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Parametric analysis and modeling of die-sinking Electric Discharge Machining of Al6061/Al_2O_3 Metal Matrix Composite

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Abstract

MMCs (metal matrix composites) are commonly used in modern engineering products like automobiles, defense, biomaterials, and aerospace. Aluminum 6061 reinforced with alumina particles has been fabricated using the self-developed stir casting set-up. Die-sinking EDM of fabricated MMC has been performed using titanium electrode. Response surface method (RSM) based second order regression model for MRR, and R_a have been developed for the die sinking EDM of fabricated composite. Experiments were conducted using the box-behnken design (BBD) approach of RSM. Parametric analysis was performed to investigate the impact of input parameters like peak current (I_p), gap voltage (V_g), pulse-on-time (T_{on}), and duty factor (t) on material removal rate (MRR) and surface roughness (R_a). According to the analysis of variance (ANOVA), the current is the most important factor for both MRR and R_a, whereas the interaction effect of duty factor with voltage and current has major contribution on MRR and R_a, respectively. The increase of current at constant value of T_{on} and t increases MRR. Duty factor plays more significant role in enhancing the MRR compared to T_{on}. R_a increases very rapidly with increase of pulse current. But voltage do not have many major impacts on SR at certain value of pulse current.

Keywords: MMC, Electric discharge Machining, voltage, current, material removal rate, surface roughness

1. Introduction

Aluminium based MMCs are extensively used in automobile, biomedical, defence, aerospace etc. It has superior mechanical properties i.e., high strength, stiffness, hardness with respect to its weight. It also possesses good fatigue and thermal properties. Aluminum based composites find preference for fabricating piston rings, pistons and brake disks etc. The successful application of this composite depends on its machinability. The presence of hard reinforced particles in MMCs decreases its machinability and tends to produce high surface roughness. In order to reduce the surface and subsurface damage during traditional machining, nonconventional machining method are used to shape the MMC. Electro discharge machining (EDM) has been used by several authors to create desired feature in MMCs. EDM is normally used to produce blind holes, complex cavities in dies, molds etc. Repeated discharge energy between two electrodes in form of spark is used to remove materials from the work piece by erosion phenomena. The work piece is kept submerged inside the dielectric medium during machining. When the potential difference between the tool and workpiece exceeds the dielectric strength of the liquid, spark formation take place and material is removed due to spark erosion. Alumina as a reinforcement material possesses excellent properties such as high melting point, strength, high hardness, and corrosion resistance. It is one of the most preferred reinforcement material widely used to provide high wear properties in MMCs. In Aluminium based MMC, aluminium is used as a matrix and boron, alumina or silicon carbide can be used as reinforcement. Earlier several studies have been performed to improve the machining parameter during EDM of MMCs.

Ahrwal et al. [1] investigated the machining of Al/SiCMMC using copper electrode. It was found that combination of high current and low voltage yields good material removal rate (MMR), whereas lower value of current and voltage yields lower surface roughness (SR).Malhotra et al. [2] conducted EDM of MMC Al7075 reinforced with 10% SiC. It was proposed MRR is grow by rise the pulse on time (T_{on}) and peak current (Ip). It was reported that rate of electrode wear (EWR) rises when current increases. Bhuyan et al. [3] fabricated MMC by stir casting using Al and 12% SiC and developed regression model using response surface method (RSM). Khandpal et al. [4] explored the impact of peak current (I_P), T_{on} and t during EDM of Al606/ Al_2O_3MMC.Gopalkannan et al. [5] fabricated MMC comprising of Al7075 as matrix andB_4Cnano particles (5%) using the novel ultrasonic cavitation method. It has noticed that I_P and T_{on} is major factor for MRR, TWR and SR. Hounmand et al. [6] use the copper electrode for EDM of $AlMg_2Si$ MMC. RSM model indicate that MRR depends on V, I_p and T_{on}. EDM of Al/SiC MMC using copper electrode were performed by Satapathy et al. [7]. Multiobjective optimization were performed using hybrid approach PCA and order preference based on similarity to the ideal solution (TOPSIS). Microstructure study was performed using a scanning electron microscope (SEM) on the machined surface. Talla et al. [8] fabricated the Al/Al_2O_3MMC and analysed its machining on EDM by mixing the alumina powder in the dielectric fluid kerosene. The result shows that use of alumina powder in dielectric increases MRR and decreases the surface roughness (Ra).Rajeshaet al. [9] performed EDM of Al-7075 MMC to optimize the process parameter so that SR can be reduced. Hourmand et al. [10] investigated the EDM of hybrid MMC (Al-Mg_2Si) using a copper electrode. Machining was performed mixing the alumina powder in dielectric fluid. The developed RSM model for MRR and electrode wear rate (EWR) reveals that interaction between I_P and V is most significant for MMR and T_{on} is most significant for SR. Hanif et al. [10] investigated the effect of dielectric types and electrode polarity during EDM of MMCs.

Mohanty et al. [11] fabricated the MMC using Al-12%SiC.RSM based mathematic models were developed to analyse the effect of process parameter on MRR and SR. Shandilya et al. [12] performed Wire EDM (W-EDM) of Al6061/Sic_p. Surface integrity of machined surface were examined using scanning electron microscope (SEM). Ubale et al. [13] developed W-Cu base MMCW-EDM and developed RSM based model to predict the effect of input parameters on MRR. Matharou et al. [14] prepared hybrid metal matrix composite by stir casting method and performed the multi objective optimization using the hybrid method of grey relational analysis (GRA) and principal component analysis (PCA). Raza et al. [15] examined the impact of various electrodes during EDM of Al6061-SiC-7.5 wt% composite fabricated by squeeze casting method. It was observed that brass electrode yields better MMR and SR. Thangadurai et al. [16] proposed that I_P and T_{on} has more prominent influence on the surface roughness during the machining on the Al6061-5% B_4C by EDM. Singh [17] used GRA for the multi objective optimization of EDM for 6061Al/Al_2O_3p/20P MMCs.

Here, Al6061/Al2O3 MMC has been fabricate d using the stir casting method. Second order regression based mathematical model has been developed for MRR and SR to investigate the effect of peak current, pulse on time, voltage and duty factor. Based on the developed model, parameters with significant interaction effect has been identified and parametric analysis were performed based on the response surface plots.

2. Materials and Methodology

Alloy Al6061 is chosen as a matrix material because it has improved mechanical and wear qualities. It is the most extensively utilized alloy in the automotive and aerospace industries. It contains magnesium, a high melting metal, as well as other element silicon. The stir casting method was used to produce the metal matrix composite (MMC). Aluminum oxide (Al_2O_3) in 10% equivalent weights were added as reinforcement. The matrix was melted entirely in a muffle furnace at 660°C and Al_2O_3 reinforced particle were heated to 500^0 C to reduce the oxide on the surface. The reinforced particle was gently introduced in the molten metal matrix, and mixing was done with a mechanical mixer for about 10 to 20 minutes to ensure equal matrix distribution. Finally, the molten metal was poured into a 70mmx70mmx10mm mold and allowed to cool at room temperature.

Experiments were carried out using the box-behnken design (BBD) approach of RSM.RSM is a mathematical technique to develop regression model of a physical process. BBD approach is a class of rotatable or nearly rotatable second-order designs based on three-level incomplete factorial designs. The total number of experiments (N) required in BBD approach to develop a model is $N=2k\ (k-1)\ +C_0$, (where k is number of factors and Co is the number of central points). Central composite design (CCD) is another widely used approach in RSM to develop regression model and the number of experiments in CCD is $N=2k+2k\ +C_0$. Thus, BBD approach has the advantage of developing the model with comparatively smaller number of experiments.

3. Experimental details

Experiments were conducted on ELEKTRA Pulse S-50 ZNC, die sinking EDM manufactured by Electronica Machine Tools Limited, Pune. This machine can generate maximum peak current of 50A and pulse on time of 4000µs.The input parameters selected for machining is shown in Table 1. The level of input parameters were decided based pilot experiments.

Table 1.Input parameters and its level

Input Parameter	Level		
	Low	Medium	High
Pulse current (Ip)	4	8	12

Voltage (V)	40	60	80
Pulse on time (T_{on})	100	150	200
Duty cycle (t)	4	5	6

MRR has been estimated by evaluating the difference of weight before and after the machining using Eq. (1).A digital weighing balance with an accuracy of 0.01gwas used to measure the weight of the work piece. The average surface roughness (R_a) was measured by surface roughness tester of Taylor and Hobson make.

$$MRR\left(\frac{gram}{min}\right) = \frac{\text{(Initial wt of workpiece} - \text{Final wt of workpiece)(grams)}}{\text{Machining time(min)}} \quad (1)$$

Fig.1 Die-sinking sparks EDM

Fig.2 Surface Roughness Tester

Experiments were conducted using the BBD technique and as per the plan 27experimental tests for four input parameters at three levels were carried out. The combination of input parameter for each experimental trial have been determined using MINITAB software. Each experiment was repeated thrice to reduce the chance of occurrence of error due to assignable causes. The average of output corresponding to these three repetitive experiments were taken as the final value of output response as shown in Table 2.

Table 2. Experimental result

S.No.	Current (I_p)	Voltage (V)	T_{on}(µs)	Dutycycle (t)	MRR(gm/min)	Ra(µm)
1	4	40	150	5	0.014122	8.58
2	12	40	150	5	0.089674	11.03
3	4	60	150	5	0.032787	6.26
4	12	60	150	5	0.109756	11.43
5	8	50	100	4	0.06814	7.3
6	8	50	200	4	0.063981	7.43
7	8	50	100	6	0.080863	7.4
8	8	50	200	6	0.097932	7.33
9	4	50	150	4	0.023781	6.8
10	12	50	150	4	0.085791	11.73
11	4	50	150	6	0.038615	7.8
12	12	50	150	6	0.174274	11
13	8	40	100	5	0.042553	7.7
14	8	60	100	5	0.0844559	7.6
15	8	40	200	5	0.065022	7.63
16	8	60	200	5	0.076087	7.43
17	4	50	100	5	0.046791	6.86
18	12	50	100	5	0.086806	11.3

19	4	50	200	5	0.015951	7.6
20	12	50	200	5	0.105882	11.56
21	8	40	150	4	0.030409	7.35
22	8	60	150	4	0.080495	7.8
23	4	40	150	6	0.085399	7.06
24	8	60	150	6	0.08871	7.3
25	8	50	150	5	0.077193	8.2
26	8	50	150	5	0.06852	7.7
27	8	50	150	5	0.073529	7.45

4. Results and discussion

RSM based second order regression models for MRR and SR were developed using the experimental data of Table 2. The adequcy of the developed models were checked using the statistical method. The significant interaction factors were identified using the analysis of variance approach (ANOVA) technique. In this study all analysis have been performed at 95% confidence level.

$$\begin{aligned} MRR(gm/min) = & -0.242 \\ & - 0.0190\ I_P + 0.01622\ V + 0.000092\ T_{on} - 0.0549\ t - 0.000239\ I_p{*}I_p - 0.000069\ V{*}V - 0 \\ & .000001\ T_{on}{*}T_{on} + 0.00788\ t{*}t + 0.000009\ I_P{*}V + 0.000062\ I_P{*}T_{on} \\ & + 0.00460\ I_P{*}t - 0.000015\ V{*}T_{on} - 0.001169\ V{*}t + 0.000103\ T_{on}{*}t \end{aligned} \quad (2)$$

Table 3.ANOVA of MRR

Source	DF	AdjtSS	Adjt MS	F-Value	P-Value
Model	14	0.028635	0.002045	17.96	0.000
Linear	4	0.024752	0.006188	54.33	0.000
I_p	1	0.019211	0.019211	168.67	0.000
V	1	0.001755	0.001755	15.41	0.002
T_{on}	1	0.000018	0.000018	0.16	0.698
t	1	0.003769	0.003769	33.09	0.000
Square	4	0.001011	0.000253	2.22	0.128
$I_P{*}I_P$	1	0.000078	0.000078	0.68	0.424
V*V	1	0.000255	0.000255	2.24	0.160
$T_{on}{*}T_{on}$	1	0.000036	0.000036	0.32	0.583
t*t	1	0.000331	0.000331	2.91	0.114
2-Way Interaction	6	0.002871	0.000479	4.20	0.017
$I_P{*}V$	1	0.000001	0.000001	0.00	0.948
$I_P{*}T_{on}$	1	0.000623	0.000623	5.47	0.037
$I_P{*}T_{on}$	1	0.001356	0.001356	11.91	0.005
$V{*}T_{on}$	1	0.000238	0.000238	2.09	0.174
V*t	1	0.000547	0.000547	4.80	0.049
$T_{on}{*}t$	1	0.000107	0.000107	0.94	0.352
Error	12	0.001367	0.000114		
Lack-of-Fit	10	0.001328	0.000133	6.89	0.133

Pure Error	2	0.000039	0.000019
Total	26	0.030001	

Table 4. MRR model overview

S	R-sq	R-sq(adj)
0.0106722	95.44%	90.13%

Table 4 indicates that S value of the developed model is very low and R-sq and R-sq (adj) value of the developed model for MRR is quite high which indicate that the developed MRR model is adequate and it predict the output response with fair accuracy. The p-values of interaction effect indicate that interaction effect of I_P x T_{on}, I_p x t,and voltage x duty factor play significant role in MRR.

$$Ra(\mu m) = 0.0 - 1.432\, I_P + 0.017\, V + 0.0300\, T_{on} + 3.64\, t + 0.1072\, I_P*I_P - 0.00132 V*V - 0.000054\, T_{on}*T_{on} - 0.241\, t*t + 0.01700\, I_P*V - 0.000600\, I_P*T_{on} - 0.1081\, I_P*t - 0.000050\, V*T_{on} - 0.0053\, V*t - 0.00100\, T_{on}*t \quad (3)$$

Table 5.ANOVA FOR Ra

Source	**DF**	**Adjt SS**	**AdjtMS**	**F-Value**	**P-Value**
Model	14	73.9055	5.2790	38.02	0.000
Linear	4	48.8755	12.2189	88.00	0.000
I_P	1	48.6019	48.6019	350.03	0.000
V	1	0.1951	0.1951	1.40	0.259
T_{on}	1	0.0560	0.0560	0.40	0.537
t	1	0.0225	0.0225	0.16	0.694
Square	4	22.3510	5.5878	40.24	0.000
I_P*I_P	1	15.6942	15.6942	113.03	0.000
V*V	1	0.0930	0.0930	0.67	0.429
$T_{on}*T_{on}$	1	0.0984	0.0984	0.71	0.416
t*t	1	0.3093	0.3093	2.23	0.161
2-Way Interaction	6	2.6789	0.4465	3.22	0.040
I_P*V	1	1.8496	1.8496	13.32	0.003
I_P*T_{on}	1	0.0576	0.0576	0.41	0.532
I_P*t	1	0.7482	0.7482	5.39	0.039
$V*T_{on}$	1	0.0025	0.0025	0.02	0.895
V*t	1	0.0110	0.0110	0.08	0.783
$T_{on}*t$	1	0.0100	0.0100	0.07	0.793
Error	12	1.6662	0.1389		
Lack-of-Fit	10	1.3745	0.1375	0.94	0.618
Pure Error	2	0.2917	0.1458		
Total	26	75.5717			

Table 6 Ra model overview

S	R-sq	R-sq(adj)	R-sq(pred)
0.372627	97.80%	95.22%	88.65%

Based on Table 5-6, R square (coefficient of determination) values of 95.44 percent and 97.80percent, respectively, with R square (adj) values of 90.13 percent and 95.22percent, indicate that the independent variable's ability to predict the variance of output using Eq. (3).It is apparent that the model is precise and appropriate for SR. The interaction effect of I_P x V and I_P x play dominant role in determining the SR.

Parametric analysis

The effect of significant interaction factors on MRR and SR have been discussed in this section using the RSM surface plots. Fig. 3(a) show the combined effect of I_P and T_{on} for MRR. It is observed that increase of peak current and pulse on time normally increases the MRR but increase of pulse on time at lower current (5 A - 7.5 A) reduces the MRR. The variation of MRR with pulse on time is linear in nature at higher current (12.5 A)

On raising the current, the spark energy of EDM grows rapidly in the inter electrode gap and erosion rate of material due to spark increases which results in higher MRR. Fig. 3(b) show the simultaneous effect of current and duty factor on MRR. The variation in duty factor at lower current do have any major impact on MRR but as the current increases, the rise in duty factor results in higher MRR. When the duty cycle is high, the thermal energy generation capacity increases resulting in higher MRR. Furthermore, the increase of current always increases MRR in linear manner. The hold values in Fig. 3(a) are V= 50V and t= 5. The hold values in Fig. 3(b) are V= 50V and T_{on}=150µs.

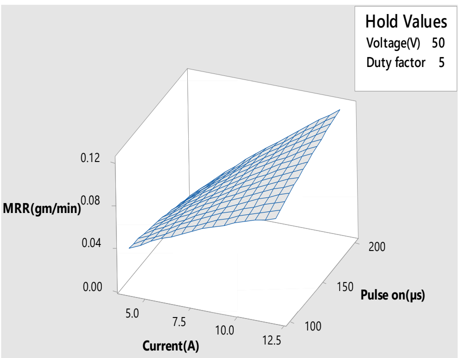

Fig. 3(a) Response of I_P and T_{on} on MRR

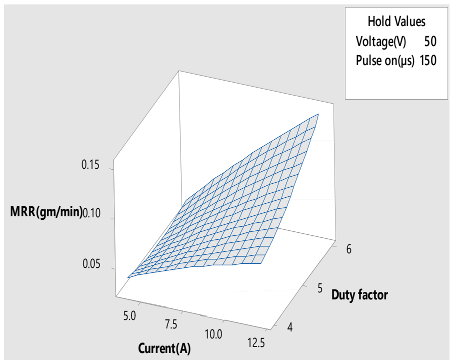

Fig. 3(b) Response of I_P and T_{on} on

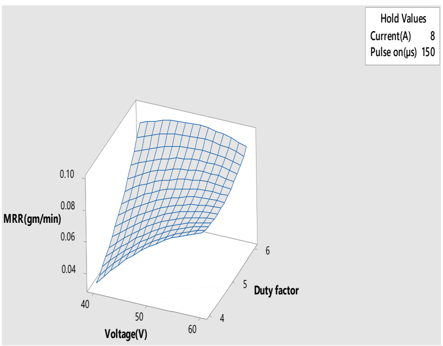

Fig. 4(a) Response of t and V on MRR

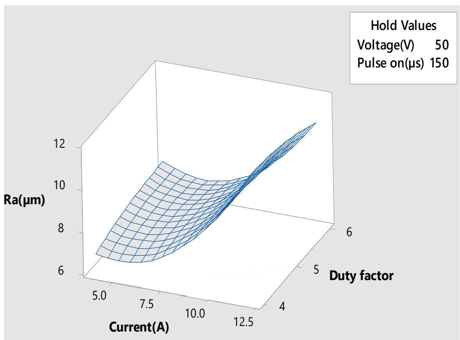

Fig. 4(b) Response of I_p and V on SR

Fig. 4(a) shows the effect of voltage and duty factor on MRR during die sinking EDM of MMC. At higher voltage, MRR increases because the speed of discharge between tool and work piece is more therefore rate of erosion due to ionic discharge increases thereby increasing the MRR. Fig. 4(b) show the response of current and voltage on SR of the machined surface. When current increases the erosion of work piece increases resulting in higher SR increases very rapidly with current. Effect of voltage on SR at any specific value of current is not significant.

5. Conclusions

Al6061/Al_2O_3metal matrix composite has been fabricated using the stir casting method and die-sinking EDM of fabricated composite were performed based on BBD approach of RSM. Statistical models for MRR and SR were created. The adequacy and fitness of the developed models were evaluated, and parametric analysis were conducted to determine the effect of input and output responses. Based on this study, The following have been some of the conclusions that can be drawn:

i. The RSM based second order regression model developed for MRR and SR during die-sinking EDM of Al6061/Al_2O_3MMCare adequate and the experimental data well fitted the model.
ii. The ANOVA for MRR and SR indicate that interaction effect of interaction effect of I_P x T_{on}, I_p x t, and V xt play significant role in MRR.
iii. The interaction effect of current x voltage and current x duty factor play dominant role in determining the SR.
iv. The increase of current at constant value of T_{on} and t increases MRR. Duty factor plays more significant role in enhancing the MRR compared to pulse on time.
v. Surface roughness increases very rapidly with increase of pulse current. But voltage do not have many major impacts on SR at certain value of pulse current.

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