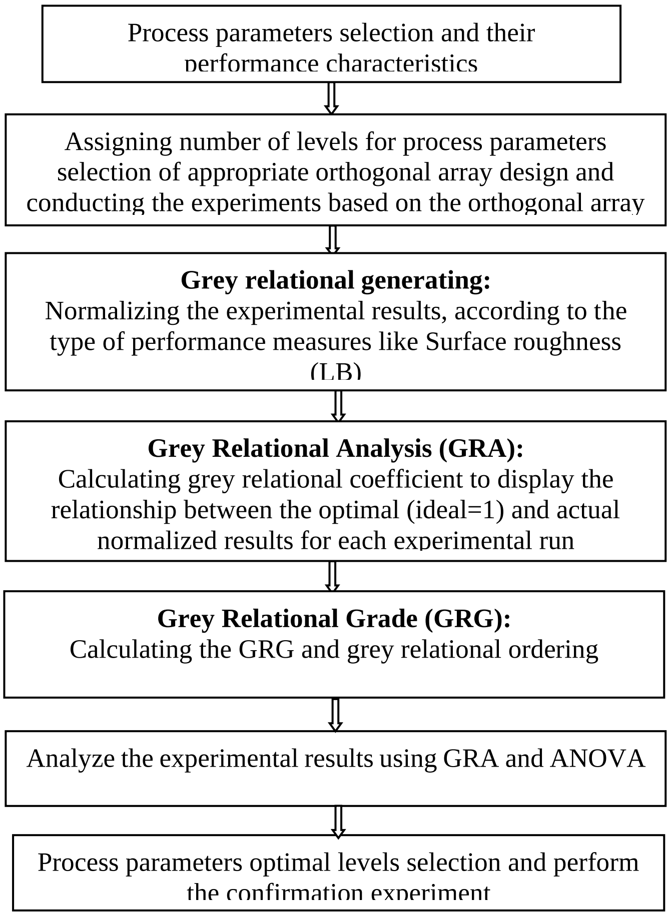
$$Z_i^*(k) = \frac{\max z_i^0(k) - z_i^0(k)}{\max z_i^0(k) - \min z_i^0(k)} \qquad (3)$$

The larger is the better

$$Z_i^*(k) = \frac{z_i^0(k) - \min z_i^0(k)}{\max z_i^0(k) - \min z_i^0(k)} \qquad (4)$$

Where

$Z_i^*(k)$ = Sequence data after pre-processing
$Z_i^0(k)$ = The original sequence of mean value
k = 1 for SR
k = 2 for MH
I = 1, 2, 3, ..., 18 for experimental numbers
$Z_0^*(k)$ = The reference sequence whose value is equal to 1.



3.2.2 Calculating the Grey Relational Coefficient (GRC) and Grey Relational Grade (GRG)

After the normalization, the subsequent step is to find the deviational sequence. Now, $\Delta_{0i}(k)$ is the deviational sequence of the reference sequence Z_0^* (k) and the comparability sequence $Z_i^*(k)$ and the obtained values is given in Table 6. The deviational sequence is computed from equation (5) as given below.

$$\Delta_{0i}(k) = |Z_0^*(k) - Z_i^*(k)| \qquad (5)$$

The GRC is calculated to display the link between the optimal and actual normalized results. As presented in Table 6, the deviational sequence $\Delta_{0i}(k)$ and grey relational coefficient $\xi_i(k)$ is obtained from the analysis model of grey theory. The average value of the grey relational coefficient $\xi_i(k)$ is the grey relational grade γ for all performance characteristics. The grey relational coefficient is calculated from equation (6), where ζ is that the identification coefficient and its value is taken as 0.5 [16].

$$\text{GRC} \quad \xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(k) + \zeta\Delta_{max}} \qquad (6)$$

After obtaining the GRC values, the GRG (γ) is processed by averaging the GRC, which is equivalent to each performance characteristic as given in equation (7). The overall evaluation of the multiple performance characteristics depends on the grey relational grade.

$$\text{GRG} \quad \gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \qquad (7)$$

The GRG values for each and every experiment in L18 orthogonal array is presented in Table 6. Higher GRG value represents closer to the ideal normalized value. The 17th experiment in Table 6 provides the largest value of grade (i.e., 0.68125) and the corresponding experiment represents the optimum machining condition.

3.2.3 ANOVA for GRG

ANOVA is a statistical technique used to identify the process parameters which has significant influence on the performance characteristics, viz., surface roughness and micro hardness. Fig. 4 represents the main effect plot of individual parameters for GRG. From the ANOVA for GRG the parameter particle size (PS) was found to be most significant process parameter (64.13%) as shown in Table 7.

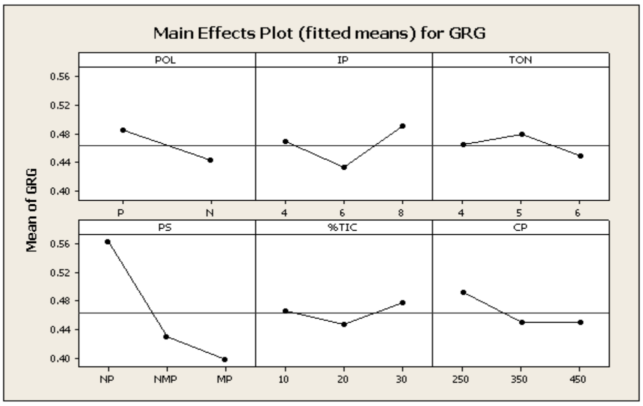


Fig.4. Main effect plot for process parameters for GRG

The GRG for each level is calculated for all the parameters. Highest and lowest values for the same parameter at different levels is identified and measured. The parameter for which maximum difference obtained is awarded with rank 1 and followed by rank 2, 3 and so on. From Table 8**,** the rank 1 for the parameter "particle size" indicates the most influential effect on the performance measures of SR and MH for simultaneous improvement and it is followed by peak current, compaction pressure, polarity, %TiC and pulse on time. Based on the optimum levels of each parameter the predicted optimum machining condition is obtained as A1B3C2D1E3F1 and it is given in Table 9, % contributions of every parameter affecting the GRG is given in Fig. 5 and it evidently explains the influence of particle size in improving the performance measures of SR and MH, especially when the particle size is reduced to nano level.

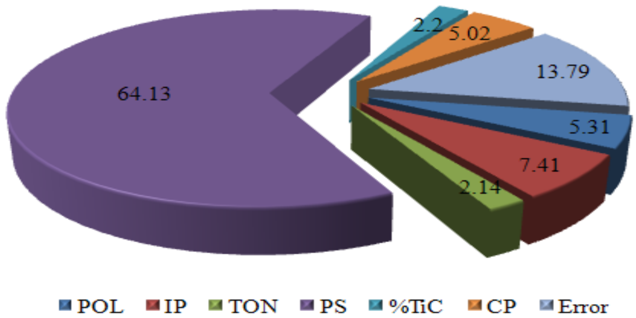


Fig. 5. Percentage contribution of each parameter for GRG

In EDM the surface alloying/modification occur due to migration of particles and frequently producing rougher surfaces. While, reduction in particle size to nano scale in the present case considerably reduced the surface roughness of workpiece. The thermal conductivity for the NMP and MP electrodes are lower than denser NP electrodes, thus material migration is relatively higher for NP electrodes. With the use of NP electrodes, the process stability increases and reduces the SR. It is attributed due to the decrease in spark gap dimension thus reducing arcing and short circuiting. It is observed that NP electrodes have more surface alloying capabilities compared to the other electrodes resulting generation of hard intermetallic phases CuTi, TiCN, Cu4Ti3,Ti2C, TiV and Fe3C on the surface hence increased micro-hardness. The formation above phases on the surface machined at optimal combination of parameters can be seen in the Fig.6. A large capillary force during the liquid phase sintering stage is created due to the particle size of the NP electrode. This results in the manufacture of denser electrodes. Denser electrodes have less tool erosion rate compared to the other electrodes as the tool particles are strongly bonded together. So more surface alloying followed by hardness is obtained for the samples machined with NP electrode. Other parameters responsible for increased MH are high discharge energies due to higher values of IP and TON.

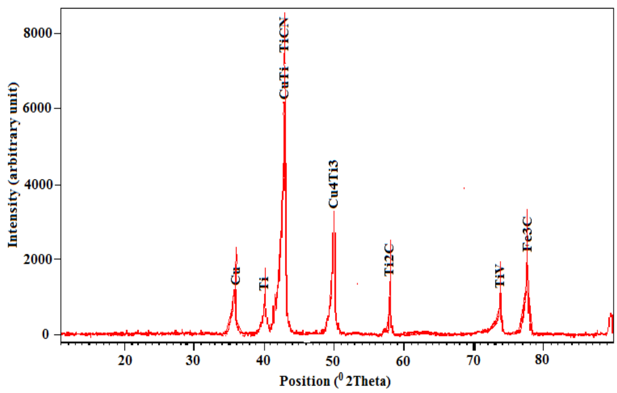


Fig. 6. Phase analysis of the specimen machined at optimum condition

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Table 6. Grey relational grade and rank for individual responses

Exp. No	Normalized Values		Deviational Sequence		GRC Values		GRG	ORDER
	SR	MH	SR	MH	SR	MH		
1	1.0000	0.0580	0.0000	0.9420	1.0000	0.3467	0.67335	2
2	0.6531	0.0181	0.3469	0.9819	0.5904	0.3374	0.46390	8
3	0.5302	0.0217	0.4698	0.9783	0.5156	0.3382	0.42690	10
4	0.6484	0.2971	0.3516	0.7029	0.5871	0.4157	0.50140	4
5	0.5067	0.2391	0.4933	0.7609	0.5034	0.3965	0.44995	9
6	0.0000	0.3587	1.0000	0.6413	0.3333	0.4381	0.38570	15
7	0.5856	0.1920	0.4144	0.8080	0.5468	0.3823	0.46455	7
8	0.0624	0.5073	0.9376	0.4928	0.3478	0.5036	0.42570	11
9	0.2108	0.8370	0.7892	0.1630	0.3878	0.7541	0.57095	3
10	0.2359	0.0036	0.7641	0.9964	0.3955	0.3341	0.36480	18
11	0.6880	0.0000	0.3120	1.0000	0.6158	0.3333	0.47455	6
12	0.1056	0.4022	0.8944	0.5978	0.3586	0.4555	0.40705	13
13	0.1566	0.2246	0.8434	0.7754	0.3722	0.3920	0.38210	17
14	0.2959	0.0942	0.7041	0.9058	0.4152	0.3557	0.38545	16
15	0.3905	0.5399	0.6095	0.4601	0.4507	0.5208	0.48575	5
16	0.3100	0.1558	0.6900	0.8442	0.4202	0.3720	0.39610	14
17	0.1205	1.0000	0.8795	0.0000	0.3625	1.0000	0.68125	1
18	0.1578	0.3841	0.8422	0.6159	0.3725	0.4481	0.41030	12

Table7 GRG ANOVA

Sources	Degree of freedom	Seq. Sum of squares	Sum of squares	Mean square	F-test	P-value	%Contribution
POL	1	0.007815	0.007815	0.007815	2.31	0.179	5.31
IP	2	0.010897	0.010897	0.005448	1.61	0.275	7.41
TON	2	0.003141	0.003141	0.001571	0.46	0.649	2.14
PS	2	0.094315	0.094315	0.047157	13.95	0.006	**64.13**
%TiC	2	0.003231	0.003231	0.001616	0.48	0.642	2.20
CP	2	0.007387	0.007387	0.003694	1.09	0.394	5.02
Error	6	0.020288	0.020288	0.003381			13.79
Total	17	0.147074					

Table 8 GRG response table

Input Parameter	Level -1	Level -2	Level -3	Difference (Max-Min)	Rank
POL	0.4847	0.4430	--	0.0417	4
IP	0.4684	0.4317	0.4915	0.0598	2
TON	0.4637	0.4801	0.4478	0.0323	6
PS	0.5645	0.4296	0.3974	0.1671	1
%TIC	0.4657	0.4467	0.4793	0.0326	5
CP	0.4925	0.4495	0.4496	0.0430	3

The GRG total mean value = 0.4639

Table 9. Optimal process parameters

Performance Parameters	Initial	Optimal Process Parameters	
		Predicted	Experiment
Level	A1B1C1 D1E1F1	A1B3C2 D1E3F1	A1B3C2 D1E3F1
SR	2.291		3.172
MH	646.6		864.7
GRG	0.498785	0.6202	0.6734
Improvement in GRG		0.1746	

In EDM the surface alloying/modification occur due to migration of particles and frequently producing rougher surfaces. While reduction in particle size to nano scale in the present case considerably reduced the surface roughness of workpiece. The thermal conductivity for the NMP and MP electrodes are lower than denser NP electrodes, thus material migration is relatively higher for NP electrodes. With the use of NP electrodes, the process stability increases and reduces the SR. It is attributed due to the decrease in spark gap dimension thus reducing arcing and short circuiting. It is observed that NP electrodes have more surface alloying capabilities compared to the other electrodes resulting generation of hard intermetallic phases CuTi, TiCN, Cu_4Ti_3,Ti_2C, TiV and Fe_3C on the surface hence increased micro-hardness. The formation above phases on the surface machined at optimal combination of parameters can be seen in the Fig.6. A large capillary force during the liquid phase sintering stage is created due to the particle size of the NP electrode. This results in the manufacture of denser electrodes. Denser electrodes have less tool erosion rate compared to the other electrodes as the tool particles are strongly bonded together. So more surface alloying followed by hardness is obtained for the samples machined with NP electrode. Other parameters responsible for increased MH are high discharge energies due to higher values of IP and TON.

IV. VALIDATION EXPERIMENT

The particular combination of factors and levels that are previously evaluated with validation experiment is performed by conducting a test. Based on the results a new experiment is designed and conducted with the optimum levels of the machining parameters. The crucial step is to predict and confirm the performance characteristics improvement. Equation (8) predicts the S/N ratio using best possible levels of machining parameters in order to verify the enhancements in performance characteristics [17].

$$\eta_{opt} = \eta_m + \sum_{j=1}^{k} (\eta_j - \eta_m) \quad (8)$$

Where

η_{opt} = The predicted optimal S/N ratio
η_m = The total mean of the S/N ratios
η_j = The mean S/N ratio at the optimal levels
k = The number of main design parameters that affect the quality characteristics.

The SR and MH experimental value are 3.172µm and 864.7HV respectively as shown in Table 9. The grey relational grade of initial, predicted and experimental values are 0.4987, 0.6202 and 0.6734. The grey relational grade experimental improvement when compared to initial value indicates that the significant improvement in performance.

V. CONCLUSIONS

This study presents multi objective optimization of surface roughness and micro hardness by considering the machining and tool parameters of EDM. From the present work the following conclusions are made:

1. During single response optimization for optimal surface roughness and hardness it is found that when compared to particle size and pulse on time, Peak current is the most significant parameter. Optimal combination for SR and MH is obtained as A1B1C1D1E1F3 and A2B3C3D1E3F1 respectively.
2. Whereas, during Multi response optimization using GRA it is found that the input parameter, particle size is found to be most significant parameter (64.13%) indicating it's dominant control over machining process. The above result revealed the importance of tool parameters apart from the machining parameters in producing the quality machined surface.
3. The surface roughness and micro hardness values at optimum machining condition A1B3C2D1E3F1 is 3.172µm and 864.7HV respectively. At initial machining condition A1B1C1D1E1F1 the SR and MH values are 2.291µm and 646.6HV respectively. So, when compared to initial machining condition the hardness value at optimal machining condition is improved but with the cost of slight increase in surface roughness.
4. High reactive surface area of the nano particles in making when compared to the NMP and MP electrodes than NP electrodes promoted greater surface alloying. So, the formation of hard intermetallic phases, viz., CuTi, TiCN, Cu_4Ti_3,Ti_2C, TiV and Fe_3C can be attributed as the reason for improved hardness at optimal machining condition. At the same increase values of TON and IP at optimal condition increased the surface roughness of the machined surface.
5. This technique successfully improved the performance measures of surface roughness and micro hardness simultaneously in machining of Ti6Al4V alloy.

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