MultiCraft

International Journal of Engineering, Science and Technology
Vol. 3, No. 8, 2011, pp. 87-101

INTERNATIONAL
JOURNAL OF
ENGINEERING,
SCIENCE AND
TECHNOLOGY
www.ijest-ng.com

Experimental investigations on machining characteristics of Al 6061 hybrid metal matrix composites processed by electrical discharge machining

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Abstract

Metal matrix composites, in particular, Aluminium Matrix Composites are gaining increasing attention for applications in aerospace, defence and automobile industries. The use of nonconventional machining techniques in shaping aluminum metal matrix composites has generated considerable interest as the manufacturing of complicated contours such as dies. Electrical discharge machining (EDM) appears to be a promising technique for machining metal matrix composites. The objective of this work is to investigate the effect of parameters like Current(I), Pulse on time(T), Voltage(V) and Flushing pressure(P) on metal removal rate (MRR),tool wear rate(TWR) as well as surface roughness(SR) on the machining of hybrid Al6061 metal matrix composites reinforced with 10% SiC and 4%graphite particles. Composite was fabricated using stir casting process. A central composite rotatable design was selected for conducting experiments. Mathematical models were developed using the MINITAB R14 software. The method of least squares technique was used to calculate the regression coefficients and Analysis of Variance (ANOVA) technique was used to check the significance of the models developed. Scanning Electron Microscope (SEM) analysis was done to study the surface characteristics of the machined specimens and correlated with the models developed.

Keywords: Electrical discharge machining, Metal matrix composites, Response surface method, Hybrid composites, Aluminium composites, stir casting process.

DOI: http://dx.doi.org/10.4314/ijest.v3i8.7

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1. Introduction

Composite refers to a material system which is composed of a discrete constituent (the reinforcement) distributed in a continuous phase (the matrix) and which derives its distinguishing characteristics from the properties of its constituents, from the geometry and architecture of the constituents as well as from the properties of the boundaries(interfaces) between different constituents (Surappa, 2003). Metal Matrix Composites (MMC's) have many advantages over monolithic metals including higher specific modules, higher specific strength, better properties at elevated temperatures, lower coefficient of thermal expansion, in addition to better wear resistance. Aluminium and its alloys have been getting most attention as matrix material for MMC's and the most common reinforcement is SiC (Rosso, 2006). Aluminum matrix composites refer to the class of light weight high performance aluminum centric material systems. Properties of aluminum matrix composites can be tailored to the demands of different industrial applications by suitable combinations of matrix, reinforcement and processing route. Aluminium composites containing solid lubricants such as graphite and MOS_2 showed better friction and wear behaviour (Mihaly Kozma, 2003). Aluminum matrix composites are produced by powder metallurgy, stir casting, metal infiltration, spraying and insitu processing techniques. These composites have been successfully used as components in automotive and aerospace applications (Torralba et al., 2003).

EDM is used in modern manufacturing industry to produce high-precision machining of all types of conductive materials, alloy's and even ceramic materials with any hardness and shape, which would have been difficult to manufacture by conventional machining. Electrical Discharge Machining (EDM) is a non-traditional machining process that uses thermo-electric energy for material removal. The material is removed by the erosive action of spatially discrete high-frequency electrical discharges (sparks) of high power density between two electrodes, one being the tool and the other being the work piece itself with a dielectric fluid in the gap between them. The application of dielectric fluid makes it possible to flush away eroded particles from the gap and cool it (Banerjee et al., 2008). Electrical discharge machining provides an economical and effective method for machining high strength, heat resistant materials for complex shapes (George et al., 2004; Leesh and Li Xp, 2001, Mahdavinejad and Mahdavinejad, 2005). Among the many unconventional processing techniques, EDM has proved to be effective in machining composite materials (Lauws et al., 1999; Muller and Monaghan 2000). Various researchers have conducted experiments on EDM with different composites.

Patel et al. (2010) reported that better metal removal rate and lower surface roughness of Al_2O_3–SiC_w–TiC ceramic composite during EDM was obtained for discharge current, pulse-on time, duty cycle and gap voltage 7 A, 50 μs, 0.80 and 50 V, respectively. Nilesh Ganpatrao Patil & Brahmankar, 2010, investigated the electric discharge machining characteristics of silicon carbide particulate reinforced aluminium matrix composites. They found that increased percentage of ceramic particulates in the MMC causes decreased MRR. The decrease in MRR is almost 12% with an increase of 10% in ceramic reinforcements. Khanra, 2005 reported that metal removal rate and tool wear rate increased with increase in applied current and pulse on time. Kung et al.. (2009) reported that electrode wear rate apparently increase with the increase of the discharge current and pulse on time. Ahamed et al. (2009) reported on the application of EDM to machine cast aluminum–silicon carbide–glass hybrid metal matrix composites and how the metal removal rate and surface finish vary in response to the various EDM parameters. They found that the metal removal rate increases with increase in flushing pressure. Based on the above considerations, a limited work has been carried out on electric discharge machining of hybrid composites. The major contribution in this research work is to fabricate a hybrid composite containing silicon carbide and graphite particles using stir casting process and its machining characteristics were studied. The objective of the present paper is to develop mathematical models for correlating the direct and interactive influences of the various machining parameters such as current, voltage, pulse on time, flushing pressure on the predominant machining criteria, i.e., the metal removal rate, tool wear rate, and surface roughness. Influence of EDM process parameters on machining performance criteria were studied with the development of mathematical models based on Response Surface Methodology (RSM).

2. Material preparation

The matrix material used in this study is Al6061 alloy. The reinforcement materials added were SiC and graphite particles. The addition of SiC particle improves the wear resistance and brittleness. The graphite particles act as solid lubricant which improve the surface finish and reduce the heat generation during machining. The composites were prepared using stir casting process. Al6061 alloy is kept in graphite crucible inside the electric induction furnace. The alloy was melted to the desired super heating temperature of 1063°K. The preheated reinforcement particles with an amount of 10 wt% of SiC and 4wt% of graphite particles and an average size of 75 microns was introduced into the vortex of the molten alloy after effective degassing. Mechanical stirring of the molten alloy for a duration of 15mins was achieved by using a graphite stirrer (Velmurugan et al., 2011). The speed of the stirrer was maintained at 600rpm. The melt was poured at 873°K into a cast iron mould. Then the mould was left in air to cool down to room temperature and then the cast composites were obtained.

3. Experimental work

A series of experiments were conducted using ARD-make die-sinking EDM machine as shown in Figure 1. A tool made of copper with diameter 10 mm was used as an electrode.

Figure 1: ARD-make die sinking machine

Figure 2: Jet flushing system

The other electrode was Al6061 composites reinforced with 10wt. %SiC and 4wt. %. of graphite particles. The size of the work piece is 10 mm diameter and 25 mm length. The density and Rockwell hardness of the composite are 2.7313g/cm^3 and 68 HRB respectively. Commercial grade EDM oil (density = 0.85, flash point= 130˚C) was used as dielectric fluid and the side injection of dielectric fluid was adopted. A jet flushing system shown in Figure 2, was employed to assure adequate flushing of the debris from the gap zone. The process parameters were being set in the EDM machine and the experiments were conducted as per the design matrix as shown in Table 2. After each experiment the weights of specimen and electrode are measured with an electronic weighing machine.

4. Experimental procedure

The experimental procedure is shown in Figure 3 and important steps are briefly explained in the following sections.

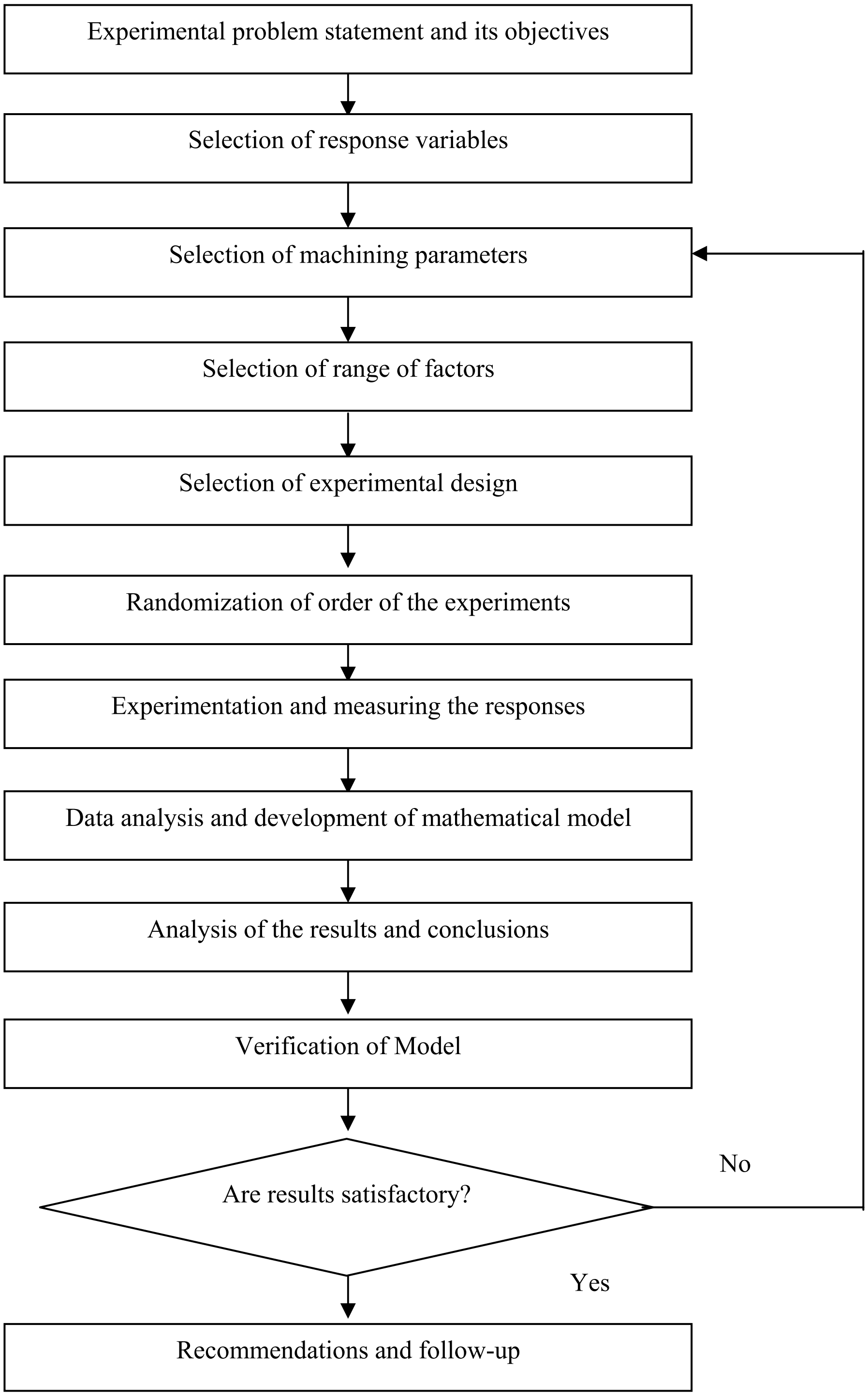


Figure 3: Experimental procedure

4.1 Machining parameters and response variables

Four controllable machining parameters were identified namely, current, pulse on time, voltage and flushing pressure. On the basis of preliminary experiments conducted using one variable at a time approach, the range of the current, pulse on time, voltage and flushing pressure were selected as 3 to 15 A, 200 to 600 µs, 30 to 70 V and 1 to 5 psi respectively. At current values less than 3A, it was observed that metal removal rate (MRR) was not significant and for current values more than 15A, the surface finish of the work piece was poor necessitating the selection of the intermediate values as stated above. The range selected for the pulse on time was commonly used for the EDM of ceramic composites. The range of voltage selected was available in the machine. When the flushing pressure less than 1 psi, it was observed that more tool wear occurred and for flushing pressure greater than 5 psi, work piece surface finish was poor. Control parameters and their levels are given in Table 1. The response variables selected for this work are metal removal rate (MRR), tool wear rate (TWR) and surface roughness (SR). Machining time for each experiment was taken as 10 minutes.

Table 1 Machining parameters and their levels

Machining parameters	symbols	unit	Level				
			-2	-1	0	+1	+2
Current	I	A	3	6	9	12	15
Pulse on time	T	µs	200	300	400	500	600
Voltage	V	V	30	40	50	60	70
Flushing Pressure	P	psi	1	2	3	4	5

4.2 Response variables evaluation

Metal removal rate (MRR) is expressed as the ratio of the difference of weight of the work piece before and after machining to the machining time, i.e.:

$$\text{MRR} = \left[\frac{W_{jb} - W_{ja}}{t}\right] \quad \text{(g/min)} \qquad (1)$$

where W_{jb} and W_{ja} are the weights of the work piece before and after machining, and t is the machining time.

Tool wear rate is expressed as the ratio of the difference of weight of the tool before and after machining to the machining time, i.e.:

$$\text{TWR} = \left[\frac{W_{tb} - W_{ta}}{t}\right] \quad \text{(g/min)} \qquad (2)$$

where W_{tb} and W_{ta} are the weights of the tool before and after machining and t is the machining time.

MRR and TWR are directly calculated from the experimental data. The weight of the specimen is taken before and after the machining process using a digital weighing machine with an accuracy of 0.001g. Before weighing, the specimen is cleaned and dried to relieve it from debris and dirt. The difference of weight before and after machining gives the weight loss of the work piece during machining process. This weight is divided with machining time to get the metal removal rate and tool wear rate in g/min.

Surface roughness of the machined work piece is evaluated using a Mitutoyo talysurf tester shown in Figure 4 with a diamond stylus tip and a sampling length of 8mm. The centre line average value of surface roughness (R_a in micron) for each experiment was obtained directly from the tally profile software integrated with the machine.

Figure 4: Surface roughness tester

4.3 Design of Experiments

In the present investigation, experiments were designed on the basis of the Design of Experiments (DOE) technique proposed by Box and Hunter (Cochran and Cox, 1987). A 2^k factorial, where k is the number of variables, with central composite second-order rotatable design was used to improve the reliability of results and to reduce the size of experimentation without loss of accuracy.

In this work, central composites rotatable design was selected for experimentation. The process parameter selected for the present work were current, voltage, pulse on time and flushing pressure and the effect of these parameters on the metal removal rate, tool wear rates and surface roughness were studied. The working ranges of all selected factors were set by conducting trial runs with one of the factors was varied while keeping rest of them at constant values (Kuppan et al., 2006; Murugan and Parmar, 1995). The levels of each factor were chosen as -2,-1, 0, 1, and 2 in closed form to have a rotatable design.

The coded values for intermediate values of a variable were calculated using the following Eq. (3)

$$X_i = \frac{2\left[2X - \left(X_{max} + X_{min}\right)\right]}{X_{max} - X_{min}} \tag{3}$$

where X_i is the required coded value of a variable X, X any value of the variable from X_{min} to $X_{max,}$ X_{min} the lower limit of the variable, and X_{max} the upper limit of the variable.

For the four variables chosen the central composite rotatable design required 31 experiments with 16 factorial points, eight axial points to form central composite design and seven center points for replication to estimate the experimental error. The experiment has been carried out according to the run order in the experiment design matrix as given in Table2. At the end of each run, settings for all four parameters were changed and reset for the next run. This was essential to introduce variability caused by errors in experimental settings (Harris and Smith, 1983).

Table2 Design Matrix

Run order	Std. Order	Current (I) A	Pulse on time (T) µs	Voltage (V) V	Flushing pressure (P) psi	Experimental value			Predicted value		
						MRR (g/min)	TWR (g/min)	SR ($\times 10^{-1}$ µm)	MRR (g/min)	TWR (g/min)	SR ($\times 10^{-1}$ µm)
1	6	1	-1	1	-1	0.481	0.044	65	0.480	0.045	68.253
2	12	1	1	-1	1	0.53	0.026	91	0.542	0.026	93.586
3	27	0	0	0	0	0.464	0.034	81	0.486	0.033	80.143
4	18	2	0	0	0	0.583	0.036	91	0.552	0.036	86.310
5	14	1	-1	1	1	0.515	0.041	105	0.507	0.041	104.086
6	31	0	0	0	0	0.491	0.035	85	0.486	0.033	80.143
7	10	1	-1	-1	1	0.524	0.031	84	0.527	0.031	83.753
8	7	-1	1	1	-1	0.449	0.037	68	0.429	0.037	71.920
9	22	0	0	2	0	0.419	0.048	94	0.435	0.046	91.250
10	23	0	0	0	-2	0.431	0.039	45	0.459	0.037	44.310
11	1	-1	-1	-1	-1	0.45	0.032	40	0.434	0.032	41.753
12	29	0	0	0	0	0.464	0.031	77	0.486	0.033	80.143
13	24	0	0	0	2	0.521	0.03	111	0.513	0.029	115.976
14	30	0	0	0	0	0.497	0.034	79	0.486	0.033	80.143
15	4	1	1	-1	-1	0.51	0.029	56	0.515	0.030	57.753
16	19	0	-2	0	0	0.476	0.041	64	0.471	0.039	68.075
17	25	0	0	0	0	0.483	0.033	80	0.486	0.033	80.143
18	28	0	0	0	0	0.486	0.034	81	0.486	0.033	80.143
19	15	-1	1	1	1	0.454	0.033	108	0.456	0.033	107.753
20	20	0	2	0	0	0.542	0.031	89	0.510	0.030	89.976
21	21	0	0	-2	0	0.495	0.027	48	0.474	0.026	50.584
22	11	-1	1	-1	1	0.461	0.022	89	0.475	0.023	87.420
23	26	0	0	0	0	0.495	0.033	78	0.486	0.033	80.143
24	13	-1	-1	1	1	0.451	0.036	98	0.441	0.038	97.920
25	16	1	1	1	1	0.519	0.036	110	0.522	0.036	113.920
26	5	-1	-1	1	-1	0.441	0.042	62	0.420	0.042	62.086
27	8	1	1	1	-1	0.492	0.039	74	0.495	0.040	78.086
28	2	1	-1	-1	-1	0.498	0.035	48	0.500	0.035	47.920
29	9	-1	-1	-1	1	0.46	0.028	78	0.460	0.028	77.586
30	3	-1	1	-1	-1	0.453	0.025	52	0.449	0.026	51.586
31	17	-2	0	0	0	0.41	0.031	73	0.420	0.030	73.976

4.4 Development of Mathematical models

The function representing any of the response variables can be expressed using Eq. (4)

$$Y=f\,(X_1, X_2, X_3, X_4)+\text{€} \tag{4}$$

where Y is the response (e.g. metal removal rate), € is the error, X_1 the current (I) (A), X_2 the pulse on time (T) (μs), X_3 the voltage (V) (V), and, X_4 the flushing pressure (P) (psi).

The second order response surface model (Montgomery, 2003) for the four selected factors is given by Eq.(5)

$$Y=\beta_o+\sum_{i=1}^{4}\beta_i X_i+\sum_{i=1}^{4}\beta_{ii} X_i^{\,2}+\sum_{\substack{i=1\\ i<j}}^{4}\beta_{ij} X_i X_j \tag{5}$$

The above second order response surface model equation could be expressed as follows:

$$\begin{aligned}Y=\beta_o+\beta_1 I+\beta_2 T+\beta_3 V+\beta_4 P+\beta_{11} I^2+\beta_{22} T^2+\beta_{33} V^2+\beta_{44} P^2+\beta_{12} IT+\beta_{13} IV+\\ \beta_{14} IP+\beta_{23} TV+\beta_{24} TP+\beta_{34} VP\end{aligned} \tag{6}$$

where β_o is the free term of the regression equation, the coefficients $\beta_1, \beta_2, \beta_3 and \beta_4$ are linear terms, the coefficients $\beta_{11}, \beta_{22}, \beta_{33}, \beta_{44}$ are the quadratic terms, and the coefficients $\beta_{12}, \beta_{13}, \beta_{14}, \beta_{23}, \beta_{24} and \beta_{34}$ are the interaction terms of the regression equation.

The values of the coefficient of the polynomial Eq. (6) were calculated as shown by Kannan and Murugan (2006) by Eqs. (7)-(10)

$$\beta_o=0.142857\sum Y-0.035714\sum\sum(X_{ii}Y) \tag{7}$$

$$\beta_i=0.041667\sum(X_i Y) \tag{8}$$

$$\beta_{ii}=0.03125\sum(X_{ii}Y)+0.035714\sum\sum(X_{ii}Y)-0.035715\sum Y \tag{9}$$

$$\beta_{ij}=0.0625\sum(X_{ij}Y) \tag{10}$$

The β coefficients, used in the above model can be calculated by means of using least square method. The regression coefficients were calculated using MINITAB R14 software and used to develop the mathematical models. The insignificant coefficients were eliminated without affecting the accuracy of the developed model. This was done by back elimination technique, available in MINITAB R14 software. The coefficients given in Table 3 are used to obtain the mathematical models. The Mathematical models developed for the response variables with machining parameters in coded form are given in equations 11-16. The insignificant coefficients are eliminated and the final reduced models are given in equations 11-13 and the full models are given in equations 14-16.

Metal removal rate (MRR) (g/min) = 0.485874+ (0.03316*I) + (0.0075*T) - (0.00983*V) + (0.01333*P)- (0.00790*V*V) (11)

Tool wear rate (TWR) (g/min) = 0.033442+ (0.0015*I)-(0.00258*T) + (0.00508*V) - (0.002*P) + (0.00070*V*V) (12)

Surface roughness (SR) (μm) = 80.1429+ (3.0833*I) + (4.9167*T) + (10.1667*V) + (17.9167*P)-(2.3065*V*V) (13)

Metal removal rate (MRR) (g/min) = 0.485874+ (0.03316*I) + (0.0075*T) - (0.00983*V) + (0.01333*P)+ (0.002723*I*I) + (0.005848*T*T) - (0.007152*V*V) –(0.002402*P*P)+(0.001125*I*T) –(0.001625*I*V)+ (0.004625*I*P)+ (0.000250 *T*V)- (0.001250 *T*P) +(0.000750*V*P) (14)

Tool wear rate (TWR) (g/min) = 0.033442+ (0.0015*I)-(0.00258*T) + (0.00508*V) - (0.002*P)–(0.000295*I*I)+ (0.000330*T*T) +(0.00790*V*V) –(0.000045*P*P)-(0.000001*I*T) –(0.000125*I*V)+ (0.000250*I*P)+ (0.000375*T*V)+ (0.000250 *T*P) – (0.000125*V*P) (15)

Surface roughness (SR) (μm) = 80.1429+ (3.0833*I) + (4.9167*T) + (10.1667*V) + (17.9167*P))+(0.4435*I*I)-(0.9315 *T*T) - (2.3065*V*V) –(0.5565*P*P)-(0.6250*I*T) –(0.1250*I*V)- (0.2500*I*P)- (0.5000*T*V)- (0.1250*T*P) +(0.3750*V*P) (16)

Table 3 Estimated values of the coefficients of the models

Sl.No.	Coefficient	Value		
		MRR	TWR	SR
1	β_o	0.485874	0.033442	80.1429
2	β_1	0.03316	0.0015	3.0833
3	β_2	0.0075	-0.00258	4.9167
4	β_3	-0.00983	0.00508	10.1667
5	β_4	0.01333	-0.002	17.9167
6	β_{11}	0.002723	-0.000295	0.4435
7	β_{22}	0.005848	0.000330	-0.9315
8	β_{33}	-0.00790	0.00070	-2.3065
9	β_{44}	0.002402	-0.000045	-0.5565
10	β_{12}	0.001125	-0.000001	-0.6250
11	β_{13}	-0.001625	-0.000125	-0.1250
12	β_{14}	0.004625	0.000250	-0.2500
13	β_{23}	0.000250	0.000375	-0.5000
14	β_{24}	0.001250	0.000250	-0.1250
15	β_{34}	0.000750	0.000125	0.3750

It was found that the reduced models are better than the full models because the reduced models have higher values of R^2 than that of full models. The values of R^2 for full and reduced models are given in Table 4.

Table 4 Comparison of R^2 values for full and reduced models

Response variable	R^2 values	
	Full model	Reduced model
Metal removal rate (MRR)	88.3%	89.2%
Tool wear rate (TWR)	96.7%	97.1%
Surface roughness (SR)	98.1%	98.8%

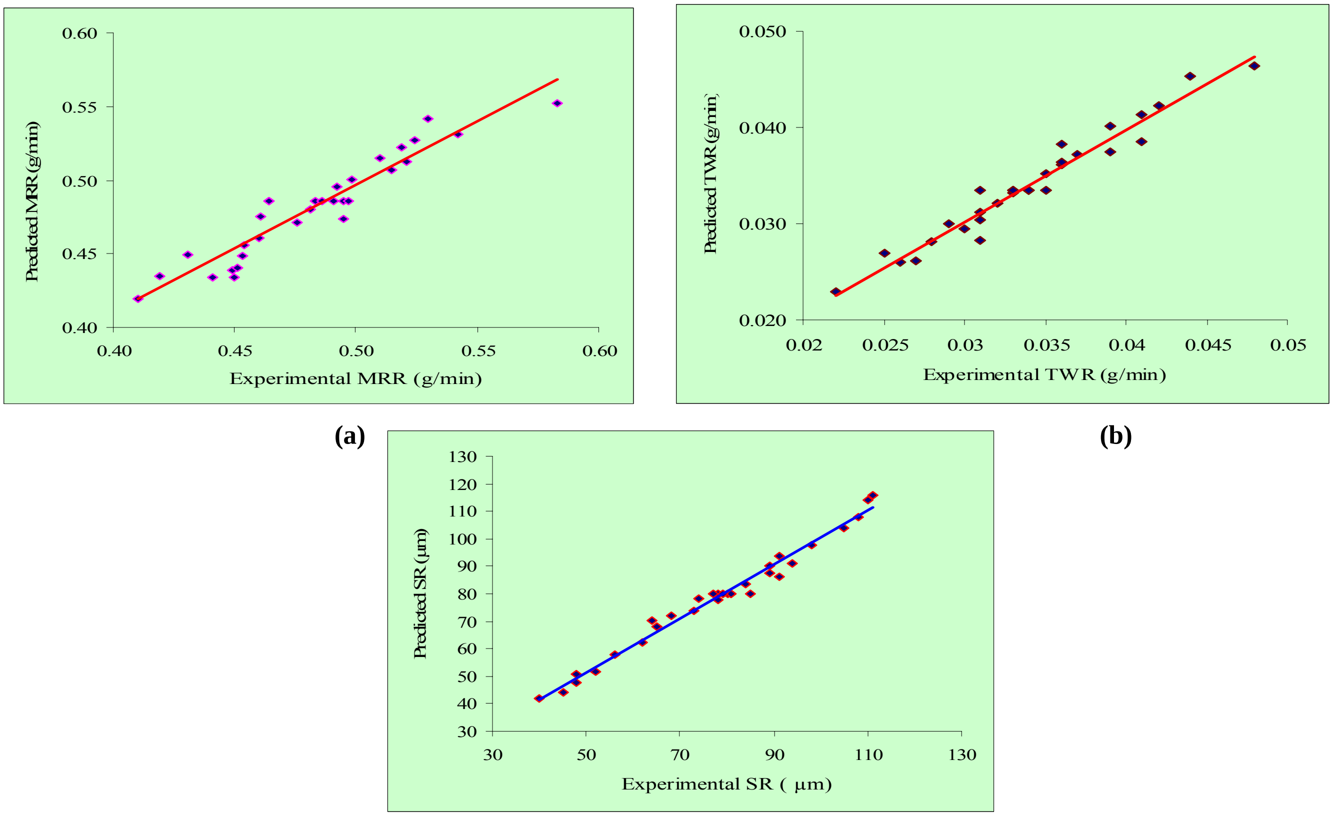
4.5 Verification of the adequacy of the developed models

The adequacies of the developed models were tested using the Analysis of the Variance (ANOVA) technique (Gunaraj and Murugan, 1999). According to this technique, if the calculated F-ratio values for the developed models do not exceed the standard tabulated values of F-ratio for a desired level of confidence (95%) then the models are said to be adequate within the confidence limit. This condition was satisfied for all the developed models, which are given in Table 5. The validity of these models was again tested by drawing scatter diagrams as shown in Figure 5a-c and error profile graph as shown in Figure 6a-c.

Table 5 Analysis of variance for testing adequacy of the models

Parameter		Metal removal rate (MRR)	Tool wear rate (TWR)	Surface roughness (SR)
First order terms	SS	0.034338	0.000930	10993.2
	d.f.	4	4	4
Second order terms	SS	0.003691	0.000026	199.2
	d.f.	10	10	10
Lack of fit	SS	0.004330	0.000023	102.4
	d.f.	10	10	10
Error terms	SS	0.000721	0.000010	40.9
	d.f.	6	6	6
F-ratio		3.60	1.43	1.50
P value		0.161	0.343	0.320
Whether model is adequate		Adequate	Adequate	Adequate

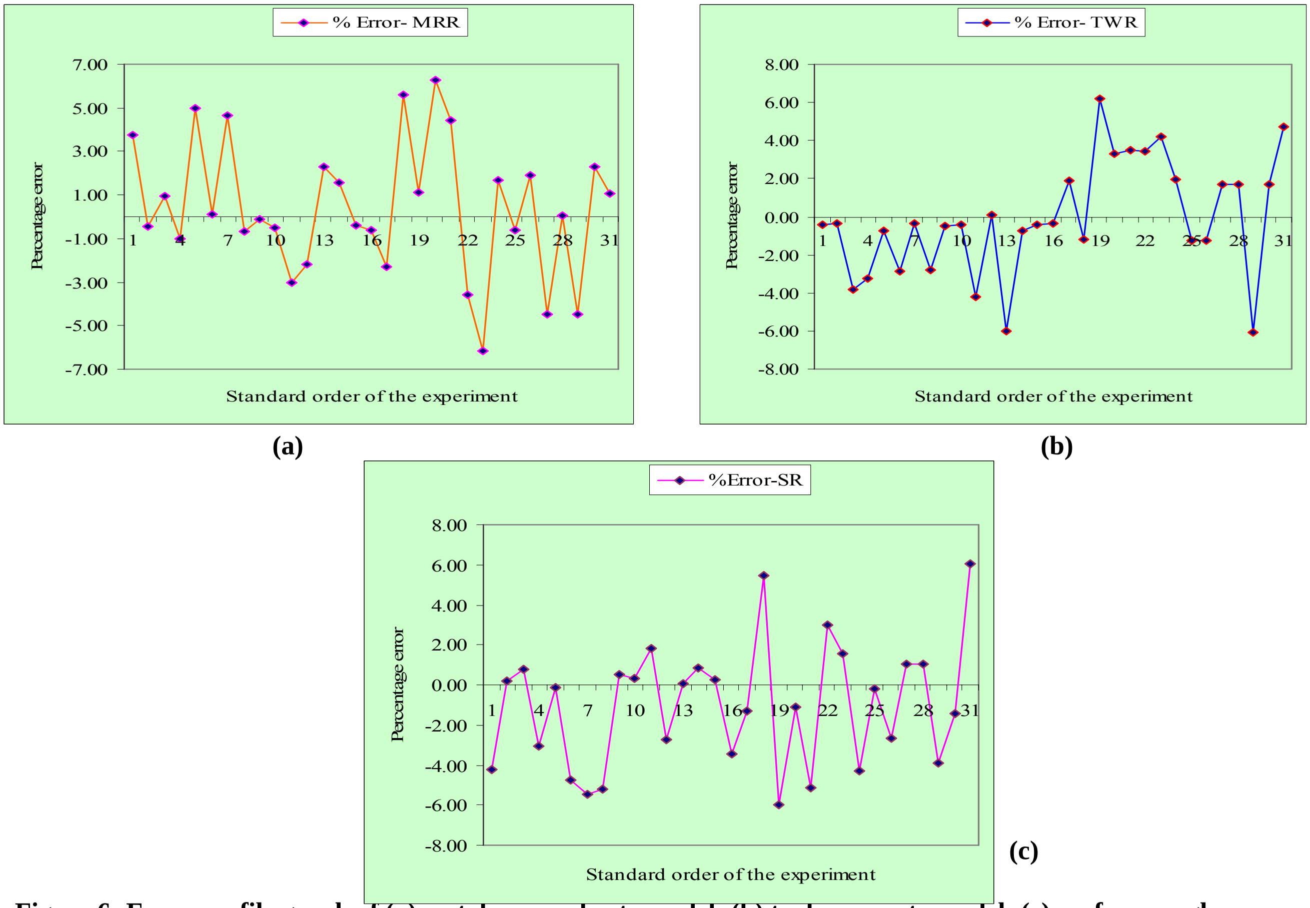
Standard tabulated value of F-ratio (10, 6, 0.05) =4.06; SS, Sum of Squares; d.f., degrees of freedom.



(a) **(b)**

(c)

Figure 5: Scatter diagram of (a) metal removal rate model; (b) tool wear rate model; (c) surface roughness model



(a) **(b)**

(c)

Figure 6: Error profile graph of (a) metal removal rate model; (b) tool wear rate model; (c) surface roughness model

It was observed from the scatter diagram that the predicted values of the response variables are fairly close to the corresponding experimental values of the response variables. The error profile graph shows the percentage error between predicted values and experimental values for the response variables.

4.6 Conformity tests

Conformity tests were conducted using the same experimental setup to confirm the results of the experiment and demonstrate the reliability of the predicated values.

$$\%Error = \left({actual\,value - predicted\,value} \middle/ {predicted\,value} \right) \times 100$$

Table 6 Comparison of predicted and actual values of response variables

Machining parameter in coded form				Predicted values of response variables			Actual values of response variables			Error (%)		
I	T	V	P	MRR (g/min)	TWR (g/min)	SR($\times10^{-3}$ μm)	MRR (g/min)	TWR (g/min)	SR($\times10^{-3}$ μm)	MRR	TWR	SR
-0.12	-0.21	0.08	-0.4	0.474	0.035	72.372	0.475	0.034	73.21	0.21	-2.85	1.16
-0.77	-0.33	0.97	1.08	0.455	0.037	103.188	0.450	0.036	104.12	-1.09	-2.7	0.89
-0.88	0.06	0.96	1.11	0.455	0.035	105.246	0.452	0.034	104.66	-0.65	-2.85	-0.57

The conformity tests show the accuracy of the models developed, which is above 96% (Table 6.)

5. Results and discussion

5.1 Mechanism of material removal

Conventional machining is difficult to perform on metal matrix composites due to increased tool wear and associated problems. The electrical and thermal insulating properties of the reinforcement particles generally posses problems. These problems become more severe for machining of intricate shapes. The advantage of EDM process is its capability to machine difficult to machine materials with desired shape and size with a required dimensional accuracy and productivity. The machining mechanism in electric discharge machining is melting and vaporizing of matrix material. Melting and vaporization of matrix material by the plasma channel causes detachment the reinforcement. The presence of unmelted ceramic particles with its cutting edges in the debris collected, confirmed the proposed mechanism for composites. This machining mechanism has confirmed with the earlier findings (Ponappa et al., 2009. Chiang. 2008).

The microstructure of the cast hybrid composite is shown in Figure.7. It shows that the reinforcement particles are uniformly distributed with in the matrix material. Figure 8 shows the SEM photograph of electric discharge machined surface of the composite. When the discharge current increases from 3A to 15A, electric discharges strike the surface of the work piece more intensely. Due to this, the diameter and the depth of craters of electric discharge machined surface increases hence the surface roughness consequently increases. Owing to the insulating nature of reinforcement particles, abnormal arcing and random spark discharges occur in region where micron-sized reinforcements are seen. Fall out of particles can be observed due to the impact of spark. Bands and craters observed at the machined surfaces of composites as shown in Fig.8 c and d confirm the irregular spark discharges during machining. In general, at low discharge energy the craters are shallow and the surface irregularities are smooth, shallow and less frequent. At high discharge energy the craters are deeper and surface irregularities are larger (Riaz Ahamed, 2009). When the flushing pressure was increased, the rate of solidification of debris scattered over the electric discharge machined surface by molten material droplets from the tool and work piece electrodes also increased. Because of this the surface roughness of the machined work piece was decreased. The obtained variation in surface roughness of the composite (Ra = 4– 11 μm) for all the selected experimental conditions is also minimal due to the flushing of debris.

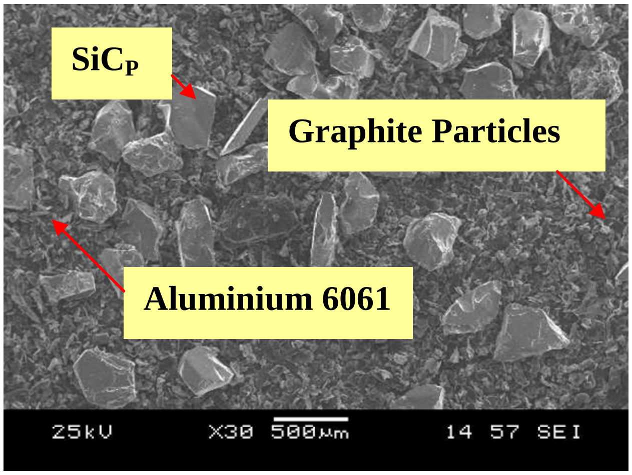


Figure 7: SEM photograph of as cast hybrid composites

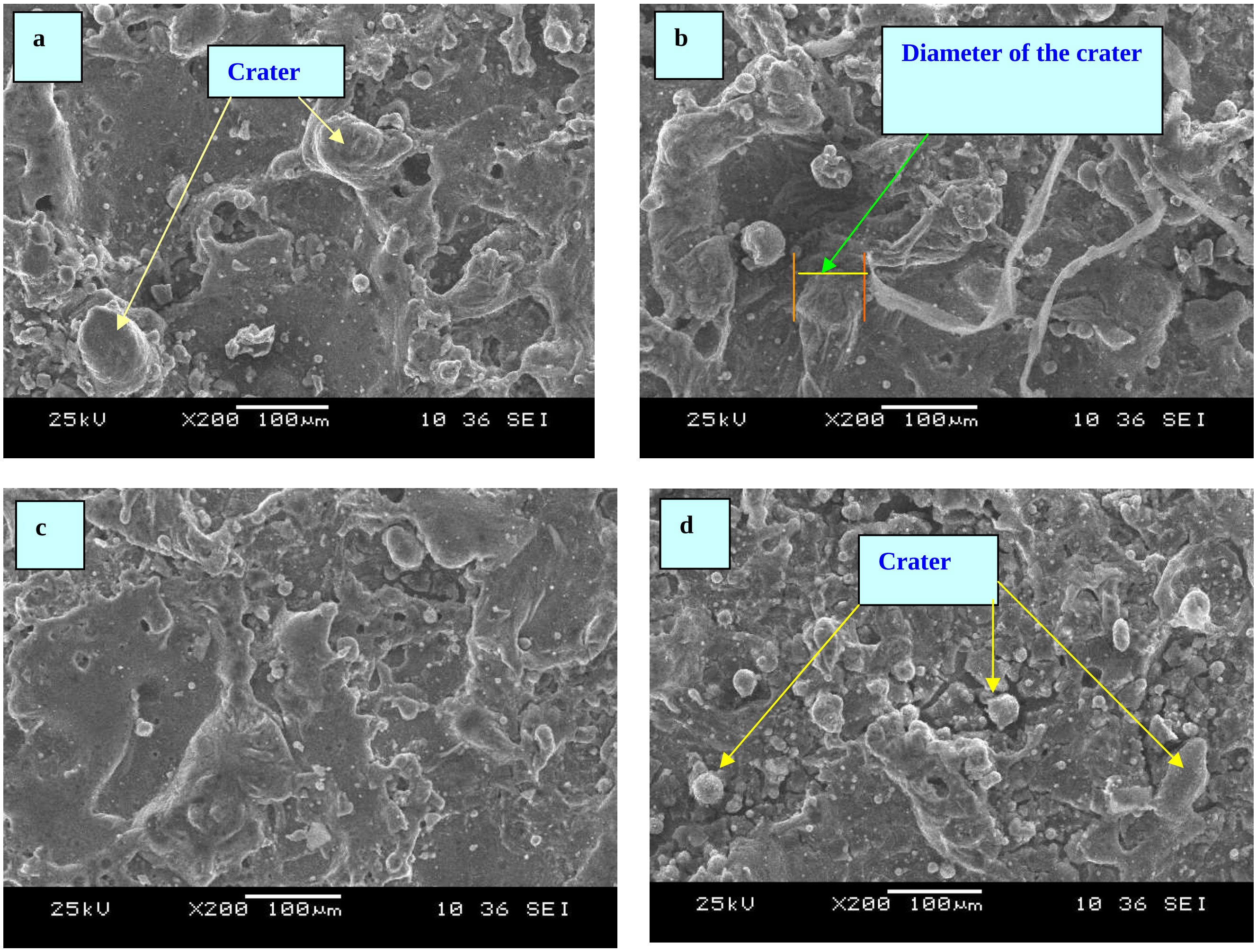


Figure 8: SEM photograph of electric discharge machined surface of Al 6061 composites reinforced with SiC and graphite particles at a voltage 50V and a flushing pressure 3psi: a) 3A,400µs, b) 15A,400µs, c) 9A,200µs, d) 9A,600µs.

5.2 Effect of machining parameters on response variables

The Equations.11, 12 and 13 can be used to predict the response variables by substituting the coded values of the respective process parameters. The responses calculated from these models for each set of coded machining parameters are represented in graphical form in Figure 9-12. In addition, by substituting the values of desired response variables, the values of the machining parameters, in coded form can be obtained. The influence of process parameters such as the current, pulse on time, voltage and the surface roughness are analyzed based on mathematical models.

5.2.1. Effect of current (I) on response variables

Figure 9 shows the effect of current on the response variables. It is observed that the metal removal rate of the composites increases linearly with increasing the value of current. The tool wear rate slightly increasing with increasing the value of current. The increase in metal removal rate and tool wear rate is due to the fact that the spark discharge energy is increased to facilitate the action of melting and vaporization and advancing the large impulsive force in the spark gap. High current values results in higher thermal loading on both tool and work piece electrode lead to high metal removal rate and tool wear rate. The surface roughness value also slightly increases with increase in current. This is similar to the observation confirmed by other researchers (Mahdavinejad and Mahdavinejad, 2005; Narender singh et al., 2004, Simul Banerjee, 2008) who have stated that increase in current results in increasing metal removal rate, tool wear rate and surface roughness.

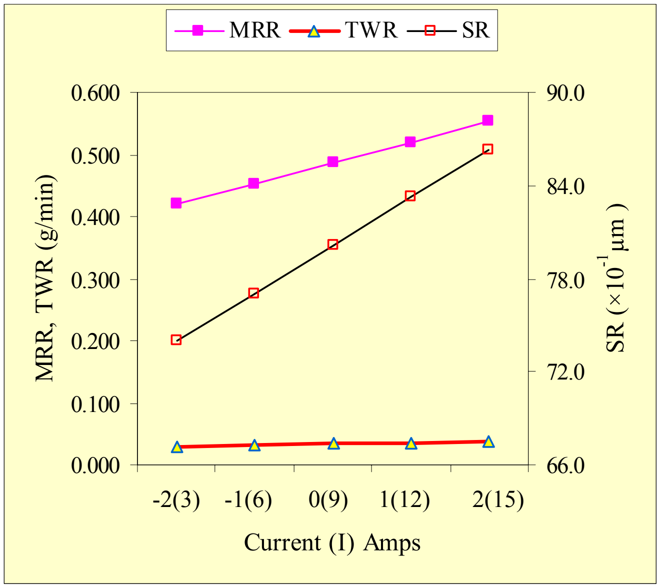


Figure 9: Effect of current on the response variables

5.2.2. Effect of pulse on time (T) on response variables

It can be observed the effect pulse on time (T) on MRR and SR is shown in Figure 10 that the metal removal rate and surface roughness increases with increasing the value of pulse on time while the tool wear rate decreases. The increase in the pulse on time means applying the same heating temperature for longer time. This will cause an increase in the evaporation rate and the number of gas bubbles, which explode with high ejecting force when the discharge ceases, causing removal of bigger volume of the molten metal. Increase in the discharge current strengthens the pulsation energy so the material is removed more easily by higher current densities. In addition, increasing the pulse on time possibly results in the expansion of the discharge column, promoting the material removal rate and surface roughness. The coefficient (β_2) associated with pulse on time (T) in the developed mathematical model for metal removal rate and surface roughness are shown in Eqs. 11and 13 is seen to be positive and for tool wear rate shown in Eq.12 is negative. This suggests that the metal removal rate and surface roughness are directly proportional to the pulse on time whereas the tool wear rate is opposite. The decrease of tool wear rate with increase in pulse on time is very low almost constant. Reduction in tool wear rate can be attributed to the fact that rate of evaporation from tool is lower because of the presence of both silicon carbide and graphite particles in the metal. A similar observation for the effect of pulse on time on metal removal rate and surface roughness was confirmed in a previous study carried out on machining of composites using electric discharge machining (Kao et al., 2009) who has used copper as the tool material. However, the effect of pulse on time with tool wear rate is in disagreement with yet another researcher (Narender singh et al., 2004) who has stated that an increase in pulse on time results in increasing the tool wear rate due to the presence of SiC particles only in aluminium matrix.

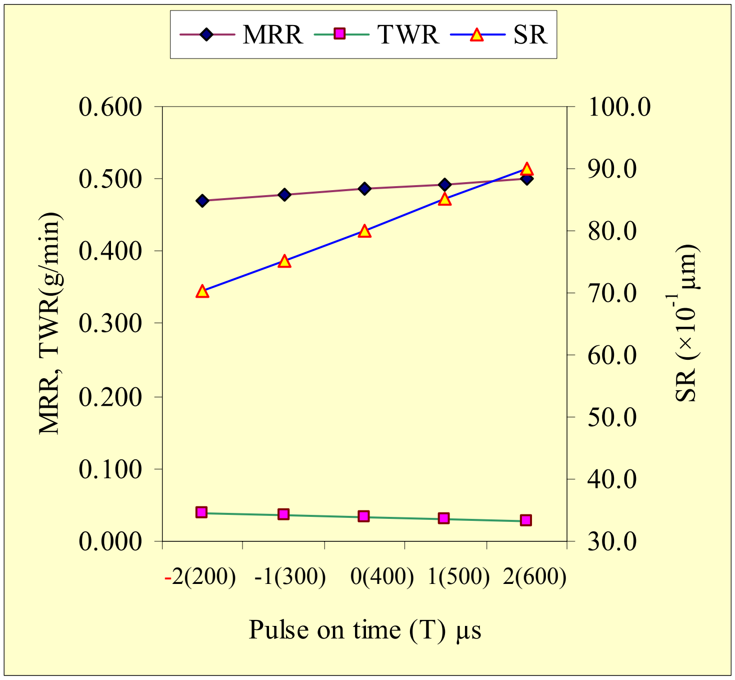


Figure 10: Effect of pulse on time on the response variables

5.2.3. Effect of voltage (V) on response variables

The variation of machining parameters of the composites with voltage during EDM is shown in Figure 11. The coefficient (β_3) in the developed mathematical model for tool wear rate and surface roughness associated with the voltage shown in Eqs. 12 and 13 is seen to be positive, while for metal removal rate shown in Eq.11 is negative. This suggests that the tool wear rate and surface roughness are directly proportional to the voltage whereas the metal removal rate is opposite. From Figure.11it can be observed that, at the low voltage ranges metal removal rate is high and at the higher voltage range metal removal rate is low. However, application of very low values promotes arcing tendency. Higher values of gap voltage can causes relatively lower removal rates. This is in opposition to the previous study carried out on electric discharge machining of mixed alumina based ceramic with titanium carbide composites (Ko-Ta Chiang, 2008), where it was stated that increase in voltage leads to increase in metal removal rates, however the effect of voltage on tool wear rate and surface roughness is in agreement with the previous study carried out on the electric discharge machining of composites (Narender singh et al., 2004).

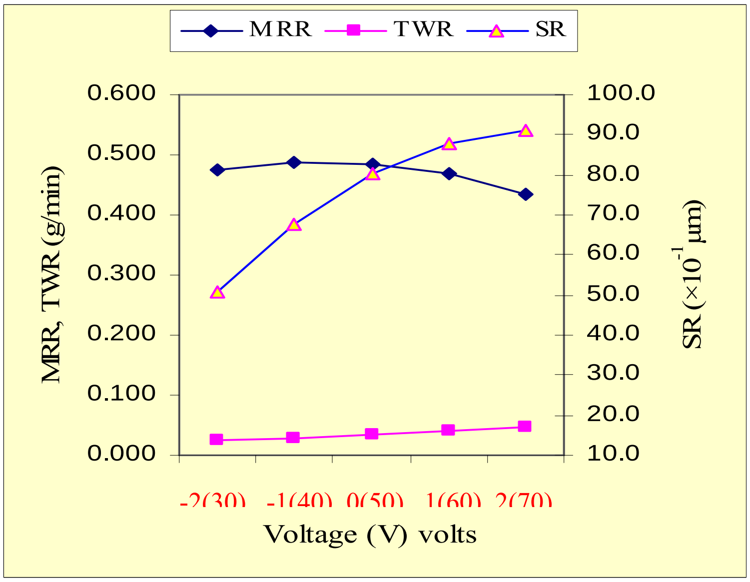


Figure 11: Effect of voltage on the response variables

5.2.4 Effect of flushing pressure (P) on response variables

In electric discharge machining, flushing is of very much importance, since the dielectric flushing of the spark gap keeps the gap clean and removes spark eroded particles continuously from the gap. It has a great influence on machining stability, which in turn affects the removal rate and tool wear rate. From Figure 12 it is found that the dielectric flushing pressure has positive effect on metal removal rate and surface roughness. The metal removal rate and surface roughness increases with the increase of dielectric flushing pressure. This is because when the flushing pressure is low, flushing cannot remove the gaseous and solid debris adequately after each discharge and the dielectric is increasingly unable to clear away the molten material, causing it to build upon the surface of the parent material. Further, the increase of the flushing pressure decreases the tendency for arcing and increases the metal removal rate. The tool wear rate decreases with increasing flushing pressure. This is possibly due to the increase in cooling rate of the tool with increase in flushing pressure. The similar observation has been confirmed by the previous researchers Narender singh et al., 2004; El-Taweel, 2009; Muller and Monaghan, 2000.

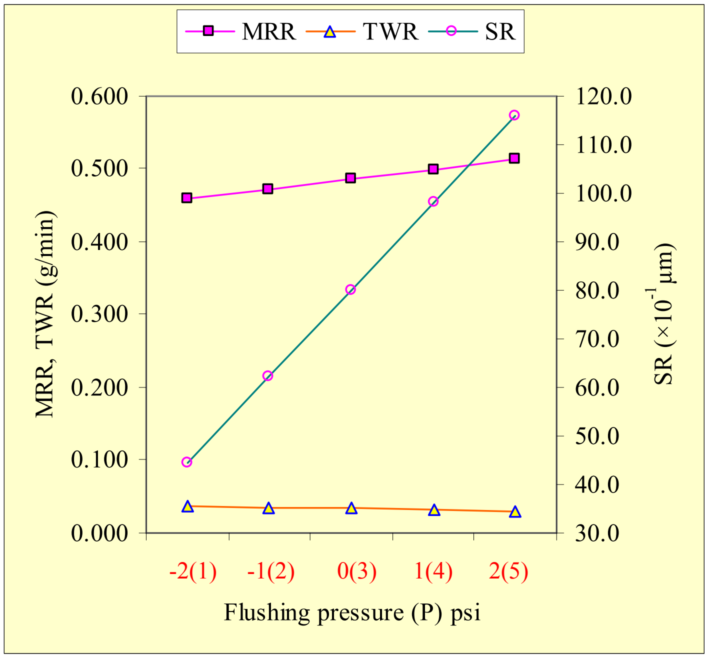


Figure 12: Effect of flushing pressure on the response variables

6. Conclusions

- Metal removal rate of the composite increases with increase in current, pulse on time and flushing pressure of the dielectric fluid while it decreases with increase in voltage.
- Tool wear rate of the developed composite increases with increase in current and voltage and it decreases with increase in pulse on time and flushing pressure of the dielectric fluid.
- Surface roughness of the composite during electric discharge machining increases with increase in current, pulse on time, voltage and flushing pressure.
- It is found that all the four machining parameters have significant effect on the response variables considered in the present study.

References

Cochran G. and Cox M. 1987. Experimental designs. John Wiley&sons, Newyork.

El-Taweel T.A. 2009. Multi-response optimization of EDM with Al–Cu–Si–TiC P/M composite electrode. *International Journal of Advanced Manufacturing Technology*, 44, pp.100–113. DOI 10.1007/s00170-008-1825-6.

George P.M. Ragunath B.K. Manocha L.M. and Warrier A.M., 2004. EDM Machining of carbon-carbon composites-a taguchi approach. *Journal of Materials Processing Technology*, 145(1), pp.66-77.

Gunaraj V. and Murugan N. 1999. Prediction & comparision of the area of the heat effected zone for the bead on plate &bead on joint in submerged arc welding of pipes. *Journal of Materials Processing Technology*, 95, pp.246-261.

Harris P. and Smith B.L. 1983. Factorial technique for weld quality prediction. Met construct,15: pp.661-666.

Kao J.Y. Tsao C.C. Wang S.S. and Hsu C.Y. 2009. Optimization of the EDM parameters on machining Ti–6Al–4V with multiple quality characteristics. *International Journal of Advanced Manufacturing Technology*, DOI 10.1007/s00170-009-2208-3.

Ko-Ta Chiang. 2008. Modeling and analysis of the effects of machining parameters on the performance characteristics in the EDM process of Al2O3+TiC mixed ceramic. *International Journal of Advanced Manufacturing Technology*, 37, pp.523–533. DOI 10.1007/s00170-007-1002-3.

Khanra. A.K. 2005. Electrical discharge machining behavior of hotpress $MoSi_2$. Journal of Materials science, pp.3027-3030.

Kuppan P. Rajadurai A. and Narayanan S. 2006. Experimental investigation into electrical discharge deep hole drilling of Inconel 718 using graphite electrode. In: proceedings of the 17th All India Machine Tool Design & Research Conference, PP.923-927.

Kannan T. and Murugan N. 2006. Effect of flux cored arc welding process parameters on duplex stainless steel clad quality. *Journal of Materials Processing Technology*, 176, pp.230-239.

Kuang-Yuan Kung . Jenn-Tsong Horng & Ko-Ta Chiang, 2009. Material removal rate and electrode wear ratio study on the powder mixed electrical discharge machining of cobalt-bonded tungsten carbide. *International Journal of Advanced Manufacturing Technology,* pp.95-104.

Leesh and Li Xp. 2001. Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of WC. *Journal of Materials Processing Technology*, 115(3), pp.344-358.

Lauws. Yue T.M. Lee T.C and Lee W.B., 1999. Unconventional machining of composite machining. *Journal of Materials Processing Technology*,48, pp.199-205.

Mahdavinejad R.A. and Mahdavinejad A. 2005. Electric discharge machining of WC-CO. *Journal of Materials Processing Technology*, 163, pp.637-643.

Murugan N. and Parmar R.S. 1995. Mathematical models for bead geometry prediction automatic stainless steel surfacing by MIG welding. *International journal of joining of Materials*, 7, pp.71-80.

Montgomery D.C. 2003. Design & Analysis of Experiments. 5th edition, John Wiley&Sons (Asia) Ltd.

Mihaly Kozma., 2003. Friction and wear of aluminum matrix composites. National tribology conference ROTRIB'03.The Annals of university "Dunarea De Jos" of galatiFascicle VIII, 2003 ISSN 1221-4590, pp.99-106.

Muller F. and Monaghan J. 2000. Non conventional machining of particles reinforced metal matrix composites. *International Journal of Machine Tools Manufacturing*, 40, pp.1351-1366.

Narender singh P. Raghukandan K. Rathinasabapathi M. and Pai B.C. 2004. Electric discharge machining of Al-10% SiCp as-cast metal matrix composites. *Journal of Materials Processing Technology*, 155-156, pp.1653-1657.

Nilesh Ganpatrao Patil &Brahmankar P. K. 2010. Determination of material removal rate in wire electro-discharge machining of metal matrix composites using dimensional analysis. *International Journal of Advanced Manufacturing Technology,* pp.599-610.

Ponappa K. Aravindan S. Rao P.V. Ramkumar J. and Gupta M. 2009. The effect of process parameters on machining of magnesium nano alumina composites through EDM. *International Journal of Advanced Manufacturing Technology*, DOI 10.1007/s00170-009-2158-9.

Patel K. M. Pulak M. Pandey & Venkateswara Rao.P, 2010. Optimisation of process parameters for multi-performance characteristics in EDM of Al2O3 ceramic composite. *International Journal of Advanced Manufacturing Technology*, pp.1137-1147.

Rosso M., 2006. Ceramic and metal matrix composites: Routes and properties. *Journal of Materials Processing Technology*, 175, pp.364-375.

Riaz Ahamed.A. Asokan. P & Aravindan.S, 2009. EDM of hybrid Al–SiCp–B4Cp and Al–SiCp–Glassp MMCs. *International Journal of Advanced Manufacturing Technology*, pp.520-528.

Surappa M.K., 2003. Aluminum matrix composites: challenges and opportunities. *Sadhana*, Vol (28), parts 1& 2,pp.319-334, printed in India.

Simul Banerjee, Pebasish Mahapatro, and Shishir Dubey. 2008. Some study on electrical discharge machining of ((WC+TiC+TaC/NbC)-Co) cemented carbide. *International Journal of Advanced Manufacturing Technology*, doi10.1007/S00170008-1796-7.

Torralba J.M. Dacosta C.E. and Velasco F., 2003. P/M aluminium matrix composites: an overview. *Journal of Materials Processing Technology*, 133, pp.203-206.

Velmurugan C. Subramanian R. Thirugnanm S. Kannan T. and Anandavel B. 2011. Experimental study on the effect of SiC and graphite particles on weight loss of Al6061 hybrid composite materials. *Journal of Tribology and Surface Engineering*, Vol.2, pp.49-68.

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Received November 2011
Accepted January 2012
Final acceptance in revised form March 2012