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Multi Response Optimization of Wirecut Electrical Discharge Machining Process on AA7075 Metal Matrix Composites

Ramanan G[1], Adithya Y[2], Swathy A[3]

[1]Asst.Professor, Aerospace Engineering, Noorul Islam University, Tamilnadu, India
[2]Student, Aerospace Engineering, Noorul Islam University, Tamilnadu, India
[3]Student, Aerospace Engineering, Noorul Islam University, Tamilnadu, India

Abstract: *Metal matrix composite focuses primarily on improved specific strength, high temperature and wear resistance application. Aluminium alloy 7075 reinforced with Powdered activated carbon has good potential and is used extensively in aircraft primary structures. The main challenge is to produce this composite in a cost effective way to meet the above requirements. Specific strength of the composite has increased with addition of powdered activated carbon. This composite is produced by stir casting process. Stir casting technique is the conventional and economical way of producing aluminium matrix composite. This work investigates the effect and parametric optimization of process parameters for Wire cut electrical discharge machining of AA7075. Design of experiments has been created using response surface methodology Box Behnken design. Experiments were conducted by wire cut electrical discharge machining using discharge current, pulse on time, pulse off time, and servo speed as typical process parameters. The influence of the process parameters on overall quality characteristics of the wire cut electrical discharge machining was evaluated by the analysis of variance method. The confirmation test results with optimal parameters confirmed the effectiveness of the proposed method in this project. Grey relational analysis was proved to be a better technique than response surface method for optimization of multiple responses.*

Keywords: *Wire electrical discharge machining, Material removal rate, Surface roughness, Metal matrix composites, Box Behnken design, Analysis of Variance, Grey relational analysis*

1. INTRODUCTION

Metal matrix composites have high strength, hardness and light weighted. This paper work focuses mainly on the preparation of Al7075 alloy reinforced with powered activated carbon composites using stir – casting process. This composite with improved properties have wide range of applications in aerospace, defense, and automobile industries. Due to abrasive nature of reinforcement non–conventional methods are used for machining purpose. Wire electrical discharge machining is a diversified machine tool and has numerous advantages. It can machine anything that is electrically conductive regardless of the hardness. Material removal rate (MRR) and surface roughness (SR) are the most important performance parameters in Wire EDM that are influenced by input parameters such as discharge current, pulse on time, pulse off time, and servo speed. To find the effect of these process parameters on the responses response surface methodology (RSM) is used. Response surface methodology explores the relationships between several explanatory variables and one or more response variables. The high value of MRR and the low value of SR reduce the cost of production and improve product quality respectively.

1.1 Preparation of metal matrix composites

Stir casting process is used for fabricating the composite. The composite consists of 9 wt% PAC and 1 wt% Mg in metal matrix Al7075 alloy. Aluminium alloy 7075, with zinc (5.65 wt %) as the primary alloying element, is strong, has good fatigue strength and average machinability. The other elements and their corresponding weight percentage are shown in Table 1.

Table 1: *Composition of Al7075 alloy*

Elements	*Weight %*
Al	90.0
Zn	5.6
Mg	2.5
Cu	1.6
Cr	0.23
Ti	0.20

The Al7075 and powdered activated carbon is melted in the graphite crucible. Firstly grinded Al7075 alloy is placed in the crucible which is at 900 K. After the complete melting of Al7075 alloy, powdered activated carbon is added in the crucible. The stirrer blade is introduced into the molten Al7075 alloy and powdered activated carbon for further mixing. This mixture is poured into the die and allowed to cool at room temperature. After cooling the specimen is fragmented out from the die.

1.2 Machining parameters and responses

The input parameters, discharge current, pulse on time, pulse off time, and servo speed, were chosen for machining the composite. The ranges of the input parameters were selected and levels of the various parameters are given in Table 2.

Table 2: *Input parameters and their levels*

Factor	*Levels*	*Values*	Unit
Discharge Current	3	1500,1750,2000	mA
Pulse On time	3	5, 10, 15	µs
Pulse off time	3	25, 50, 75	µs
Servo Speed rate	3	50, 100, 150	RPM

2. BOX- BEHNKEN DESIGN

Box Behnken design is a type of response surface design that does not contain an embedded factorial or fractional factorial design box Behnken designs have treatment combinations that are at the mid points of the edges of the experimental space and require at least three continuous factors. The four input parameters, discharge current (I_A), pulse on time (T_{ON}), pulse off time (T_{OFF}), servo speed (SS), at three levels were selected and the 27 experiments were done.

3. EXPERIMENTAL SETUP FOR WEDM PROCESS

In wire electrical discharge machining process, the wire does not touch the work piece, so there is no physical pressure imparted on the work piece compared to grinding wheels and milling cutters. The amount of clamping pressure required to hold small, thin and fragile parts is minimal, preventing damage or distortion to the work piece. The wire electrical discharge machine is shown in fig 1. A wire EDM system is comprised of computerized numerical control, power supply, mechanical section, and dielectric system. In wire EDM, the conductive materials are machined with a series of electrical discharges that are produced between an accurately positioned moving wire and the work piece.

Fig 1: *WEDM machine*

High frequency pulses of alternating or direct current is discharged from the wire to the work piece with a very small spark gap through an insulator dielectric fluid. The volume of metal removed during the short period of spark discharge depends on the desired cutting speed and the surface finish required. These particles are flushed away from the cut with a stream of de-ionized water through the top and bottom flushing nozzles. The design of experiments consisted of 27 combinations of four input parameters at three levels and The observed average values of material removal rate (MRR) and surface roughness (SR) at different levels of the WEDM process parameters are shown in Table 4.

The wire cut electrical discharge machining pieces are shown in the Fig -2. The strength and hardness of the work materials are not affected in WEDM, but melting point of the work material is an important property. This is why WEDM finds extensive uses in machining of hard materials. The movement of wire is controlled numerically to achieve the desired cut in the workpiece. The wire is held by a pin guide at the upper and lower parts of the workpiece. Since the wire is subjected to complex oscillations due to electrical discharge between wire and the workpiece.

Table 4: *Experimental design using Response Surface Methodology*

Exp No	Current (mA)	Pulse on time (µs)	Pulse off time (µs)	Servo speed (RPM)	MRR (mm^3/min)	SR (µm)
1	1750	10	25	50	10.20	3.50
2	1750	15	75	100	10.24	3.64
3	2000	10	75	100	11.24	3.78
4	1750	15	25	100	9.57	3.32
5	1750	5	50	150	10.12	3.29
6	1750	5	75	100	9.99	3.10
7	1500	5	50	100	8.97	2.76
8	1500	10	75	100	9.05	2.85
9	1750	15	50	50	9.57	3.43
10	2000	15	50	100	11.13	3.76
11	1750	10	50	100	9.79	3.65
12	2000	10	50	150	11.45	3.77
13	2000	10	50	50	11.32	3.74
14	1750	10	25	150	10.22	3.69
15	1750	10	75	50	9.70	3.58
16	2000	10	25	100	10.96	3.73
17	1500	15	50	100	8.97	2.68
18	1750	5	50	50	9.23	3.35
19	1750	5	25	100	9.89	3.29
20	1500	10	50	50	8.61	2.53
21	1750	10	50	100	9.97	3.66
22	1500	10	25	100	9.51	2.73
23	1750	15	50	150	10.24	3.69
24	1750	10	50	100	10.46	3.71
25	1750	10	75	150	10.77	3.75
26	2000	5	50	100	10.81	3.72
27	1500	10	50	150	9.57	3.05

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4. ANALYSIS OF VARIANCE (ANOVA)

Analysis of variance (ANOVA) is a collection of statistical models use to analyze the differences among group means and their associated procedures. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are equal. ANOVAs are useful for comparing three or more means for statistical significance. It is conceptually similar to multiple two-sample t-tests, but is less conservative and is therefore suited to a wide range of practical problems. Analysis of variance (ANNOVA) was carried out to check the adequacy of the developed models. Table-5 shows the analysis of Variance (ANOVA) for MRR. The p value for the model is lower than 0.05 (i.e. at 95% confidence level) indicates that the developed model is statistically significant. The same and similar analysis was carried out for SR and listed in Table-6 the multiple regression coefficients for MRR, and SR were found 0.9164 and 0.9275 respectively. This shows that second order models can explain the variation in the MRR, and SR up to the extent of 91.64 % and 92.75% respectively. The R2 values are very high and close to the unity, it indicates that the second order models were adequate to represent the machining process.

Table 5: *Analysis of Variance for Material Removal Rate (MRR)*

Source	*Degree of freedom (DF)*	*Sum of square (SS)*	*Mean square (MS)*	*F-Value*	*P-Value*
Current	2	12.5251	6.26254	86.12	0.000
Pulse on time	2	0.3776	0.18878	2.60	0.102
Pulse off time	2	0.0645	0.03223	0.44	0.649
Servo speed	2	1.1714	0.58571	8.05	0.003
Error	18	1.3089	0.07272		
Lack-of-Fit	16	1.0684	0.06678	0.56	0.803
Pure Error	2	0.2405	0.12023		
Total	26	15.6619			

Table 6: Analysis of Variance for Surface Roughness (SR)

Source	*Degree of freedom (DF)*	*Sum of square (SS)*	*Mean square (MS)*	*F-Value*	*P-Value*
Current	2	3.42306	1.71153	95.28	0.000
Pulse on time	2	0.29129	0.14564	8.96	0.002
Pulse off time	2	0.05062	0.02531	1.56	0.238
Servo speed	2	0.10721	0.05361	3.30	0.060
Error	18	0.29262	0.01626		
Lack-of-Fit	16	0.29055	0.01816	17.57	0.055
Pure Error	2	0.00207	0.00103		
Total	26	4.03741			

4.1 Calculation of predicted MRR and SR

To determine the regression coefficients of the developed model, software, MINITAB 17 version was used. The second order models were developed for the responses due to lower predictability of the first order models. The following equations were obtained in terms of actual factors.

Mathematical Model Equation for Material removal rate

MRR = 10.0494 - 0.9836I_A_1500 - 0.0711I_A__1750 + 1.0547 I_A__2000 - 0.1428 T_{ON}_5 + 0.1672 T_{ON}_10 - 0.0244 T_{ON}_15 - 0.0282 T_{OFF}_25 - 0.0503 T_{OFF}__50 + 0.0785 T_{OFF}_75- 0.3007 SS_50 - 0.0219 SS_100 + 0.3226 SS_150 (1)

Mathematical Model Equation for surface roughness

SR = 3.2606 - 0.5960 I_A_1500 + 0.2086 I_A_1750 + 0.3874 I_A_2000 - 0.1497 T_{ON}_5 + 0.1311 T_{ON}_10 + 0.0186 T_{ON}_15- 0.0635 T_{OFF}_25 + 0.0536 T_{OFF}__50 + 0.0099 T_{OFF}__75 - 0.1022 SS_50 + 0.0194 SS_100 + 0.0828 SS_150 (2)

The influences of various machining parameters are shown on Chart 3. The discharge current has a highly significant effect on MRR and it has directly proportional effect. MRR is increasing with Pulse on time up to approximately 10 µs and then decreases with increasing value of Pulse on time. It may be due to decrease of flushing time with increasing of pulse on time, which causes debris recast on machining surface. Hence MRR decreases so it is required to choose an optimum machining parameter. MRR increases with pulse off time up to 50 µs and then decreases with increase in pulse off time.

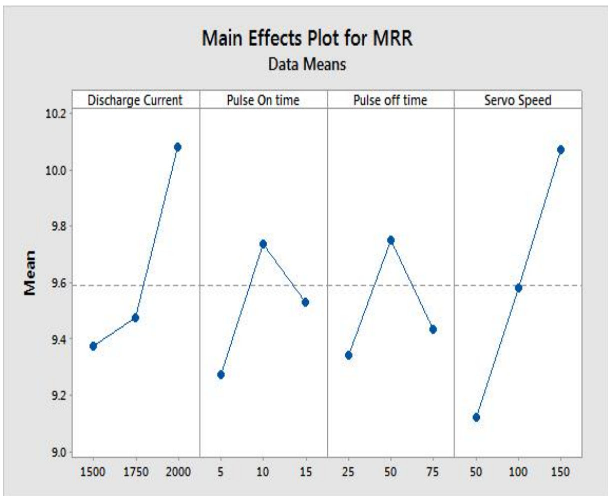

Chart 3: *Main effects plot for MRR*

The effects of various input parameters on SR are shown in Chart 4. Pulse on time influences the SR in the same manner as it affects the MRR. The discharge has a highly significant effect on SR. Surface roughness is increasing with pulse on time up to 10 μs and pulse off time up to 50 μs then decreases with increase in pulse off time and pulse on time.

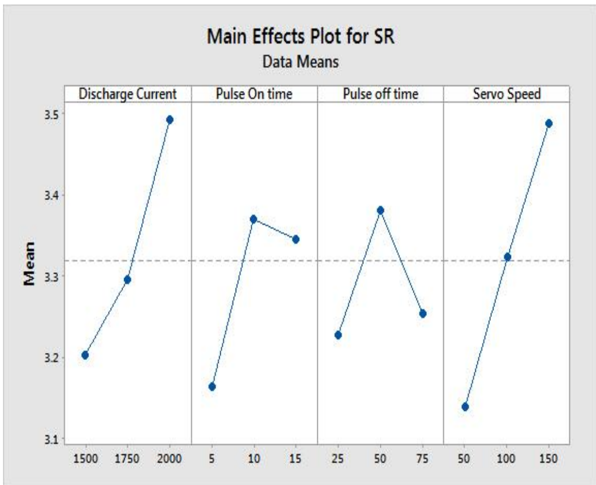

Chart 4: *Main effects plot for SR*

5. GREY RELATIONAL ANALYSIS

Grey theory is an essential uncertain knowledge acquisition method for small sample, poor information. In view of the universality of the normal distribution, the normality grey number is proposed. Then, the corresponding definition and calculation method of the relational degree between the normality grey numbers are constructed. Using the grey relational method, different process parameters of the wire EDM machining such as discharge current, pulse on time, pulse off time and servo speed were optimized to achieve the best multiple quality characteristics.

5.1 Grey relational analysis method

In the grey relational analysis, experimental results were first normalized and then the grey relational coefficient was calculated from the normalized experimental data to express the relationship between the desired and actual experimental data. Then, the grey relational grade was computed by averaging the grey relational coefficient corresponding to each process response. The overall evaluation of the multiple process responses is based on the grey relational grade.

As a result, optimization of the complicated multiple process responses can be converted into optimization of a single grey relational grade. In other words, the grey relational grade can be treated as the overall evaluation of experimental data for the multi response process. Optimization of a factor is the level with the highest grey relational grade.

MRR is the dominant response in EDM which decides the machinability of the material under consideration. For the "larger-the-better" characteristic like MRR, the original sequence can be normalized as follows:

$$x_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (3)$$

Where, $x_i^*(k)$ and $x_i(k)$are the sequence after the data preprocessing and comparability sequence respectively, k=1, 2… for MRR; i=1, 2, 3…, 27 for experiment numbers 1 to 27.

$$x_i^*(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (4)$$

Where, $x_i^*(k)$ and $x_i(k)$ are the sequence after the data preprocessing and comparability sequence respectively for SR; i=1, 2, 3…, 27for experiment numbers 1 to 27.

All the sequences after data pre-processing using equations are presented in Table 8. After data pre-processing is carried out, coefficient of MRR and coefficient of SR can be calculated with the pre-processed sequence. It expresses the relationship between the ideal and actual normalized experimental results. The coefficient values are defined as follows:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{io}(k) + \zeta\Delta_{\max}} \quad (5)$$

Where Δ_{oi}(k) is the deviation sequence of the reference sequence $x_0^*(k)$and the comparability sequence is $x_i^*(k)$, distinguishing or identification coefficient. If all the parameters are given equal preference, is taken as 0.5.

Table 8: *The sequences of each performance characteristic after data processing*

Ex No	MRR	SR	Normalised MRR	Normalised SR
1	10.2	3.5	0.559859155	0.224
2	10.24	3.64	0.573943662	0.112
3	11.24	3.78	0.926056338	0
4	9.57	3.32	0.338028169	0.368
5	10.12	3.29	0.531690141	0.392
6	9.99	3.1	0.485915493	0.544
7	8.97	2.76	0.126760563	0.816

8	9.05	2.85	0.154929577	0.744
9	9.57	3.43	0.338028169	0.28
10	11.13	3.76	0.887323944	0.016
11	9.79	3.65	0.415492958	0.104
12	11.45	3.77	1	0.008
13	11.32	3.74	0.954225352	0.032
14	10.22	3.69	0.566901408	0.072
15	9.7	3.58	0.383802817	0.16
16	10.96	3.73	0.827464789	0.04
17	8.97	2.68	0.126760563	0.88
18	9.23	3.35	0.218309859	0.344
19	9.89	3.29	0.450704225	0.392
20	8.61	2.53	0	1
21	9.97	3.66	0.478873239	0.096
22	9.51	2.73	0.316901408	0.84
23	10.24	3.69	0.573943662	0.072
24	10.46	3.71	0.651408451	0.056
25	10.77	3.75	0.76056338	0.024
26	10.81	3.72	0.774647887	0.048
27	9.57	3.05	0.338028169	0.584

After obtaining the grey relational coefficient, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristic. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, that is:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \qquad (6)$$

Where γ_i the grey relational grade for the i_{th}experiment and n is is the number of performance characteristics.

Table 9: *Calculation of coefficient of MRR and coefficient of SR*

Ex No	MRR	SR	Coefficient of MRR	Coefficient of SR	Grey relational grade
1	10.2	3.5	0.046728972	0.125	0.109228972
2	10.24	3.64	0.046554935	0.120772947	0.106941408
3	11.24	3.78	0.042589438	0.11682243	0.101000653
4	9.57	3.32	0.049652433	0.130890052	0.115097459
5	10.12	3.29	0.047080979	0.131926121	0.11304404
6	9.99	3.1	0.047664442	0.138888889	0.117108887
7	8.97	2.76	0.05279831	0.153374233	0.129485427
8	9.05	2.85	0.052356021	0.149253731	0.126982887
9	9.57	3.43	0.049652433	0.127226463	0.113265665
10	11.13	3.76	0.042992261	0.117370892	0.101677707
11	9.79	3.65	0.048590865	0.120481928	0.108831829
12	11.45	3.77	0.041841004	0.117096019	0.100389014
13	11.32	3.74	0.042301184	0.117924528	0.101263449
14	10.22	3.69	0.046641791	0.119331742	0.106307662
15	9.7	3.58	0.049019608	0.12254902	0.110294118
16	10.96	3.73	0.043630017	0.11820331	0.102731672
17	8.97	2.68	0.05279831	0.157232704	0.131414663
18	9.23	3.35	0.051387461	0.12987013	0.116322526
19	9.89	3.29	0.048123195	0.131926121	0.114086256
20	8.61	2.53	0.054884742	0.165016502	0.137392993
21	9.97	3.66	0.047755492	0.120192308	0.107851646
22	9.51	2.73	0.04995005	0.154798762	0.127349431
23	10.24	3.69	0.046554935	0.119331742	0.106220806
24	10.46	3.71	0.045620438	0.118764846	0.105002861
25	10.77	3.75	0.044365572	0.117647059	0.103189102
26	10.81	3.72	0.044208665	0.118483412	0.103450371
27	9.57	3.05	0.049652433	0.14084507	0.120074968

Table 10 shows the grey relational grade for each experiment. The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value.

Experiment 20has the best multiple performance characteristics among 27 experiments because it has the highest grey relational grade. It can be seen that in the present study, the optimization of the complicated multiple performance characteristics of WEDM of Al 7075 alloy has been converted into optimization of a grey relational grade. The grey relational grade is calculated based on the equation. The higher the grey relational grade represents that the corresponding experimental results is closer to the ideally normalized value. The combination of A1, B2, C2, and D1 shows the largest value of Grey relational grade for the factors A, B, C, and D, respectively where A, B, C, and D represents discharge current, pulse on time, pulse off time and servo speed. Therefore it is observed that when discharge current of 1500 mA, pulse on time of 10 µm, pulse off time of 50 µm and servo sped of 50 RPM is the optimal parameter combination of the WEDM operations. When these values are taken as the input parameters the material removal rate is improved and the surface roughness is minimized.

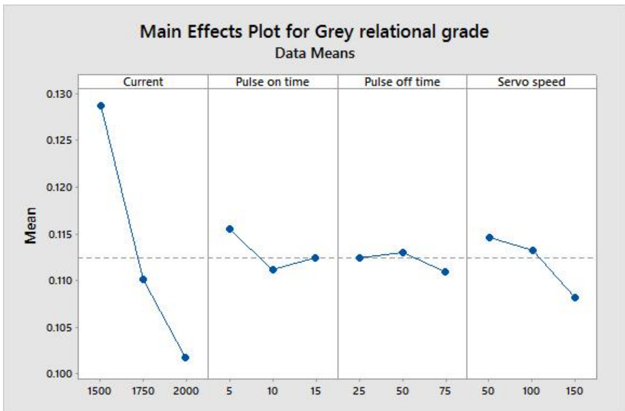

Chart 5: *Main effects plot for grey relational grade*

The chart 5 shows the grey relational grade graph and the total mean of the grey relational grade are indicated. The predicted grey relational grade is calculated and the error between the grey relational grade and the predicted grey relational grade is taken. Predicted grey relational grade

$$Grade = 0.11505 + 0.015579 I_A\_1500 - 0.004127 I_A\_1750 - 0.011452 I_A\_2000 + 0.003008 T_{ON}\_5 - 0.002869 T_{ON}\_10 - 0.000139 T_{ON}\_15 + 0.001050 T_{OFF}\_25 - 0.000553 T_{OFF}\_50 - 0.000497 T_{OFF}\_75 + 0.003350 SS\_50 - 0.000275 SS\_100 - 0.003074 SS\_150 \quad (7)$$

Graph between Experimental grey relational grade and Predicted grey relational grades is shown in chart 6

Table 11 shows the calculation of predicted grey relational grade

5.2 Analysis of variance of grey relational grade

Table 11: *Calculation of predicted grey relational grade*

Ex no	***Grey relational grade***	***Predicted grey relational grade***	***error***
1	0.109228972	0.10102355	0.07512
2	0.106941408	0.10991235	0.02778
3	0.101000653	0.11234988	0.11237
4	0.115097459	0.11102341	0.0354
5	0.11304404	0.11892346	0.05201
6	0.117108887	0.12345673	0.0542
7	0.129485427	0.15356783	0.18599
8	0.126982887	0.0812346	0.36027
9	0.113265665	0.14345679	0.26655
10	0.101677707	0.11657896	0.14655
11	0.108831829	0.12456094	0.14453
12	0.100389014	0.11908765	0.18626
13	0.101263449	0.13098764	0.29353
14	0.106307662	0.11807654	0.11071
15	0.110294118	0.12569054	0.13959
16	0.102731672	0.11908765	0.15921
17	0.131414663	0.10908765	0.1699
18	0.116322526	0.06123457	0.47358
19	0.114086256	0.1345679	0.17953
20	0.137392993	0.12789765	0.06911
21	0.107851646	0.12348907	0.14499
22	0.127349431	0.14789644	0.16134
23	0.106220806	0.08908764	0.1613
24	0.105002861	0.12890877	0.22767
25	0.103189102	0.11908071	0.154
26	0.103450371	0.11109081	0.07386
27	0.120074968	0.10807061	0.09997

The grey relational grades obtained from the experimental values are statistically studied by ANOVA to inspect the effects of each machining parameter on the observed values and to clarify which machining parameter significantly affects the observed values. The purpose of ANOVA is to investigate which machining parameters significantly affect the performance characteristics. In addition, the F-test has been used to determine which process parameters have a significant effect on the performance characteristics. Table 12 shows the calculated F-values for material removal rate and surface roughness respectively to determine the relative significances of different control factors.

The results of the F –test clearly indicate that the discharge current have statistically significant effect on material removal rate and surface roughness at the 95 % confidence level. Therefore, discharge current is found to be the significant factor that influences the material removal rate and surface roughness. Percentage contribution indicates the relative power of a factor to reduce variance. For a factor with a higher percent contribution, a small variation will have a great influence on the performance. The percent contribution of the machining parameters on the material removal rate and surface roughness, shown in table 12, reveals that discharge current and servo speed have maximum influence on material removal rate and surface roughness. It can be seen from Chart 7 that discharge current is the most significant factor that affects the grey relational grade.

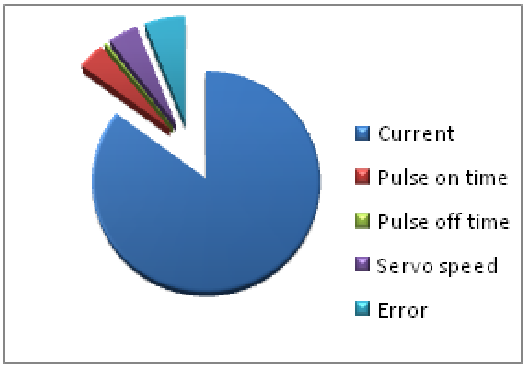

Chart 7: *Percentage contributions of factors on the grey relational grade*

6. CONFIRMATION TEST

Confirmation test has been carried out to verify the improvement of performance characteristics in wire EDM machining in Al 7075 alloy. The optimum parameters are selected for the confirmation test. The estimated grey relational grade using the optimal level of the machining parameters can be calculated using following equation.

$$\eta = \eta_m + \sum_{i=1}^{q} (\eta_i - \eta_m) \quad (8)$$

Where η_m the total mean of the grey relational grade is η_i is the mean of the grey relational grade at the optimal level, and q is the number of the machining parameters that significantly affect multiple-performance characteristics. The obtained process parameters, which give higher grey relational grade, are presented in Table 12. The predicted MRR, SR and grey relational grade for the optimal machining parameters are also presented. Based on Table 13, MRR is accelerated from 8.61 to 10.34 mm^3/min; the SR is decreased from 2.53 to 2.50μm. It is clearly shown that the multiple performance characteristics in the EDM process are greatly improved through this study.

7. CONCLUSION

In this paper work an experimental study on material removal rate and surface roughness by wire cut electrical discharge machining (WEDM) of AA7075 metal matrix composites is presented and the effects of four process parameters on Material removal rate (MRR) and Surface roughness (SR) have been studied. From the experimental results an empirical mathematical model for the prediction of material removal rate in WEDM machining process of AA7075 metal matrix composites has been developed using Response surface methodology (RSM) and regression analysis. Within the scope of this experiment, the MRR value increases with increase of current. It is obvious that in high values of current and pulse on time the MRR values increases. SR value decreases with higher influence of current. This model was experimentally confirmed and its great consistency and applicability were within the experiment range used. The experimental value and predicted values are close to the linear values. The error value which shows very less value which is modelled by regression analysis. Multi response optimization is done using grey relational analysis, when values current 1500mA, pulse on time 10μs, pulse off time 50μs and servo speed 50 rpm are used as input parameters we can achieve high Material removal rate and low Surface roughness.

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