Journal of Engineering and Applied Sciences 13 (24): 10173-10181, 2018
ISSN: 1816-949X

Multi-Objective Optimization to Improve Surface Integrity in WEDM of AL/WC_p Metal Matrix Composites Using Grey Relational Analysis

Saad Hameed Al-Shafaie
Department of Metallurgical Engineering, College of Materials Engineering,
University of Babylon, Hillah, Iraq

Abstract: Demand for low weight to strength ratio for specific application in aerospace components and automobile created a field for advance studies on Metal Matrix Composites (MMCs). The main response selected to evaluate the processes are White Layer Thickness (WLT) and Surface Crack Density (SCD) whereas the corresponding machining conditions are discharge current (I_p), Voltage (V), pulse on Time (T_{on}) and pulse off Time (T_{off}). Wire Electrical Discharge Machining (WEDM) process is principally with multi response, thus, Grey Relational Analysis (GRA) is especially adopted to decide the optimum combination of machining parameters of Al6061 reinforced with volume fraction of 10% WC_p. Design of experiments was carried out based on a standard L_{27} orthogonal array of Taguchi method. Minitab16 Software was performed to analyze the results obtained from experimental runs at confidence level 95%. For the present experimental study, it is observed that WLT and SCD are mainly affected by all process parameters except T_{off} has little effect on the SCD. The values corresponding to the response parameters were calculated using mathematical formulas and confirmed by the verification experiment. The values of confirmation tests, all being found to be quite satisfactory (10.92% in the worst case), prove the efficacy and reliability of the suggested approach.

Key words: WEDM, MMCs, Taguchi method, ANOVA, GRA, surface integrity

INTRODUCTION

Composite materials, especially Metal Matrix Composite (MMC) are commonly used in automobile, aerospace, medical and electronics industries. This is due to their high mechanical properties like specific strength and raised thermal conductivity. The characteristics required are mainly manipulated by a matrix, the reinforcement material and interface (Satheesh *et al*., 2013). There is a major challenge facing the current industry as a result of the progress of these materials are often difficult to machine, demanding surface quality, high precision this means increased operating costs rise machining cost (Vishwakarma *et al*., 2012). Therefore, novel processes with sophisticated methodology and tools must be developed to confront these challenges (Shrivastava and Sarathe, 2014). Traditional methods like turning, drilling and milling are ineffectual in the machining of these advanced materials because its result is an extreme tool wear, low productivity and surface finish (Pandey and Singh, 2010).

To obtain the required parts, the appropriate machining method is selected. Electrical Discharge Machining (EDM) is the extensively utilized and swimmingly performed for hard to machine materials. Wire EDM (WEDM) is a specific method of EDM which carried out on conductive materials (Singh and Kumar, 2012). There are a large number of process parameters that dominate this complex process. If one of the process parameters changes simply, it will influence the performance measures (Khaja *et al*., 2015). The surface machined by WEDM includes several defects on Heat Affected Zone (HAZ) as stated by Yan and Chien (2007). Therefore, tensile stress generates on the surface and subsurface in this process attached by the forming of a superficial “white layer” (Han *et al*., 2007). The molten material by electric sparks and resolidified on the surface without being removed nor ejected by flushing called recast layer or white layer (Fukuzawa *et al*., 2009). During pulse-off time or pulse interval (T_{off}) and due to rapid cooling, part of the molten material resolidified and quenched. This rapid cycle (cooling and heating) results in forming of surface crack on the white layer (Dewangan *et al*., 2015). The surface integrity of the finished part is one of the major concerns in the machining of MMCs to attain superior quality to the better extent. Thus, the estimate of surface integrity such (White Layer Thickness (WLT) and Surface Crack Density (SCD)) will contribute for preferable machining of MMCs.

The detailed literature review refers that there are very little works focused on machining of MMCs, especially by WEDM moreover various researchers have made a great deal work to optimize and reveal the relationship between the machining parameters and performance measure (output) like MRR, EWR and SR. However, the efforts are less concentrated towards the WLT and SCD. Patil and Brahmankar (2010b) studied about the determination of MRR of WEDM of Al/SiC_p based on the dimensional analysis. They proposed model of MRR in WEDM depended on thermo physical characteristics of the workpart, pulse on Time or duration (T_{on}) and Voltage (V). An empirical model depended on the response surface method was developed. Satishkumar *et al*. (2011) examined the impact of WEDM machining conditions such T_{on}, T_{off}, V and Wire Feed (WF) on MRR and SR of Al6063 as master alloy and Al6063 reinforced with 5, 10 and 15% volume fractions SiC_p depended on response graphs and ANOVA. They found that the rise in reinforcement material resulted in reduced MRR and elevated SR. Base on the experimental data, the researchers were developed regression model for the prediction of responses for two materials. Shandilya *et al*. (2013) investigated the impact of process parameters on wire breakage frequency and microstructure of cut surface during WEDM of SiCp/Al6061. They found that SR down with the increase reinforcement. Marigoudar and Sadashivappa (2013) emphasized in their research on behavior of ZA43 reinforced with 5, 10 and 15% volume fractions SiC_p when machined with WEDM process. MMCs were casted in the form of cylindrical specimen. Machining was carried-out by varying applied peak current (I_p), (T_{on}) and (T_{off}). They were observed that there was a reduction in MRR and increase in SR when reinforcement material of composite increased. Patil and Brahmankar (2010a) studied effect of Al_2O_3 particulate as reinforcement of MMC (Al matrix) using WEDM. The impact of interaction for reinforcement, I_p, T_{on}, T_{off}, V, Flushing Pressure (FP), Wire Speed (WS), maximum Feed Speed (FS) and Wire Tension (WT) on Cutting Speed (CS), SR and Kerf Width (KW) and they used Taguchi orthogonal array to determine the best conditions. The optimum machining parameter combinations were obtained for SR, CS and KW separately.

Surface integrity cannot be considered as a single response because it generally involves formation of WLT and SCD. Therefore, the aim of this research is used to model and multi-objective optimization method (Taguchi-based Grey Relation Analysis (GRA)) to attain a reasonable minimum value of WLT and SCD on WEDM of Al10% vol WC_p.

MATERIALS AND METHODS

Experimental setup and procedures

Material selection: Material selection is one of the important processes for any investigation based on the recent development and their end applications. The base material is Al6061 with a chemical composition as presented in Table 1. Tungsten carbide (WC_p) with 10% volume fraction is used as reinforcement. The size of WC_p particles was measured by particle size analyzer was 3.980 μm as shown in Fig. 1. Al 10% vol WC_p MMC was prepared using stir casting technique with dimensions 100×100×50 mm (Table 2).

Table 1: Chemical composition of aluminum alloy 6061

Material	Si	Fe	Cu	Mn	Ti	Mg	Zn	Cr	Al
Weight (%)	0.6	0.25	0.27	0.12	0.06	0.9	0.05	0.10	Rem.

Table 2: Process parameters and their levels

Parameters	Units	Coded/Actual level 1	2	3
Current (I_p)	A	11	13	15
Voltage (V)	V	75	100	125
Pulse on Time (T_{on})	μsec	110	120	130
Pulse off Time (T_{off})	μsec	40	50	60

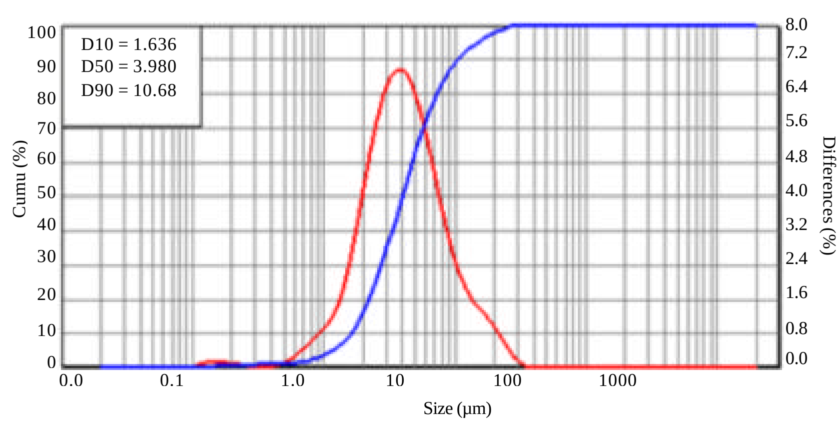

Fig. 1: Particle size distribution of WC_p

Machining conducted: The machining was conducted on the 5 axis ACRA-W-A430 CNC wire cut machine. A brass wire of 0.25 mm diameter was used as the cutting tool. The distilled water was used as dielectric medium.

Selection of the machining parameters and their levels: The machining parameters and their levels fixed in Table 2 were selected based on some preliminary experimental and considering the range limitation of WEDM machine. Taguchi method has been chosen for experiment design in Minitab 16. Each 27 experiments were carried out with WLT and SCD as response variables.

Measurement of response

White Layer Thickness (WLT): To measure WLT after WEDM process, the top surface of each sample was ground successively with the emery papers of up to (2500), followed by polishing with a slurry of Alumina (Al_2O_3), finally, washed with acetone fluid under a standard procedure for metallography observation. The image was captured at maximum places of each sample by Scanning Electron Microscopy (SEM) (model: Inspect S50) at a magnification of 500X. This image was then utilized to decide the WLT.

Surface Cracks Density (SCD): To measure SCD, the side (machining) surface morphology was studied using the same SEM but the magnification here 1000 X. Four sample areas were selected randomly on each specimen and the cracks length was measured by software (PDF X-change viewer). By dividing the average crack length on each specimen over the area of each micrograph (12400 μm^2) to obtain the SCD.

RESULTS AND DISCUSSION

Performance characteristics like WLT and SCD have been utilized to analyze the influence of input process parameters, the obtained results of total 27 runs were summarized in Table 3.

Table 3: Input process parameters and experimental results

Expt. No.	Input process parameters: I_p (A)	V (V)	T_{on} (μsec)	T_{off} (μsec)	Response variables: WLT (μm)	SCD (μm/μm^2)
01	11	75	110	40	07.502	0.0627
02	11	75	120	50	08.184	0.0424
03	11	75	130	60	08.928	0.0633
04	11	100	110	50	08.866	0.0430
05	11	100	120	60	09.672	0.0291
06	11	100	130	40	14.044	0.0461
07	11	125	110	60	10.478	0.0295
08	11	125	120	40	15.214	0.0212
09	11	125	130	50	16.597	0.0317
10	13	75	110	50	09.548	0.0406
11	13	75	120	60	10.416	0.0274
12	13	75	130	40	15.124	0.0434
13	13	100	110	60	11.284	0.0278
14	13	100	120	40	16.384	0.0200
15	13	100	130	50	17.874	0.0297
16	13	125	110	40	17.750	0.0203
17	13	125	120	50	19.363	0.0137
18	13	125	130	60	21.123	0.0204
19	15	75	110	60	12.152	0.0270
20	15	75	120	40	17.644	0.0194
21	15	75	130	50	19.248	0.0290
22	15	100	110	40	19.115	0.0197
23	15	100	120	50	20.853	0.0133
24	15	100	130	60	22.748	0.0200
25	15	125	110	50	22.590	0.0135
26	15	125	120	60	24.644	0.0091
27	15	125	130	40	35.783	0.0144

influence of process parameters on WLT: The influence of different machining parameters (I_p, V, T_{on} and T_{off}) on WLT is shown through main effect plots in Fig. 2 at 0.05 significance level or 95% confidence interval. Also, note that the I_p is directly proportional to WLT. Increasing the I_p means increasing the discharge energy in the sparks zone and thus increasing the recast layer on the machined surface. The same figure also obviously indicates WLT is strongly impacted by V, so that, the relationship between them is directly proportional. The large energy associated with high V, elevate the pressure energy in a plasma channel due to melting and evaporation of material which plough out the material from the research surface and create large size irregularities on research surface. Because the energy increases with the increase of the T_{on}, the result is increasing the thickness of the molten metal which cannot be removed by flushing and this leads to increase the WLT. Further, the effect of T_{off} on WLT is also shown in the same Fig. 2. The WLT reduces with the rise of T_{off}. This is due to the fact that an increase in T_{off} leads to a dissipate the heat and thus lower WLT.

Therefore, it can be concluded that all machining parameters are very impacting parameters. This is confirmed by Analyzing the Variance (ANOVA) results presented in Table 4. Due to rarity of area and simple comparison with the other responses, a summarized ANOVA is shown including Fisher-value (F-ratio) and probability value (p-value).

Excess in WLT with a raise in I_p, V and T_{on} as well as its decrease with an increase in T_{off} is evident from Fig. 3 which depicts SEM snap of transverse plane of the machining zone.

Influence of process parameters on SCD: The influence of several machining parameters (I_p, V, T_{on} and T_{off}) on SCD is shown through main effect plots in Fig. 4. It is obvious that both the I_p and the V have the inverse effect

Table 4: The ANOVA for the fitted WLT and SCD Models

Response/Source	DF	Seq SS	Adj SS	Adj MS	F-values	p-values	Remark
WLT							
I_p (A)	2	509.54	509.54	254.768	90.85	0.000	MS
T_{on} (µsec)	2	312.89	312.89	156.443	55.79	0.000	MS
T_{off} (µsec)	2	151.96	151.96	75.978	27.09	0.000	MS
V (V)	2	41.11	41.11	20.554	7.33	0.005	S
Residual error	18	50.48	50.48	2.804			
Total	26	1065.96					
R^2 = 95.3 (%); R^2 (adj.) = 93.2 (%)							
SCD							
I_p (A)	2	0.002345	0.002345	0.001173	64.04	0.000	MS
T_{on} (µsec)	2	0.001847	0.001847	0.000923	50.43	0.000	MS
T_{off} (µsec)	2	0.000686	0.000686	0.000343	18.72	0.000	MS
V(V)	2	0.000011	0.000011	0.000006	0.31	0.741	NS
Residual error	18	0.000330	0.000330	0.000018			
Total	26	0.005218					
R^2 = 93.7 (%); R^2 (adj) = 90.9 (%)							

MS: More Significant; S: Significant factor; NS: Non-Significant

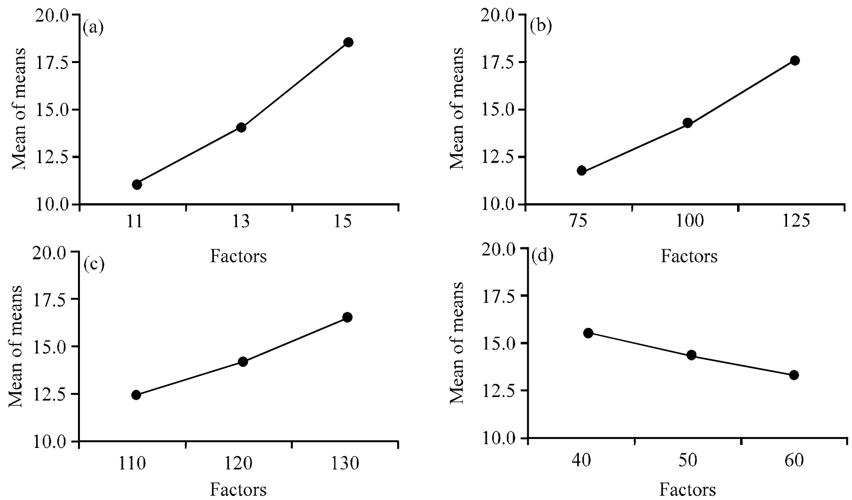

Fig. 2: Effect of factors on WLT: a) I_p; b) V; c) T_{on} and d) T_{off}; Main effects plot for means (data means)

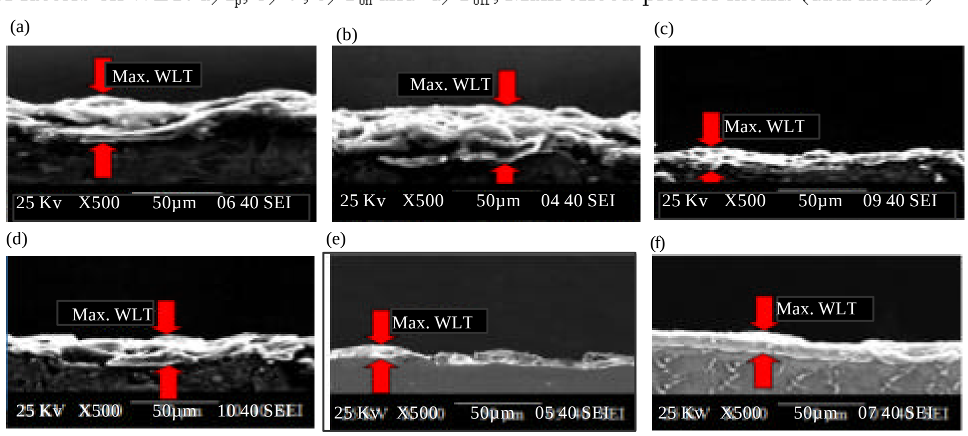

Fig. 3: a-e) SEM snap WLT at process parameters: SEM snap WLT at 11/125/120/40; SEM snap WLT at 15/125/120/60; SEM snap WLT at 13/75/120/60; SEM snap WLT at 13/100/110/60; SEM snap WLT at 11/75/110/40; SEM snap WLT at 11/100/130/60

on SCD. Increasing each of the parameters (I_P and V) leads to thickening of the molten layer which tends to fill the voids and thus decrease the crack propagation. The SCD first reduces with T_{on} up to a certain level (optimum) and then begins rising. At higher T_{on} 130 µsec, WLT is exceedingly and the induced stress is more severe, lead to

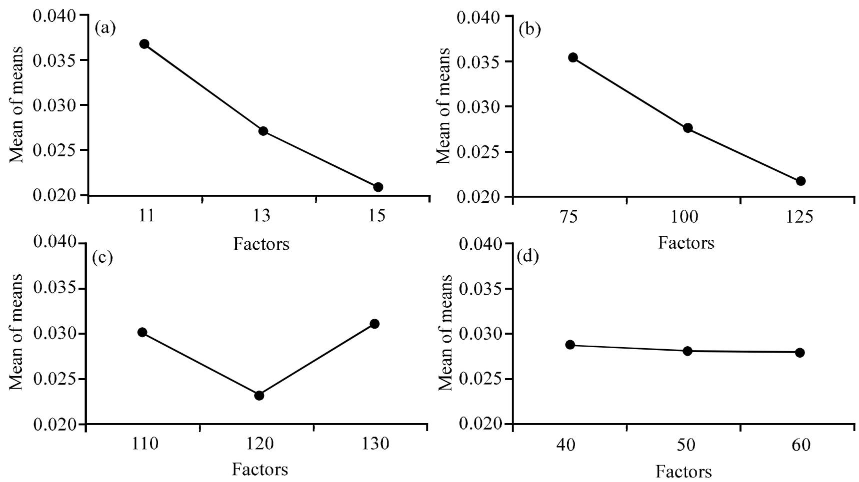

Fig. 4: Effect of factors on SCD: a) ID; b) V; c) T_{on} and d) T_{off}; Main effects plot for means (data means)

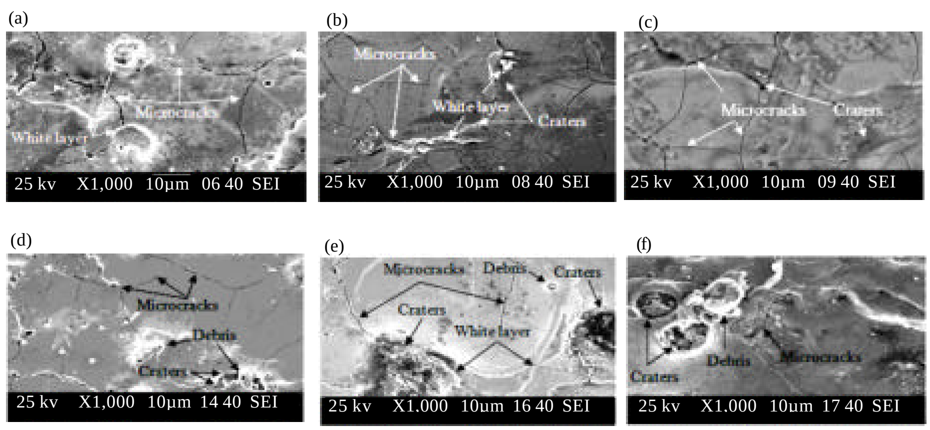

Fig. 5: a-e) SEM snap SCD at process parameters; SEM snap SCD at 11/75/130/60; SEM snap SCD at 11/125/130/50; SEM snap SCD at 13/100/110/60; SEM snap SCD at 15/100/120/50; SEM snap SCD at 13/75/120/60; SEM snap SCD at 15/125/120/60

increase in SCD. The SCD could not be largely reduced by rising T_{off}. Therefore, it can be concluded that I_p, V and T_{on} are more influencing parameters compared to T_{off}. ANOVA Table 4 refer that the T_{off} is not a significant parameter as far as formation of SCD is interested. Decrease in SCD with a rise in I_P and V moreover drop and rise of SCD with increase T_{on} is evident from Fig. 5 which depicts SEM micrograph of the WEDM machined surfaces.

Grey relational analysis method: In this research, GRA was performed to optimize the output (responses) based on Taguchi method (orthogonal array). The first step in GRA is to turn the experimental results into normalized after that, the Grey Relational Coefficient (GRC) is computed from the normalized data to establish a relationship between the preferred and actual data. Finally, the Grey Relational Grade (GRG) was calculated by averaging the GRC corresponding to every response. The total assessment of the multiple responses (output) is built on the GRG (Deris *et al*., 2017).

Data pre-processing: It is needful when the range and unit in one data sequence is different from the other and the range of sequence scatter is very large or when different target directions in the sequence. Conveying the original sequence to an identical sequence called data pre-processing. Therefore, the results or outputs in general are normalized between zero and one.

WLT and SCD are vital measures of WEDM. It is not clear, yet, selection of optimum process parameters of Al/WC_P by WEDM especially WLT and SCD. The "smaller-the-better" has been utilized for both the WLT

Table 5: The sequences of each performance characteristic after data processing

Expt. No.	WLT	SCD
Reference sequence	1.0000	1.0000
01	1	0.01107
02	0.975885	0.385609
03	0.949577	0
04	0.95177	0.374539
05	0.92327	0.630996
06	0.768679	0.317343
07	0.89477	0.623616
08	0.727308	0.776753
09	0.678406	0.583026
10	0.927655	0.418819
11	0.896963	0.662362
12	0.73049	0.367159
13	0.866271	0.654982
14	0.685938	0.798893
15	0.633252	0.619926
16	0.637637	0.793358
17	0.580602	0.915129
18	0.518369	0.791513
19	0.835579	0.669742
20	0.641385	0.809963
21	0.584668	0.632841
22	0.589371	0.804428
23	0.527916	0.922509
24	0.46091	0.798893
25	0.466497	0.918819
26	0.393869	1
27	0	0.902214

and SCD to get optimum machining performance where the original sequence should be normalized as follows Eq. 1:

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

where x_i^* and $x_i(k)$ are the sequence after the data preprocessing and comparability sequence, respectively, min x_i (k) is the smallest value of xi (k) for the kth response and max $X_i(k)$ is the largest value of $X_i(k)$ for the kth response, k = 1 and 2 for WLT and SCD; i = 1, 2, 3, ..., 27 for experiment numbers 1-27. All the sequences of each performance characteristic after data preprocessing using Eq. 1 are presented in Table 5. Now, $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence x_0^* (k) and the comparability sequence $x_i^*(k)$, i.e., Eq. 2:

$$\Delta_{0i}(k) = \left|X_0^*(k) - X_i^*(k)\right| \quad (2)$$

Using Eq. 2 the deviation sequence Δ_{0i} can be computed and the results are clear in Table 6.

GRC and GRG: After data pre-processing is performed, GRC is computed from the normalized data to establish a relationship between the preferred and actual data. The GRC is known as follows Eq. 3:

$$\xi_i(k) = \frac{\Delta_{min.} + \xi\Delta_{max.}}{\Delta_{0i}(k) + \xi\Delta_{max.}} \quad (3)$$

Table 6: The deviation sequences

Deviation sequences (Expt. No.)	$\Delta_{0i}(1)$	$\Delta_{0i}(2)$
01	0	0.98893
02	0.024115	0.614391
03	0.050423	1
04	0.04823	0.625461
05	0.07673	0.369004
06	0.231321	0.682657
07	0.10523	0.376384
08	0.272692	0.223247
09	0.321594	0.416974
10	0.072345	0.581181
11	0.103037	0.337638
12	0.26951	0.632841
13	0.133729	0.345018
14	0.314062	0.201107
15	0.366748	0.380074
16	0.362363	0.206642
17	0.419398	0.084871
18	0.481631	0.208487
19	0.164421	0.330258
20	0.358615	0.190037
21	0.415332	0.367159
22	0.410629	0.195572
23	0.472084	0.077491
24	0.53909	0.201107
25	0.533503	0.081181
26	0.606131	0
27	1	0.097786

Table 7: Grey relational grade and its order in the optimization

	Grey relational coefficient			
Expt No.	WLT $\xi_i(1)$	SCD $\xi_i(2)$	Grey relational grade $\gamma_i = 1/2\ (\xi_i(1)+\xi_i(2))$	Rank
01	1	0.335812	0.667906	14
02	0.953989	0.448675	0.701332	4
03	0.908393	0.333333	0.620863	19
04	0.912026	0.444262	0.678144	9
05	0.866957	0.575372	0.721164	2
06	0.683694	0.422777	0.553235	26
07	0.826133	0.570526	0.698329	6
08	0.647088	0.691327	0.669207	12
09	0.608573	0.545272	0.576922	23
10	0.873598	0.462457	0.668028	13
11	0.829136	0.596916	0.713026	3
12	0.649765	0.441368	0.545566	27
13	0.78898	0.591703	0.690342	7
14	0.614203	0.713158	0.663681	15
15	0.576869	0.568134	0.572502	24
16	0.579802	0.707572	0.643687	17
17	0.543834	0.85489	0.699362	5
18	0.509356	0.705729	0.607543	20
19	0.752535	0.602222	0.677378	10
20	0.582333	0.724599	0.653466	16
21	0.54625	0.576596	0.561423	25
22	0.549071	0.718833	0.633952	18
23	0.514359	0.865815	0.690087	8
24	0.48119	0.713158	0.597174	21
25	0.483792	0.860317	0.672054	11
26	0.452026	1	0.726013	1
27	0.333333	0.83642	0.584877	22

The distinguishing or identification coefficient ξ has been used to compensate for the effect of the data series and is defined between zero to one. The value of ξ has been taken equal to 0.5. The GRC for each experiment OA is shown in Table 7.

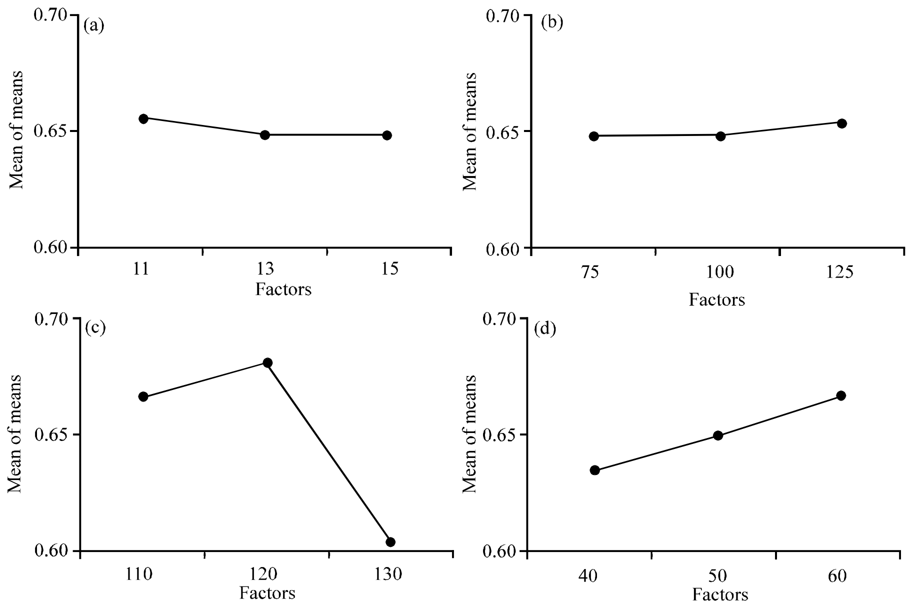

Fig. 6: Main effect of factors on GRG: a) I_p; b) V; c) T_{on} and d) T_{off}; Main effects plot for means (data means)

Table 8: Response table for the grey relational grade

Symbol	Machining parameters	Grey relational grade Level 1	Level 2	Level 3	Main effect (max-min)	Rank
A	I_p	0.654122*	0.644860	0.644047	0.010075	3
B	V	0.645443	0.644476	0.653110*	0.008635	4
C	T_{on}	0.669980	0.693038*	0.580012	0.113026	1
D	T_{off}	0.623953	0.646650	0.672426*	0.048473	2

The total mean value of the grey relational grade γ_m = 0.647676; *Levels for optimum grey relational grade

Table 9: Improvements in grey relational grade with optimized EDM machining parameters

Condition description	Optimal machining parameters: Machining parameters in the initial of OA	Grey theory prediction design
Level	A1B3C2D3	A1B3C2D3
WLT	13.286	11.834
SCD	0.0200	0.0174
grey relational grade	0.667906	0.729668

Improvement in grey relational grade = 0.061762

After get the GRC, the GRG is calculated by averaging the GRC corresponding to every response. The overall evaluation of the multiple responses (output) is based on the GRG that is Eq. 4:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{4}$$

where, γ_i the GRG for the ith experiment and n is the number of output or responses. Table 7 shows the GRG for each experiment. The higher GRG explains that the corresponding response is near to the optimum normalized value. Thus, experiment 26 is optimal among 27 experiments because it has the highest GRG.

It is then simple to separate the impact of every input parameter on the GRG at different levels, since, the design of experiments is orthogonal as shown in Table 8.

Figure 6 shows the GRG got for different machining conditions. The mean of the GRG for every parameter is clear by horizontal lines. Principally, the larger the GRG is the nearer will be the product quality to the optimum value. Thus, the larger GRG is coveted for optimum performance. Therefore, (A1B3C2D3) as presented in Table 8 is the optimum parameters which owns less WLT and SCD. The level with the maximum GRG is an optimal level of the process parameters.

Confirmation test: It has been performed to verify the enhancement of responses in WEDM of Al/WC_p metal matrix composites. The optimal parameters were selected for this test as shown in Table 8 and 9.

The estimated GRG ($\hat{\gamma}$) using the optimum level of the process (input) parameters can be computed by the Eq. 5 (Puh *et al*., 2016):

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q}(\gamma_i - \gamma_m) \tag{5}$$

Where:

γ_m = The total mean of the GRG
γ_i = The mean of the GRG at the optimal level
q = The number of the process (input) parameters that expressively affect multiple-responses (output)

The got process parameters which give greater GRG, are shown in Table 9. The predicted WLT, SCD and GRG for the optimum machining parameters are got by Eq. 5 and also presented in Table 9. It which shows the comparison of the experimental results using the initial (OA, A1B1C1D1) and optimal (grey theory prediction design, A1B3C2D3) machining parameters. Based on this table, WLT is decreased from 13.286-11.834 μm and the SCD is also decreased from 0.0200-0.0174 μ/μm^2. The corresponding improvements in WLT and SCD are 10.928 and 13%, respectively. It is clearly shown that the multiple performance characteristics in the WEDM process are greatly improved through this study.

CONCLUSION

Research has been successful in assessing feasibility of Al 10%Vol WC_p MMC by WEDM. All input parameters are directly proportional to WLT except T_{off} is inversely proportional to it. I_p and V are inversely proportional to SCD. With the increase in T_{on}, the SCD decreases up to an optimum level and then it starts increasing. T_{off} has no considerable effect on SCD.

From the response table of the average grey relational grade, it finds that the largest value of the grey relational grade for I_p, V, T_{on} and T_{off} are 11 A, 125V, 120 and 60 μsec, respectively. These are the recommended levels of controllable process factors when lesser WLT and SCD are simultaneously obtained. Based on the confirmation test, the improvements in WLT and SCD is 10.928 and 13%, respectively.

REFERENCES

Deris, A.M., A.M. Zain, R. Sallehuddin, S. Sharif and S. Yusuf, 2017. Grey Relational Analysis (GRA) of electrode wear rate in die sinking electric discharge machining. J. Eng. Appl. Sci., 12: 1795-1799.

Dewangan, S., S. Gangopadhyay and C.K. Biswas, 2015. Study of surface integrity and dimensional accuracy in EDM using Fuzzy TOPSIS and sensitivity analysis. Meas., 63: 364-376.

Fukuzawa, Y., N. Mohri, H. Gotoh and T.A.N.I. Takayuki, 2009. Three-dimensional machining of insulating ceramics materials with electrical discharge machining. Trans. Nonferrous Met. Soc. China, 19: 150-156.

Han, F., J. Zhang and I. Soichiro, 2007. Corner error simulation of rough cutting in wire EDM. Precis. Eng., 31: 331-336.

Khaja, M., R. Kumar and V. Singh, 2015. Modeling and optimization of WEDM process parameters on machining of AISI D2 steel using Response Surface Methodology (RSM). Intl. J. Adv. Res. Eng. Sci. Technol., 2: 49-53.

Marigoudar, R.N. and K. Sadashivappa, 2013. Effect of machining parameters on MRR and surface roughness in machining of ZA43/SiC_p composite by WEDM. Intl. J. Appl. Sci. Eng., 11: 317-330.

Pandey, A. and S. Singh, 2010. Current research trends in variants of electrical discharge machining: A review. Intl. J. Eng. Sci. Technol., 2: 2172-2191.

Patil, N.G. and P.K. Brahmankar, 2010b. Determination of material removal rate in wire electro-discharge machining of metal matrix composites using dimensional analysis. Intl. J. Adv. Manuf. Technol., 51: 599-610.

Patil, N.G. and P.K. Brahmankar, 2010a. Some studies into wire electro-discharge machining of alumina particulate-reinforced aluminum matrix composites. Intl. J. Adv. Manuf. Technol., 48: 537-555.

Puh, F., Z. Jurkovic, M. Perinic, M. Brezocnik and S. Buljan, 2016. Optimization of machining parameters for turning operation with multiple quality characteristics using Grey relational analysis. Tehnicki Vjesnik, 23: 377-382.

Satheesh, J., T. Pasha, Harish and T. Madhusudhan, 2013. Optimal machining conditions for turning of AlSiC metal matrix composites using ANOVA. Intl. J. Innovative Res. Sci. Eng. Technol., 2: 6171-6176.

Satishkumar, D., M. Kanthababu, V. Vajjiravelu, R. Anburaj and N.T. Sundarrajan *et al*., 2011. Investigation of wire electrical discharge machining characteristics of Al6063/SiC_p composites. Intl. J. Adv. Manuf. Technol., 56: 975-986.

Shandilya, P., P.K. Jain and N.K. Jain, 2013. RSM and ANN modeling approaches for predicting average cutting speed during WEDM of SiC_p/6061 Al MMC. Procedia Eng., 64: 767-774.

Shrivastava, S.M. and A.K. Sarathe, 2014. Influence of process parameters and electrode shape configuration on material removal rate, surface roughness and electrod e wear in die sinking EDM. Intl. J. Emerging Technol. Adv. Eng., 4: 138-145.

Singh, J. and V. Kumar, 2012. Investigation on the material removal mechanism and the thermal aspects in the electrical discharge machining process. Intl. J. Eng. Technol., 2: 1503-1507.

Vishwakarma, M., V. Parashar and V.K. Khare, 2012. Advancement in electric discharge machining on metal matrix composite materials in recent: A review. Intl. J. Sci. Res. Publ., 2: 86-93

Yan, M.T. and H.T. Chien, 2007. Monitoring and control of the micro wire-EDM process. Intl. J. Mach. Tools Manuf., 47: 148-157.