Research Article

INTERACTIONS OF PROCESS PARAMETERS DURING WEDM OF WC-Co COMPOSITE

[1]Muthuraman.V, [2]Ramakrishnan.R, [3]Puviyarasan M

Address for Correspondence

[1]Research Scholar, Mechanical Engineering Department, Sathyabama University, Jeppiaar Nagar, Chennai-600119, India.
[2]Professor and Head, Department of Sports Technology, Tamilnadu Physical Education and Sports University, [3]Melakotaiyur Post,Vandalur,Chennai-600 048. 1. Assistant Professor, Department of Mechanical Engineering, Panimalar Engineering College, Poonamallee, Chennai-600123, Tamil Nadu, India.

ABSTRACT

Wire electro Discharge machining (WEDM) is an advanced manufacturing process widely used to manufacture complex profiles precisely on hard, difficult to machine materials. In WC-Co, Tungsten and Carbide are hard wear resistant materials; cobalt is the binder that binds them made through powder metallurgy technique. Due to composite phases: melt, evaporation temperature varies and the thermo electric nature of process makes analysis complex and stochastic. To derive best operating inputs in order to attain best output, the influential parameters and their interactions need be studied, as some variables are basically contradictory in nature. The experiments were conducted in Taguchi L32 orthogonal array, with four levels of input parameters on, cobalt percentage, on time, off time, wire feed, wire tension, ignition current and dielectric pressure. The outputs studied in this work were material removal rate (MRR) and surface roughness (Ra) which are important in any machining process. ANOVA table constructed and the response study indicate ignition current as the critical parameter, followed by on time, off time, dielectric pressure and wire feed respectively. The interaction plot between cobalt binder percentage and on time show definite high level interaction. This work helps gain understanding the significant machining parameters, interaction of wedm process in machining of WC-Co composite

KEYWORDS: WEDM; WC-Co; Interactions; MRR; Surface roughness.

1. INTRODUCTION

Machining of composite is difficult due to the presence of reinforcement. The hard and brittle phase while improving wear resistance does decrease machinability. Attempts by conventional methods led to severe problem in tool wear, vibration, heat and roughness. Amongst advanced machining technique tried, WEDM is most suitable for electrically conductive materials as it offers reasonable economy, finish, reduced stress and cutting time (1, 2). It uses an electrically conducting (Cu-Zn) wire to create a spark which removes a tiny chunk of work material. A dielectric fluid, (distilled water) acts as a carrier of removed material and also to create spark of sufficient intensity to melt and vaporize work material (3,4). Taguchi's approach is found very effective and suitable for single response optimizing (Palanikumar.2011).Lower-the-better characteristic (Ra) for one factor may affect the performance of factors that demand higher-the-better characteristics (MRR), (5 Roy, 2001). Studies on Sintered-Carbides by Kim and Kruth (6 2001) revealed that increase of cobalt percent in carbides affect the metal removal rate and worsen the surface quality as greater quantity of solidified metal gets deposited on the eroded surface. Lauwers et.al.(2006) reported the influence of composition and grain size of WC-based cermets by WEDM and shown that the cutting rate decreases with increasing grain size and cobalt percentage, due to the change in thermal conductivity of the material. Jangra et al. (8,2011) machined WC-Co composite by WEDM and grouped influencing factors as, work material, machine tool, tool electrode, cutting conditions and geometry to be machined. They concluded that the machine tool is the most influencing factor affecting the machinability of WC-Co composite. Low cobalt concentration and small grain size favors high MRR; for cutting conditions, good conductivity and high flow rate of distilled water results in high MRR. In general ignition current and pulse on time- the electric parameters have a greater influence on wedm. Di- electric pressure and wire feed can assist a particular output depending on its level. In this work for the control factors considered, the analysis of variance (ANOVA) is used to examine the most significant factor which affects the WEDM process.

2. EXPERIMENTAL WORK

The experiments were carried out on WC-Co metal matrix composites with two different cobalt binder phase percentages (10 % and 20 %).Sodick AQ 427 wedm machine, with ceramic parts and linear motors to reduce friction and backlash, enabling high speed machining was used to slice cross sections of 5 X 5 mm with 10mm depth. Copper–zinc wire electrode of 0.25 mm diameter employed as tool electrode, distilled water applied as di-electric fluid. Three trials were conducted for each experiment planned and the mean of them was taken as the final result. Table 1 shows the parameters and levels used. Figure1 shows the Experimental Setup.

Table 1. Process parameters and levels

Symbols	Parameters	Levels			
		1	2	3	4
A	WC-Co%	10	20	--	--
B	Pulse on time(μsec)	6	9	12	15
C	Delay Time (μsec)	10	15	20	25
D	Wire Feed (mm/min)	70	80	90	100
E	Wire Tension (N)	6	8	10	12
F	Ignition Current(A)	8	12	16	20
G	Di-electric Pressure(Pa)	30	35	40	45

Fig.1.Experimental Setup

3. Process parameters and experimental design

Material removal rate was calculated using Eq.1.

$MRR=V_c \times B \times H.$ mm^3/min (1)

Where,

V_c = machining speed mm/min, $B = (2W_g + d)$. mm, H = thickness of the job. mm, d = diameter of electrode wire. mm, W_g = wire gap. mm;

Surface roughness was measured directly and to account for waviness, averages of three trials were used. The parameter range was selected in consultation with industry experts, sodick machine manufacturer's catalogue, and literature study. Surface roughness (Ra) of the wire electric discharge machined tungsten carbide cobalt metal matrix composites was measured using Surf coder SE-1200 and the average value taken. The calculated MRR and Ra and the coded input parameters are presented in Table2.Next the signal to noise ratio, mean value were evaluated. Finally analysis of variance and interaction that are significant were sorted and analyzed; a confirmation test was carried out to verify the validity of the findings.

Signal to noise ratio for Ra = $\eta ij = -10 \log 10 \left\{\frac{1}{n}\sum_{i=1}^{n} yij^2\right\}$ (2-a)

Signal to noise ratio for MRR = $\eta ij = -10 \log 10 \left\{\frac{1}{n}\sum_{i=1}^{n} \frac{1}{yij^2}\right\}$ (2-b)

Where,

n is the number of replications, and yij is the observed response value.

Whatever the category the higher the signal to noise ratio is the better the performance characteristics becomes. By applying the Equations (2, a-b) the S/N ratio was calculated, mean values for each experiment evaluated by selecting the corresponding parameter's level values and averaging it as shown Table 3.

Table 2. Experimental design using orthogonal array with coded factors and responses

Exp. Run	Input Process parameters							Responses	
	A	B	C	D	E	F	G	Ra	MRR
1	1	1	1	1	1	1	1	2.17	18.33
2	1	1	2	2	2	2	2	2.422	22.122
3	1	1	3	3	3	3	3	2.983	18.99
4	1	1	4	4	4	4	4	2.37	22.12
5	1	2	1	1	2	2	3	2.2	20.683
6	1	2	2	2	1	1	4	2.22	20.681
7	1	2	3	3	4	4	1	2.243	18.523
8	1	2	4	4	3	3	2	2.81	22.123
9	1	3	1	2	3	4	1	2.67	18.88
10	1	3	2	1	4	3	2	2.33	18.41
11	1	3	3	4	1	2	3	2.984	20.44
12	1	3	4	3	2	1	4	2.02	18.17
13	1	4	1	2	4	3	3	2.32	20.17
14	1	4	2	1	3	4	4	2.024	20.87
15	1	4	3	4	2	1	1	2.981	17.65
16	1	4	4	3	1	2	2	2.394	22.121
17	2	1	1	4	1	4	2	2.25	20.99
18	2	1	2	3	2	3	1	2.98	17.25
19	2	1	3	2	3	2	4	2.23	18.12
20	2	1	4	1	4	1	3	2.3	17.49
21	2	2	1	4	2	3	4	2.47	20.682
22	2	2	2	4	2	3	4	2.39	17.23
23	2	2	3	2	4	1	2	2.5	17.95
24	2	2	4	1	3	2	1	2.9	22.124
25	2	3	1	3	3	1	2	2.65	20.39
26	2	3	2	4	4	2	1	2.54	17.68
27	2	3	3	1	1	3	4	2.982	18.92
28	2	3	4	2	2	4	3	2.95	18.52
29	2	4	1	3	4	2	4	2.85	17.24
30	2	4	2	4	3	1	3	2.14	19.19
31	2	4	3	1	2	4	2	2.12	17.82
32	2	4	4	2	1	3	1	2.24	17.76

4. Tabulation and calculation

Table3, a) SN Ratio for HB of Mrr

I/P	Level				Delta	Rank
	1	2	3	4		
A	**26.00**	25.41	-	-	0.59	5
B	25.73	**25.99**	25.53	25.59	0.46	7
C	25.86	25.62	25.36	**26.00**	0.64	2
D	25.70	25.68	25.42	**29.04**	0.61	4
E	25.80	25.59	**26.04**	25.41	0.63	3
F	25.44	**26.01**	25.68	25.71	0.57	6
G	25.33	**26.09**	25.60	25.82	0.76	**1**

Table3,b) Mean Ratio for HB of Mrr

I/P	Level				Delta	Rank
	1	2	3	4		
A	20.02	18.71	-	-	1.31	5
B	19.43	20.00	18.93	19.10	1.07	7
C	19.67	19.18	18.55	20.05	1.50	2
D	19.33	19.28	18.74	20.11	1.37	4
E	19.56	19.11	20.09	18.70	1.39	3
F	18.73	20.07	19.29	19.37	1.33	6
G	18.52	20.24	19.09	19.60	1.72	**1**

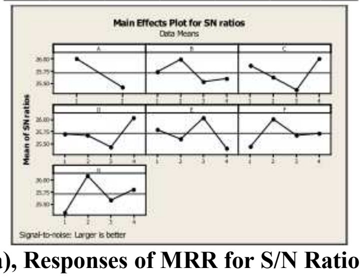

Fig 2 a), Responses of MRR for S/N Ratio (HB)

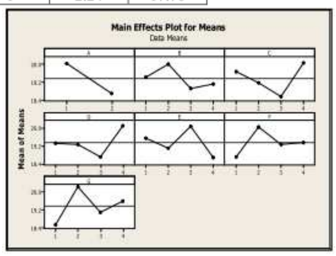

Fig2 b), Responses of MRR for Mean (HB)

Table 4,a) Responses of Ra for SN Ratio (LB)

I/P	Level				Delta	Rank
	1	2	3	4		
A	**7.69**	8.00	-	-	0.31	7
B	7.76	7.79	8.36	**7.47**	0.90	2
C	**7.73**	7.48	8.30	7.88	0.82	3
D	**7.44**	7.72	8.10	8.13	0.69	5
E	7.73	7.92	8.05	**7.69**	0.36	6
F	**7.44**	8.13	8.37	7.46	0.93	**1**
G	8.20	7.69	7.99	**7.51**	0.70	4

Table 4,b) Responses of Ra for Mean (LB)

I/P	Level				Delta	Rank
	1	2	3	4		
A	2.44	2.53	-	-	0.08	7
B	2.46	2.46	2.64	2.38	0.26	2
C	2.45	2.38	2.63	2.50	0.25	3
D	2.40	2.44	2.56	2.60	0.19	5
E	2.45	2.52	2.55	2.43	0.12	6
F	2.37	2.56	2.64	2.40	0.27	1
G	2.59	2.43	2.53	2.39	0.20	4

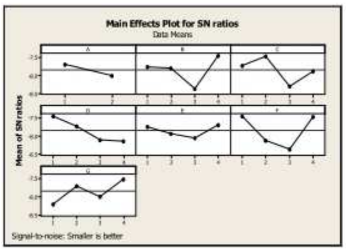

Figure 3, a) S/N Mean graph for Ra

Figure 3, b) Mean graph for Ra

5. Analysis and Discussion.

Table 3,(a& b) respectively, corresponds to the S/N and Mean responses for MRR. With reference to the maximum signal to noise ratio(Table3,a) the input parameters to maximize MRR are, low(10%)cobalt percentage, medium pulse on duration time (9µsec),highest pulse off time(25 µsec) and t wire feed rate (100mm/min),medium wire tension(10N),ignition current(12A)and di- electric pressure(35Pa) are recommended to attain best material removal rate. Figure 2(a&b) represents the graph for SN ratio and data means for MRR. The mechanical parameter di-electric pressure is of highest priority, closely followed by delay time, wire tension, wire feed and cobalt percentage. Di electric pressure to be medium so that gaseous substances and part of debris utilized for better machining. Higher, Delay time allows sufficient time to charge between successive sparks so that stronger spark is issued that removes more material. Mechanical parameter Wire tension to be moderate such that wire electrodes are flexible enough to vibrate to remove more material at places of lowest electrode gap. This has the tendency to produce surface waviness but MRR is bettered. The Wire feed to be maximum such that fresh wire is exposed for sparking, as each and every spark remove a smaller chunk of work material, a portion of wire too gets removed. This deposit partly on work surface voids created by reinforcement pullout and part is evaporated due to intense heat and part gets washed away with di-electric. More rounded wire sparks better as spark happens between shortest distances between wire-work combinations. High wire feed is good for bettering MRR but become un- economic as wire consumed is more and wire wastage is also more as all the wire is not utilized effectively. Low binder (cobalt) percentage yields better MRR as they have low melting temperature and dislodging/pull-out of tungsten-carbide particles become relatively easy once the binder is off. The binder graph slope also indicates this can increase production output. In data mean plot (Table3, b) also it assumes sixth rank, least significant but perfect choice for mean adjusting factor.

Corresponding to maximum signal to noise ratio, the input parameters for Ra (Table3,a) suggest statistically, low (10%) cobalt percentage, maximum(15 µsec) pulse on time, minimum (10 µsec) pulse off time, slow wire feed(mm/min) ,maximum wire tension(12N),minimum ignition current(8A), highest (45Pa) di-electric pressure combination can yield best surface finish. The negative bias is due to roughness scale, lower the better.

Figure 3(a& b) shows the graph for SN ratio and data means for Ra. Keeping the primary electrical parameter, Ignition current lowest ensures smooth finish (highest rank), followed by pulse on duration, the time to issue spark, kept high so that charges get diluted and then the time to charge the capacitor, pulse off be lower to allow as little time to charge the capacitor preventing from issuing intense sparks and irregular craters. Low feed rates and high wire tension improve surface finish at the cost of material removal rate.

It is observed form graphs that, in general cobalt percent increase, increases roughness, rise in on -time decrease smoothness, rise in feed rate of wire electrode increase roughness and dielectric increase increases smoothness.

6. Analysis of variances

ANOVA creates insight, information about the system just like an X-ray to a physician. It provides conformity information. Other benefits are, it states the percentage influence in numeric terms, the relative influence of factors and interactions to the variability of results, while the factors and interactions information is also indicated by the slopes of the main effects plots. ANOVA is preferable and statistically valid information for collective influences of factors that are excluded (error) in the study. Table 5(a & b) shows the anova for means for MRR and Ra respectively.

Table 5, a) Anova for means – MRR

I/P	DF	SS	MS	F%	P
A	1	13.38	13.38	43.75	0.01
B	3	5.32	1.77	5.80	0.44
C	3	10.1	3.37	11.02	0.20
D	3	7.64	2.55	8.34	0.30
E	3	8.53	2.84	9.30	0.26
F	3	7.18	2.39	7.82	0.33
G	3	12.84	4.28	14.00	0.13
Error	12	22.42	1.87		
Total	31	87.7		100	

Table 5, b) Anova for means –Ra

I/P	DF	SS	MS	F%	P
A	1	0.057	0.057	10.40	0.53
B	3	0.282	0.094	17.15	0.59
C	3	0.263	0.088	16.10	0.62
D	3	0.209	0.070	12.77	0.69
E	3	0.074	0.025	4.56	0.91
F	3	0.436	0.150	**27.37**	0.4
G	3	0.192	0.064	11.70	0.7
Error	12	1.706	0.142		
Total	31	3.217		100	

$P < 0.1$ is significant. From table 5(a) above of MRR, it lies on factor A. The percent contribution from column F signifies the relative power of a factor to reduce variation. Greater the percent contribution, even smaller variation will influence performances. According to the above analysis among the input parameters selected the statistically significant parameters for MRR is the Cobalt percentage in tungsten carbide cobalt metal matrix composite (43.75% contribution).But further analysis is required as the degrees of freedom is less here in the selected mixed design Analysis of variance for Ra was performed and test results presented in table5,(b).It was observed that none of the parameters have $P < 0.1$. i.e., not much significance among variables. The most dominant factor in F column is ignition current (27.37% contribution).The smallest variation in this will influence results drastically. Lowest contributor is wire tension which could be altered for optimization.

Interaction among variables need be evaluated to be more precise in analysis and to know which parameter is more interactive. The interactions among variables need be studied as not only individual parameters but their pooled combination need be understood to select a set of parameter range for optimization. The selection of interaction parameter was done as follows. From SN table it was identified, that significant parameter is G, a mechanical parameter and deserves interaction. Hence interactions of dielectric pressure with other parameters were studied in this work for MRR. From SN table for Ra it was observed, factor ignition current holds higher rank. Hence it was selected to interact with other input variables. Anova for interaction was calculated and presented in Table 6 for both MRR and Ra.

Table6,a) ANOVA with interaction for MRR

I/P	DF	SS	MS	F	P
A	1	13.86	0.004	0.00	0.969
B	1	1.673	1.013	0.36	0.556.
C	1	0.109	5.563	**1.98**	0.177
D	1	1.295	0.910	0.32	0.577
E	1	1.036	0.590	0.21	0.652
F	1	0.515	2.597	0.92	0.349
G	1	1.723	1.546	0.55	0.468
A* G	1	3.852	3.739	**1.33**	0.264
B* G	1	0.080	0.080	0.03	0.868
C* G	1	7.232	6.582	**2.34**	0.144
D*G	1	1.378	2.329	0.83	0.375
E*G	1	0.327	1.517	0.54	0.472
F*G	1	4.204	4.204	**1.49**	0.237
Error	18	50.65	2.814		
Total	31	87.766		10.9	

Table6,b) ANOVA with interaction for Ra.

I/P	DF	SS	MS	F	P
A	1	0.057	0.0000	0.00	0.998
B	1	0.0017	0.0042	0.03	0.864
C	1	0.0636	0.0008	0.01	0.940
D	1	0.1901	0.1273	0.92	0.351
E	1	0.0004	0.0111	0.08	0.781
F	1	0.0031	0.0331	0.24	0.631
G	1	0.0942	0.1463	**1.06**	0.318
A*F	1	0.0002	0.0002	0.00	0.970
B*F	1	0.0431	0.0431	**0.31**	0.584
C*F	1	0.0317	0.0141	0.10	0.754
D*F	1	0.1224	0.1224	**0.88**	0.360
E*F	1	0.0316	0.0127	0.09	0.766
F*G	1	0.0823	0.0823	**0.59**	0.451
Error	18			2.49	0.138
Total	31			4.31	

The Fisher's F test indicate the percent contribution of interaction, for MRR between pulse off time and dielectric maximum interaction takes place followed by interaction between ignition current with dielectric followed by interaction between cobalt percent and dielectric pressure. Fig.4(a) represents interaction graph for MRR.

In the graph 4 (a) and (b) for, if the lines are parallel or close there is minimal interaction. At further wide apart there is significant interaction. With cobalt percent and dielectric being low in p value it is considered in the analysis. The graph indicates higher interaction with increased cobalt percentage. Further, the interactions at lower dielectric rate are lower than the interaction at higher flushing rate.

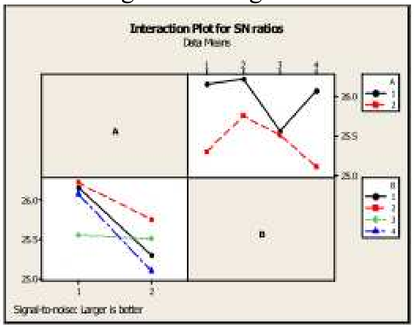

Figure4 (a) Interaction graph of SN for MRR

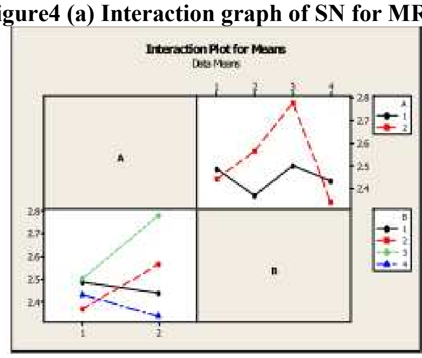

Figure4 (b) Interaction graph of means for MRR

The declining bias indicates MRR does reduce. The interaction plot for MRR with data means is given in figure 4(b). This plot confirms that at higher cobalt levels MRR deteriorates, pulse on time is not that significant, wire feed rise increases MRR at higher levels, increased ignition current and di electric can increase MRR.

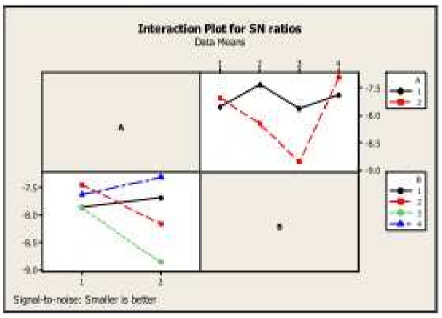

Figure 5 (a) Interaction graph of SN for Ra

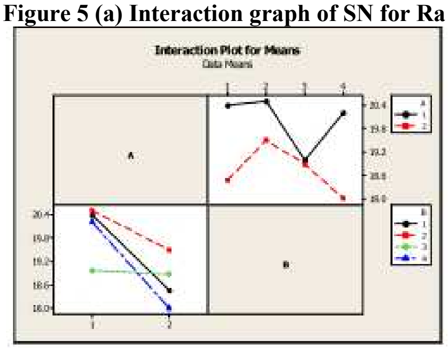

Figure 5 (b) Interaction graph of means for Ra

In case of surface roughness, the plot indicates the highest contributing factor, whose sensitivity affect outcome was dielectric pressure, and the wire feed, followed by interactions between wire feed-ignition current,and dielectric pressure with ignition current. Figure 5,(a) presents the interaction plot of SN for Ra.

The figure 5(b) resembles that of interaction plot between MRR and the means. The interaction effect is low at low levels and increases at higher levels. From the plots it is noted that higher cobalt content increases roughness sharply. Feed-rate increase to higher values results in reduced surface smoothness. Di electric pressure rise leads to increased surface smoothness.

7.Confirmation Experiment

The final step involved in the composite machining process is to predict and verify the performance characteristic with respect to the optimal level of the machining parameters in the WEDM.. The confirmation experiment was carried out to verify the feasibility and reproducibility of the optimization method adopted in this work by using the optimal parameters. To predict SN ratio ηopt using the optimal levels of the machining parameters the following formulae is used.

$$\eta opt = \eta m + \sum_{i}^{p} (\eta i - \eta m) \quad (6)$$

where,

ηm is the total mean of S/N ratio,

ηi is the mean of S/N ratio at the optimal level, and, p is the number of main machining parameters that significantly affect the performance.

The results of the confirmation test obtained through the confirmation experiment is presented in Table 7. The results for material removal rate in mm/min and surface roughness in microns were calculated separately Table 7(a), shows the comparison of the predicted MRR with the actual MRR using optimal machining parameters. The result indicates the MRR improves to 20.7mm/min a percentage rise of 4.45%. Table 7(b) represents the comparison of predicted Ra with actual Ra obtained through confirmation experiment.

The results conclude that the surface roughness decreases to 2.36 microns, a percent reduction of 4.5. Thus experimental results confirmed the validity of the Taguchi method for enhancing the machining performance and optimizing the machining parameters (MRR and surface finish).

Table 7.(a) Confirmation experiment for MRR

Element	Cutting Parameters		
	Initial	Predicted	Experiment
Level	A2B4C2D4 E3F1G3	A1B2C4D4E4F2G2	
MRR	19.19	--	20.07
SN	26.10	26.45	26.41

The improvement in SN =0.289 db.
Improvement in MRR =4.45%

Table 7.(b) Confirmation experiment for Ra

Element	Cutting Parameters		
	Initial	Predicted	Experiment
Level	A2B4C2D4 E3F1G3	A1B4C2D1E4F1G4	
Ra	2.47	--	2.36
SN	7.924	7.569	7.635

The improvement in SN =0.31 db
Improvement in Ra =4.5%

8. CONCLUSION

In this work analysis of wire electrical discharge machining (WEDM) for WC-Co composite with seven input variable and two output parameters were studied. Taguchi L 32 mixed orthogonal design was analysed by analysis of variance, interaction plots found. Anova was used to optimize the material removal rate (MRR) and surface roughness (Ra).

Based on the results and discussions, the following conclusions are made:

- Using Taguchi method, MRR and Ra were optimized individually. Two different optimal settings of process parameters were found for MRR and Ra. The optimal predicted values for MRR and Ra are 20.07 and 3.36 respectively.
- Using ANOVA on experimental results, Ignition current (27.37%) significantly affects MRR, Cobalt percentage (43.755 %) significantly affects Ra.
- Interaction study revealed pulse off time singularly affects (18.14%) outcome of MRR, and interaction with off-time (21.46%), di- electric pressure contributes (13.70%), followed by cobalt (12.20%).
- With respect to Ra, singularly, di- electric pressure and feed rate contribute 24.59% and 21% respectively. Interaction of feed rate with igniton-current contributes (20,50%).Whereas with dielectric pressure the contribution is 13.77%.
- The optimal combination of the process parameters, using taguchi optimization is set to:
  For MRR: A1(10%),B2(9μsec),C4(25μsec), D4 (100 mm/min),E4(12N),F2(12A) and G2(35Pa).
  For Ra: A1(10%)B4(15 μsec),C1(10 μsec), D1(70 mm/min)E4(12N)F1(8A) andG4(45 Pa) respectively.

This paper reveals importance of interaction study. The more the number of variables, the more the number of experiments considered the more relevant the result becomes.

ACKNOWLEDGEMENT

The author wishes to thank Dr. K. Palanikumar, Principal, Sairam Institute of Technology, Chennai for his solid guidance, and Mr. Balamugundan of Panimalar Engg.college,chennai for the support .

REFERENCES

[1] Nilesh Ganpatrao Patil, Brahmankar P K. (2008),"Determination of material removal rate in wire electro-discharge machining of metal matrix composites using dimensional analysis", The International Journal of Advanced manufacturing technology; 51,pp 599-610

[2] Mahapatra S S, Amar Patnaik. (2006)," Optimization of wire electrical discharge machining (WEDM) process parameters using genetic algorithm", Indian Journal of Engineering and Materials Sciences; 13.pp 494-502

[3] Muthuraman.V,Ramakrishnan,(2012), 'Microstructural Characterization of Wire Electro Discharge Machined Tungsten Carbide Cobalt Metal Matrix Composite", Advanced Materials Research Vols. 383-390 pp 3223-3228

[4] Ki Young Song, Do Kwan Chung, Min Soo Park, Chong Nam Chu1(2010), "Micro electrical discharge milling of WC-Co using a deionized water spray and a bipolar pulse", Journal of Micromechanics and Microengineering,20(4),pp221-230

[5] Roy, R.K.(2001)," Design of Experiments Using the Taguchi Approach: 16 Steps to Product and Process Improvement, John Wiley & Sons, Inc, New York.

[6] Palanikumar. K (2011),"Experimental investigation and optimisation in drilling of GFRP composites", Measurement 44,pp 2138–2148

[7] Chang-Ho Kim and Jean Pirre Kruth, 2001," Influence of the Electrical Conductivity of Dielectric Fluid of Sintered Carbide, KSME International Journal Vol. 15, No. 12, pp. 1676-1682

[8] Lauwers, B, LiuW, Earaerts,(2006),"Influences of composition of WC based cermets on manufacturability by WEDM', Journal of Manufacturing Processes 8(20)pp 83-92

[9] Kamal Jangraa, Sandeep Grovera and Aman Aggarwal(2011)," Simultaneous optimization of material removal rate and surface roughness for WEDM of WC-Co composite using grey relational analysis along with Taguchi method", International Journal of Industrial Engineering Computations 2,pp 479–490