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Study the Effect of Material Removal Rate in Die-sinking EDM for Inconel 800 using Response Surface Methodology

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Abstract—*This investigation, presents the optimization process for MRR of die-sinking electrical discharge machining on Inconel 800 material by using RSM. Inconel 800 is widely used in construction of equipment that must have high strength and resist carburization, oxidation and other harmful effects of high temperature exposure. For conducting the experiment three controllable input parameter like pulse on time, pulse off time and pulsed current has been considered and oxygen free high conductivity copper (99.99% copper) has been also as the electrode material. An RSM method, central composite design, has been used to design the experiment and to model a second order response surface. A total of 51 experiments have been carried out for different combination of process parameter. The experimental results have been analyzed using RSM. The models have been developed at 95% confidence level. From the analysis, it has been found that pulse on time, pulsed current, pulse off time and the interaction terms have significant effect on MRR. From this observation, it can be concluded that pulsed current and pulse on time are directly and pulse off time is reciprocally proportional to the MRR. The model sufficiency has very satisfactory for MRR as the coefficient of determination (R2) 97.9% and R-Sq (adj) 97.4%.*

1. INTRODUCTION

EDM stands for electrical discharge machining. This is an electro-thermal non-traditional machining process, where electrical energy is utilised to generate electrical spark and material removal mostly happensbecause of thermal energy of the spark. The applications best suited for this metal removal process are those characterized by close tolerances machining that would be extremely difficult or impossible to handle with any other method of machining. EDM has been mainly used to machine difficult-to-machine materials and high strength temperature resistance alloys. It is a controlled metal-removal process which has been widely used to produce dies and moulds. The theory of the process has been established by two Soviet scientists B.R. and N.I. Lazarenko in the middle of 1940s [1]. In Die-sinking EDM, electrode and work piece is submerged inan insulatingliquid, mainly kerosene. The tool and the job, both being electrical conductors, are connected to the two terminal of the electrical power source. An electrical field is established between the cathode (the tool) and anode (the work piece). When, these two are brought to a close proximity, i.e. less than a millimetre, an electrical dischargein the form of a spark jumps across the cathode to the anode.

The effect of working parameters on material removal rate in an EDM [4], machinability [2], surface quality [3], have been thoroughly studied by various researchers. The effect of current, pulse-on time and air gap voltage on MRR, of a composite material (10% SiC in Al–4Cu–6Si alloy) have also been studied[5]Ko-Ta Chiang [6] developed a model and analysed the effects of machining parameters on the performance qualities in the EDM process of Al_2O_3+TiC mixed ceramic. Shashikant et al. [7] optimized the machine process parameters of EDM for material removal rate of EN19 material.

EDM is equippedto machine hard material component such as Inconel, heat treated tool steels, composites, super alloys, ceramics, carbides, heat resistant steels and many other difficult to machine materials. Inconel 800 is a high nickel and chromium base superalloy possessing high strength at elevated temperatures and resistance to oxidation and corrosion. As Inconel 800 is a new alloy material, only little information is accessible in literature for its machining characteristics. This paper examined the influence of machining parameters on material removal rate of Inconel 800 in a die-sinking EDM.

2. EXPERIMENTAL PROCEDURES

Die sinking operation was carried out in an EDM, make SPARKONIX model MOS 25A, on Inconel 800. The chemical composition of Inconel 800 are listed in Table 1. The servo-head (to maintain constant gap) of the EDM containing the tool was connected to the positive terminal. The tool was made up of oxygen free high conductivity copper (OFHC, 99.99% Cu). The properties of dielectric used, Kerosene, are shown in Table 3.

The experiment was carried on 5 mm thick Inconel 800 square plates of size 25 mm X 25 mm. The properties of the work piece material are shown in Table 2.

Table 1: Chemical Composition of Inconel 800

	Ni	Cr	Co	C	Al	Ti	Cu	Mn	S	Si	Fe
Min	30	19	-	-	0.15	0.15	-	-	-	-	
Max	35	23	2	1	0.60	0.60	0.75	1.50	0.015	1	Rest

Table 2: Properties of Inconel 800

Density (gm/cm3)	Tensile Strength (MPa)	0.2% Yield Strength (MPa)	Elongation (%)	Hardness (Brinel)
7.94	636 at 27oC	345	40	165 at 27oC

Table 3: Properties of Kerosene Oil

SURFACE TENSION (N/m)	DENSITY(Kg/m3)	DYNAMIC VISCOSITY (Ns/m2)
0.028	820	2400

All the work-pieces under study were equally machined for twenty-five minutes. The specimens were weighed before and after machining in a Sartorius digital balance to determine the material removed during machining. After, every machining operation, the copper electrode was polished on emery papers of grit size ranging from 400 to 2000, before re-using it in the next experiment. The experiment was carried out at different levels of the parameters and a total of 51 runs were taken in accordance to a design of experiments table.

2.1 Response surface methodology

In statistics, response surface methodology (RSM) investigates the connections between several explanatory variables and one or more by G. E. P. Box and K. B. Wilson in 1951 [8].

Response surface methodology is a collection of mathematical and statistical technique that is useful for modelling and analysis of problems in which a response or output is influenced by several variables and the goal is to find a relationship between the response and the variables. A Central

Composite Design (CCD) is one such RSM which gives asimilarly exact forecast of all response variable averages identified with amounts measuredduring experimentation. These relations are then demonstrated by utilizing least square error fitting of the response surface.

In the study, pulse current, pulse on time, and pulse off time were selected as the machine variables. The different levels taken for this study are shown in Table 4.

Table 4: Working Parameters and their levels

Parameter	Lowest Value	Highest Value
Ton (μs)	100	500
Toff (μs)	20	150
I (Amp.)	12	18

In the present investigation a Central Composite Face centered design (CCF) [9], a variant of CCD was used. This variety requires 3 levels for each factor, one at each of the two ends and one at the centre. The details of the CCD are presented in Table 5.

Table 5: Central Composite Design

Factors: 3	Replicates: 3
Alpha: = 1	Center points = 3
Base blocks: 1	Total blocks: 1
Base runs: 17	
Total runs: 51 (Cube points = 24; Center points in cube = 9; Axial points = 18)	

3. RESULTS AND DISCUSSIONS

The weight of the specimens were measured on a CPA 225D Sartorious electronic balance. The weights before and after die-sinking were W_S and W_f. The material removed was calculated as the difference in the weights before and after sinking. The total die sinking time was kept constant at 25 minutes. Thus, the MRR was determined by dividing the weight difference (W_d) by 25 for all cases. The details of the experiment input and output parameters are listed in Table 6.

Table 6: The design matrix and the value of MRR of machined surface along with input parameter

Run No.	Pulse on time (μs)	Pulse off time (μs)	Pulsed current (Amp.)	Wt. before EDM (gm.)	Wt. after EDM (gm.)	Difference (gm.)	MRR (gm/min)
	Ton	Toff	Ip	(WS)	(Wf)	Wd= WS-Wf	(WS-Wf) /25
1	100	20	12	25.0193	23.3393	1.6800	0.067200
2	500	20	12	24.9113	21.0363	3.8750	0.155000
3	100	150	12	25.6776	25.1512	0.5264	0.021056
4	500	150	12	24.8828	22.1828	2.7000	0.108000
5	100	20	18	25.3344	22.7088	2.6256	0.105024
6	500	20	18	25.2525	18.1275	7.1250	0.285000
7	100	150	18	25.9126	25.3269	0.5857	0.023428
8	500	150	18	24.6705	19.7955	4.8750	0.195000
9	100	85	15	24.7140	23.614	1.1000	0.044000
10	500	85	15	24.7384	20.1384	4.6000	0.184000
11	300	20	15	22.9886	19.9386	3.0500	0.122000
12	300	150	15	24.8459	22.8959	1.9500	0.078000
13	300	85	12	24.8667	22.3667	2.5000	0.100000
14	300	85	18	24.8158	20.4658	4.3500	0.174000
15	300	85	15	22.9695	20.1695	2.8000	0.112000
16	300	85	15	23.5157	20.7157	2.8000	0.112000
17	300	85	15	23.5450	20.745	2.8000	0.112000
18	100	20	12	23.5282	22.4282	1.1000	0.044000

19	500	20	12	21.7516	18.6516	3.1000	0.124000
20	100	150	12	24.6315	24.4412	0.1903	0.007612
21	500	150	12	24.0811	21.9061	2.1750	0.087000
22	100	20	18	24.0850	22.035	2.0500	0.082000
23	500	20	18	22.3271	15.4521	6.8750	0.275000
24	100	150	18	24.8475	24.666	0.1815	0.007260
25	500	150	18	24.7528	20.1988	4.5540	0.182160
26	100	85	15	24.9209	23.7879	1.1330	0.045320
27	500	85	15	24.8132	19.9852	4.8280	0.193120
28	300	20	15	24.7834	21.0584	3.7250	0.149000
29	300	150	15	24.6866	22.9897	1.6969	0.067876
30	300	85	12	24.7711	22.1763	2.5948	0.103792
31	300	85	18	24.8224	20.2414	4.5810	0.183240
32	300	85	15	24.7496	21.1395	3.6101	0.144404
33	300	85	15	24.7039	21.1186	3.5853	0.143412
34	300	85	15	24.6779	20.984	3.6939	0.147756
35	100	20	12	24.7139	23.4877	1.2262	0.049048
36	500	20	12	24.7184	21.2446	3.4738	0.138952
37	100	150	12	24.9228	24.8363	0.0865	0.003460
38	500	150	12	24.8797	22.2609	2.6188	0.104752
39	100	20	18	24.7984	22.4785	2.3199	0.092796
40	500	20	18	24.7319	17.9006	6.8313	0.273252
41	100	150	18	24.8542	24.6639	0.1903	0.007612
42	500	150	18	23.7129	19.1335	4.5794	0.183176
43	100	85	15	23.8594	22.6509	1.2085	0.048340
44	500	85	15	25.0749	20.1777	4.8972	0.195888
45	300	20	15	24.1751	20.6251	3.5500	0.142000
46	300	150	15	24.1919	22.458	1.7339	0.069356
47	300	85	12	23.7506	21.156	2.5946	0.103784
48	300	85	18	23.7780	19.2056	4.5724	0.182896
49	300	85	15	24.8536	21.3273	3.5263	0.141052
50	300	85	15	24.2827	20.7868	3.4959	0.139836
51	300	85	15	23.4476	19.8683	3.5793	0.143172

As the model was designed at 95% confidence level, it is seen in Table 7 that all the first and second order terms are significant apart from the interaction term of T_{on} and T_{off}. The fitsummary recommends that the quadratic model is statistically significant for analysis of MRR. In order to check the variance of the process an ANOVA was performed. The result of the quadratic model for MRR in the form of ANOVA is given in Table 8.

The value of R-Sq is 97.9% and R-Sq (adj) is 97.4%. This implies that the inter-relationship developed by the regression equation between the control variables and the response MRR is satisfactory. The associated p-value for the model has been lower than 0.05 (i.e. α = 0.05, or 95% confidence) indicates that the model has been considered to be statistically significant [9].

The F values for linear, square and interaction terms, as shown in Table 7, are more than their corresponding table-calculated values.

Thus, the model can be said to be statistically adequate to make further predictions. The lack of fit is insignificant (refer to Table 7), thus it implies that the insignificant terms may be removed from the model. Further, factor T_{on} (pulse on time), factor T_{off} (pulse off current), factor I (pulse current), square value of $T_{on}*T_{on}$, $T_{off}*T_{off}$, I*I and interaction effect of $T_{on}*I$, $T_{off}*I$ have significant effect. But Ton*Toff is not significant because the value of p is more then 0.05 (i.e. 0.691). The regression coefficient of significant terms for MRR is shown in Equation 1.

Table 7: Significance test for MRR

Term	Coef	SE Coef	T	P	Remarks
Constant	0.130481	0.002704	480249	0.000	Significant
Ton	0.067871	0.001999	33.960	0.000	Significant
Toff	-0.031951	0.001999	-15.987	0.000	Significant
I	0.034473	0.001999	17.249	0.000	Significant
Ton*Ton	-0.010262	0.003861	-2.658	0.011	Significant
Toff*Toff	-0.024001	0.003861	-6.216	0.000	Significant
I*I	0.012579	0.003861	3.258	0.002	Significant
Ton*Toff	-0.000895	0.002234	-0.400	0.691	Not-Significant
Ton*I	0.022923	0.002234	10.259	0.000	Significant
Toff*I	-0.011171	0.002234	-5.000	0.000	Significant

$$\mathrm{MRR} = 0.245551 - 7.39279 \times 10^{-05}\mathrm{Ton} + 0.00135417\mathrm{Toff} - 0.0370303\mathrm{I} - 2.56544 \times 10^{-07}\mathrm{Ton} * \mathrm{Ton} - 5.68073 \times 10^{-06}\mathrm{Toff} * \mathrm{Toff} + 0.00139766\mathrm{I} * \mathrm{I} + 3.82042 \times 10^{-05}\mathrm{Ton} * \mathrm{I} - 5.72897 \times 10^{-05}\mathrm{Toff} * \mathrm{I} \quad (1)$$

The above, Equation 1, shows the regression equation for MRR, expressed in its un-coded form. This second-order modelis able to predict the MRR at points on a non-linear contour. The analysis of variance (ANOVA) was used to check the sufficiency of the second order model.

The inter-relationship amongst different operating parameters and MRR was interpreted using surface plots, plotted in MNITAB [11], are shown in Fig.1 to Fig. 3. Fig.1 shows the estimated response surface for MRR in relation to the process parameters of pulsed current and pulse on time. It can be seen from the Fig. that the MRR tends to increase significantly with an increase in pulsed current for any value of pulse on time. Hence, maximum MRR is obtained at high pulse on time (500 μs) and high pulsed current (18A). This is due to their dominant control over the input energy i.e. with the increase in pulsed current generates strong spark which create the higher temperature cause more material to melt and erode from the work-piece.

The effect of I and T_{off} on the estimated response surface of MRR is depicted in Fig. 2. The Ton remains constant up to a level of 300 μs. It is seen that the MRR increases when the pulsed current (I) increases, however with the increase in T_{off}, MRR decreases. This is because when T_{off} increases; there will be an undesirable heat loss which does not contribute to MRR. This will lead to drop in the temperature of the work piece before the next spark starts and therefore MRR decreases. The maximum MRR is achieved with high I =18 A and lower T_{off} =20 μs for the given range of input parameters.

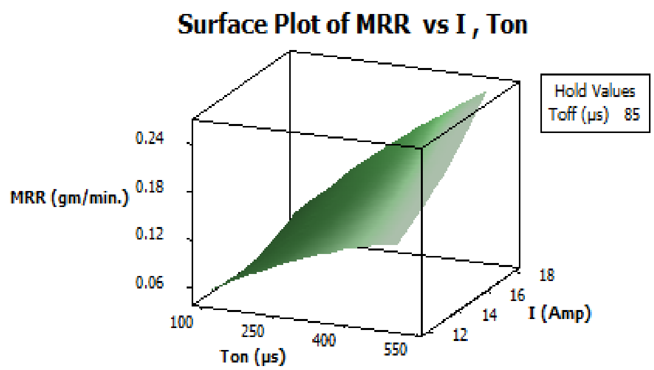

Fig. 1: Surface plot of MRR Vs. pulse on time and pulsed current.

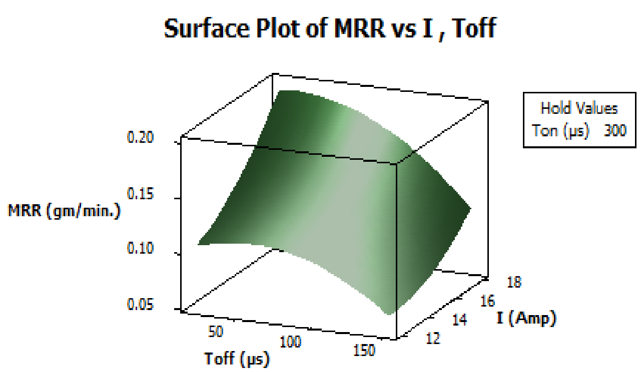

Fig. 2: Surface plot of MRR Vs. pulsed current and pulse off time.

Finally, Fig 3 represents MRR as a function of Ton and Toff, where current I remains constant in its middle level of 15 A. It can be seen that the highest MRR values occurred at the highest I and T_{on} and at lowest T_{off}. The surface plot in Fig. 3 suggest that even higher MRR could be obtained for higher T_{on}, and lower T_{off}. From this observation, it can be concluded that I and T_{on} are directly and T_{off} is reciprocally proportional to the MRR for the given range of experiments conducted for this test.

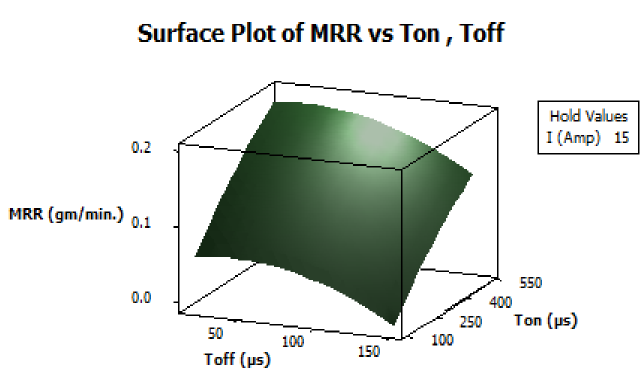

Fig. 3: Surface plot of MRR Vs. pulse on time and pulse off time.

4. CONCLUSION

In the present study on the effect of machining responses are MRR of the Inconel 800 material using a copper tool was investigated for an EDM process. The experiments were conducted under various parametric setting of Pulse on Time (T_{on}), Pulse off Time(T_{off}) and Pulsed current(I). The models for MRR were developed using pulsed current, pulse on time, and pulse off time and used in response surface methodology. Regression analysis was also conducted to determine input–output relationships of the process .Conclusion based on the regression analysis are summarized below.

The trend of MRR was satisfactorily predicated from the response surfaces plots. Results have showed that Central composite design is a powerful tool for providing experimental diagrams and statistical mathematical models, to perform the experiments efficiently and economically

A second order response model of these parameters has been developed and found that pulsed current (I), pulse on time (T_{on}), pulse off time (T_{off}) significantly affect the MRR. The MRR increased linearly with the increase in pulsed current throughout the range. However, the MRR value first increased with the increase of pulse on time up to a specified value of 500µs and decreased thereafter. An MRR 0.20gm/min was achieved with a combination of I=18 A, T_{on}=500µs and T_{off}=20µs within the experimental range. As an increase in the current value leads to an increase in spark energy across electrode gap, the MRR increases.

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