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**Research Article**

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# Electrical Discharge Machining with Hexagonal Tools on Die Steel using RSM

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***Abstract-***

***In this experimental study the electrical discharge machining (EDM) of die steel with different electrode shape namely cylindrical, rectangular, and hexagonal and process parameters of EDM such as, pulse on time, pulse off time, peak current were performed to explore the influence on MRR. The experiments were designed and conducted by employing Response Surface Methodology (RSM) by using statistical software i.e. Design Expert. The regression equation was developed using the experimental data and interactions graphs were plotted to investigate the effect of process parameters on MRR. The results reveals that the optimal setting for MRR is 35Amp peak current (IP), 7.5µs pulse on time (Ton), and 2.01µs pulse off time (Toff).***

***Keywords- Die steel, EDM, MRR, RSM***

## I. INTRODUCTION

Hexagonal holes on Die steel are difficult to be processed by conventional machining techniques, as per economic production and environmental safety. This challenge has facilitated the development of non-conventional machining techniques. It is well known that conventional methods are inadequate to produce complex geometrical shapes in the hard and temperature-resistant alloys and die steels **[1]**. EDM has been widely used to produce dies and moulds to produce complex geometrical shapes since it was developed in the late 1940s. It works based on the thermoelectric energy between the workpiece (anode) and the electrode (cathode) **[2-3]**. A pulse discharge applied in a small gap between the workpiece (anode) and the electrode (cathode) was found to remove the unwanted material from the parent material through melting and vaporizing from conducting material **[4]**.

Mahadavinejad **[5]** has investigated with a predictive controller model based on neural networks using two grades of WC-Co. The test results confirm the capability of the predictive controller model with increase in efficiency of 32.8% in MRR. Bozdana et al. **[6]** have presented a comparative study on machining and surface characteristics of through and blind holes on Ti-6Al-4V and Inconel 718 by fast hole rotary EDM process using tubular hollow copper and brass electrodes. The brass electrode exhibited higher MRR than copper electrode on both Inconel 718 and Ti-6Al-4V. MRR of Inconel 718 was higher than that of Ti-6Al-4V due to the effect of melting point. The choice of the shape of tool electrodes greatly influences the MRR, TWR and SR. However, limited research is available on tool geometry influences on process performance. Pellicer et al. **[7]** have studied the influences of different input parameters as well as tool electrode geometry on MRR, depth, slope, width and SR of copper electrode on AISI H13 tool steel. They observed that tool geometry had no influence on MRR and SR. Due to better radial wear; square and rectangle geometry performed the best. Triangle was not suitable for complex geometries due to wear.

In this work, different tool geometries were incorporated to enhance the effectiveness of the EDM process, especially generation of hexagonal shape hole.

## II. EXPERIMENTS

All the experiments have been conducted using the EDM machine model S-35, Sparkonix. Cylindrical shape, Rectangular shape and hexagonal shape electrodes were used in the machining processes which are shown in the figure 1. Copper was used as electrode for EDM to machining of die steel.

Fig 1: Electrodes used for Experiments

Every time the material is removed from the work piece due to the heat generated by the spark. The material removal rate (MRR) is determined based on volume of the hole generated. Volumes of holes are determined by taking area of the hole. Machining time is measured by stop watch in minutes.

The experiments were designed and conducted by employing RSM. The regression equation was developed using the experimental data and graphs were plotted to investigate the effect of process variables on response characteristic. The ANOVA was performed to statistically analyze the results. Various input process parameters varied during the experimentation are pulse on time, pulse off time, peak current and tool shape. Experiments were conducted according to the test conditions specified by the second order Box Behnkan design.

## III. RESULTS AND DISCUSSIONS

To decide about the adequacy of the model, three different tests viz. sequential model sum of squares, lack of fit tests and model summary statistics were performed for material removal rate. The Table 1 display tests to select an adequate model to fit MRR characteristics.

Table 1: Selection of Adequate model for MRR

| **Sequential Model Sum of Squares** | | | | | | |
|---|---|---|---|---|---|---|
| Source | SS | Df | M SS | F | Pr>F | |
| Mean | 2655.20 | 1 | 2655.20 | | | |
| Linear | 464.98 | 4 | 116.25 | 9.56 | <0.0001 | |
| 2FI | 28.46 | 6 | 4.74 | 0.32 | 0.9158 | |
| Quadratic | 212.41 | 4 | 53.10 | 14.55 | <0.0001 | suggested |
| Cubic | 26.25 | 8 | 3.28 | 0.79 | 0.6297 | Aliased |
| Residual | 24.83 | 6 | 4.14 | | | |
| Total | 3412.12 | 29 | 117.66 | | | |
| **Lack of Fit Tests** | | | | | | |
| Source | SS | Df | MS | F e | Pr>F | |
| Linear | 275.05 | 20 | 13.75 | 3.26 | 0.1302 | |
| 2FI | 246.59 | 14 | 17.61 | 4.17 | 0.0889 | |
| Quadratic | 34.19 | 10 | 3.42 | 0.81 | 0.6436 | Suggested |
| Cubic | 7.94 | 2 | 3.97 | 0.94 | 0.4629 | Aliased |
| Pure Error | 16.89 | 4 | 4.22 | | | |
| **Model Summary Statistics** | | | | | | |
| Source | Std. Dev. | R- S | Adj. R-S | Pre. R-S | Press | |
| Linear | 3.49 | 0.6143 | 0.5500 | 0.4090 | 447.34 | |
| 2FI | 3.83 | 0.6519 | 0.4585 | -0.0947 | 828.62 | |
| Quadratic | 1.91 | 0.9325 | 0.8650 | 0.7050 | 223.31 | Suggested |
| Cubic | 2.03 | 0.9672 | 0.8469 | -0.5445 | 1169.07 | Aliased |

It can be observed that the quadratic model is appropriate. The “lack of fit” test compares the residual error to the pure error from the replicated design points. The results indicate that the quadratic model does not show significant lack of fit, hence the adequacy of quadratic model is confirmed. The p value should be less than 0.5; the value of p is less than 0.5 in case of quadratic. Which shows that quadratic model is suggested.

### ANOVA for MRR

In order to statistically analyze the results, ANOVA was performed. Process variables having p-value less than 0.05 are considered significant terms for the requisite response characteristics.

Table 2: Pooled ANOVA for MRR

| Source | SS | DF | MS | F | Pr>F | |
|---|---|---|---|---|---|---|
| Model | 690.73 | 7 | 98.68 | 31.31 | <0.0001 | Significant |
| A | 373.97 | 1 | 373.97 | 116.65 | <0.0001 | |
| B | 36.12 | 1 | 36.12 | 11.46 | 0.0028 | |
| C | 46.97 | 1 | 46.97 | 14.90 | 0.0009 | |
| D | 7.92 | 1 | 7.92 | 2.51 | 0.1278 | |
| $B^2$ | 171.63 | 1 | 171.63 | 54.45 | <0.0001 | |
| $D^2$ | 17.22 | 1 | 17.22 | 5.46 | 0.0294 | |
| BD | 18.06 | 1 | 18.06 | 5.73 | 0.0261 | |
| Residual | 66.19 | 21 | 3.15 | | | |
| Lack of Fit | 49.30 | 17 | 2.90 | 0.69 | 0.7409 | Not significant |
| Pure Error | 16.89 | 4 | 4.22 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Cor Total | 756.92 | 28 | | | | |
| | | | | | | |
| Std. Dev | 1.78 | | R-Squared | | 0.9126 | |
| Mean | 9.57 | | Adj R-Squared | | 0.8834 | |
| C.V. | 18.55 | | Pred R-Squared | | 0.8127 | |
| PRESS | 141.79 | | Adeq Precision | | 21.747 | |

The insignificant parameters were pooled using backward elimination method. The pooled version of ANOVA for MRR (Table 2) indicates that (A), (B), (C), (D), the interaction terms (BD) and the quadratic terms ($B^2$, $D^2$) are significant parameters affecting MRR.

- The Model F-value of 31.31 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, $B^2$, $D^2$, BD are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.
- The "Lack of Fit F-value" of 0.69 implies the Lack of Fit is not significant relative to the pure error. There is a 74.09% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.
- The "Pred R-Squared" of 0.8127 is in reasonable agreement with the "Adj R-Squared" of 0.8834. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 21.747 indicates an adequate signal. This model can be used to navigate the design space.

**Final Equation in Terms of Actual Factors of MRR**

By using table 1, the regression equation for the MRR as a function of four input process variable was developed from the software (RSM).

$$MRR = 10.98+5.58*Ip + 1.73*Ton -1.98*Toff -0.81*TS -4.99*Ton^2 +1.58*TS^2 -2.13*Ton*TS$$

The figure 2 shows that MRR increases with increase in pulse on time and higher for cylindrical tool shape. At large value of Ton means, there will be more time duration for which current is on i.e. more number of discharges per second which implies that material erosion will be more, hence faster MRR results.

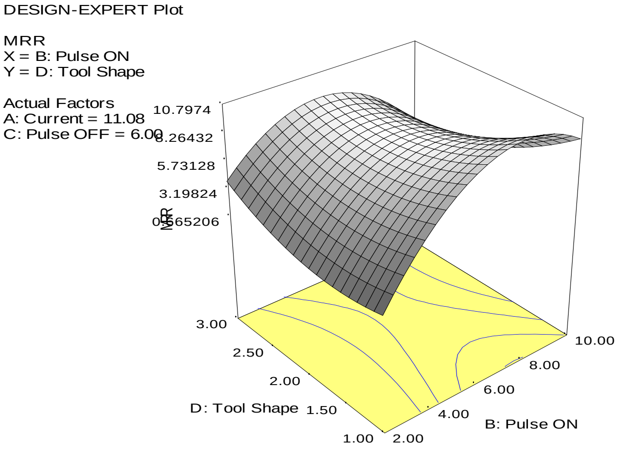

Fig 2: Interaction Plot, Ton vs TS for MRR

The figure 3 shows the normal probability plot of residuals for material removal rate. Most of residuals are found on a straight line which indicates that errors are normally distributed. This is the normality test to be qualified by the model for checking the model. After this test it has been found that models are significant.

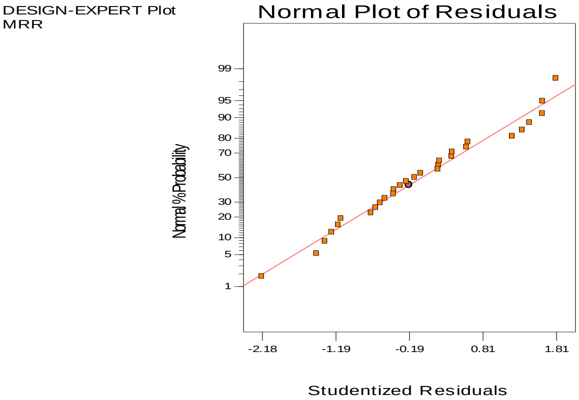

Fig 3: Normal Plot of Residual for MRR

The figure 4 shows the residuals and predicted plot for material removal rate. The residuals are distributed randomly and are not clustered. This indicates a good model.

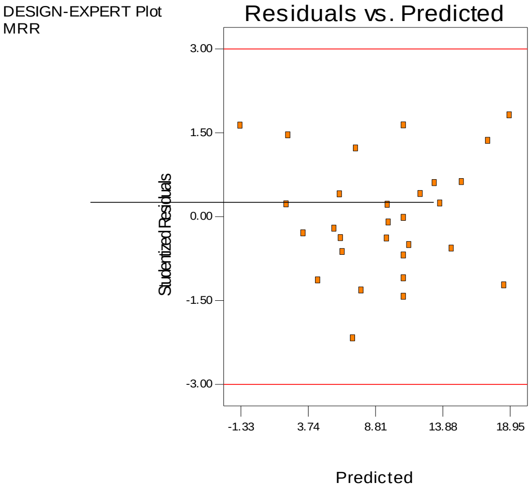

Fig 4: Residuals vs. Predicted plot for MRR

The figure 5 shows the Predicted vs Actual plot for material removal rate. Most of results are found on a straight line which indicates that errors are normally distributed. This is test to be qualified by the model for checking the model. After this test it has been found that models are significant.

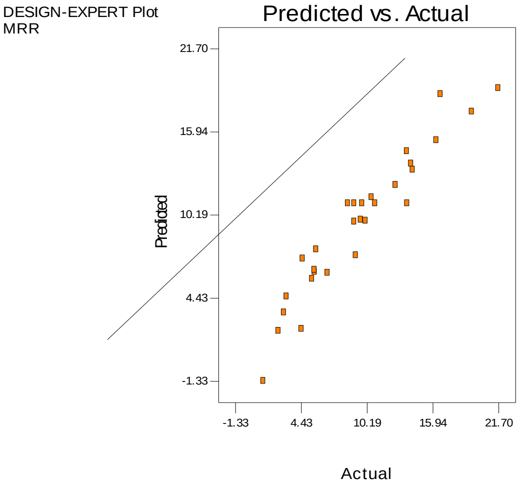

Fig 5: Actual vs. Predicted plot for MRR

The figure 6 shows the effect of current on MRR. Form the figure it is clear that the MRR is increase by increasing current.

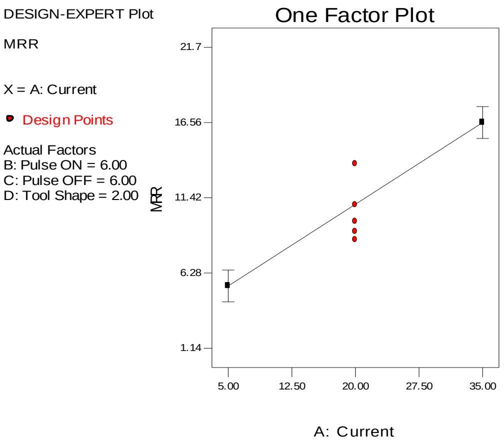

Fig 6: Effect of Current on MRR

This is due to the fact that an increase in current increases the pulse energy that leads to an increase in heat energy rate, which is subjected to both of the electrodes, and in the rate of melting and evaporation. Thus, the MRR increase with current.

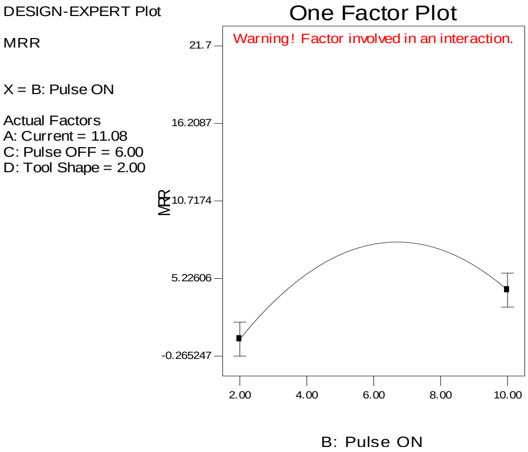

Fig 7: Effect of Pulse On Time on MRR

The figure 7 shows the effect of Pulse on time on MRR, which indicates that MRR is increase by increasing pulse on time upto a certain limit after that is remain constant and then decrease. This event has been attributed to the increase of input energy in high pulse on time duration, which results in more chopping on the gap between the workpiece and tool electrode, creating a short circuit which decreases the efficiency of electrical spark erosion. In other words, short pulse on-time duration causes less vaporization, whereas long pulse on-time duration causes the plasma channel to expand, resulting in less energy density on workpiece, which is insufficient to melt and/or vaporize the workpiece material.

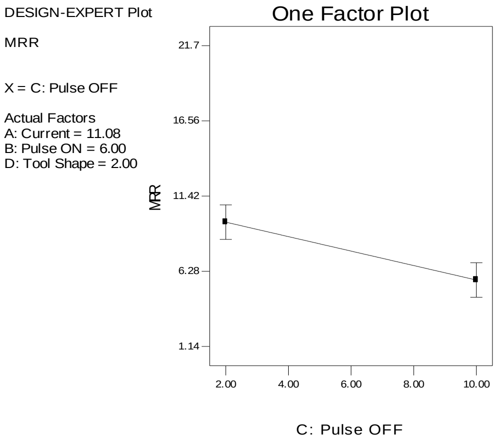

Fig 8: Effect of Pulse Off Time on MRR

The figure 8 shows the effect of Pulse off time on MRR, which indicates that MRR is decrease by increasing pulse off time. Large pulse off time means short pulse on-time duration causes less vaporization resulting in less energy density on workpiece, which is insufficient to melt and/or vaporize the workpiece material and MRR is decrease.

**Single Response Optimization using Desirability**

The constraint for the optimization of response characteristic i.e. material removal rate is given in table 3. Goals and limits were established for each response individually in order to accurately determine their impact on individual desirability.

Table 3: Range of Input Parameters and MRR for Desirability

| Name | Goal | LL | UL | LW | UW | Imp. |
|---|---|---|---|---|---|---|
| Ip | is in range | 5 | 35 | 1 | 1 | 3 |
| Ton | is in range | 2 | 10 | 1 | 1 | 3 |
| Toff | is in range | 2 | 10 | 1 | 1 | 3 |
| TS | is in range | 1 | 3 | 1 | 1 | 3 |
| MRR | maximize | 1.14 | 21.7 | 1 | 1 | 3 |

The goal of optimization is to find a good set of conditions that will meet all the goals. It is not necessary that the value of desirability is always 1.0 as the value is completely dependent on how closely the lower and upper limits are set relative to the actual optimum. A set of 5 optimal solutions is derived for the specified design space constraints for individual response characteristic i.e. Material Removal Rate using Design of Expert statistical software. The set of conditions possessing highest desirability value is selected as optimum condition for the desired response.

Table 4 reports the optimal set of conditions with higher desirability function required for obtaining desired response characteristic under specified constraints. Desirability 3D-plots were first drawn keeping input parameters in range and MRR is maximum.

Table 4: Set of Optimal Solutions for Desirability for MRR

| S.No | Ip | Ton | Toff | TS | MRR | Des. | |
|---|---|---|---|---|---|---|---|
| 1 | 35 | 7.53 | 2.01 | 1 | 21.67 | 0.999 | Selected |
| 2 | 34.76 | 7.56 | 2 | 1 | 21.59 | 0.995 | |
| 3 | 35 | 7 | 2 | 1 | 21.58 | 0.994 | |
| 4 | 35 | 6.74 | 2 | 1 | 21.47 | 0.989 | |
| 5 | 34.33 | 7.35 | 2 | 1 | 21.41 | 0.986 | |

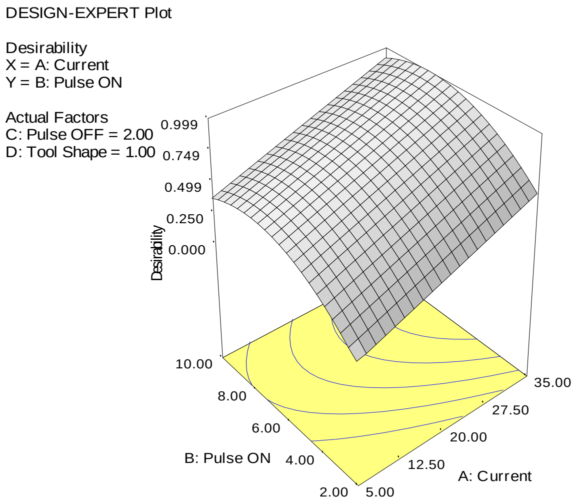

Fig 9: Desirability Graph in between Pulse On and Current for MRR

The Figure 9 shows a plot of desirability function distribution of material removal rate according to current and pulse on time. It can be visualized that high level of current and high level of pulse on time favour of high material removal rate.

## IV. CONCLUSIONS

1. From the experimental data of RSM, empirical model were developed and the confirmation experiments were performed, which were found within 95% confidence interval.
2. The regression equations for MRR is $10.98+5.58*Ip + 1.73*Ton -1.98*Toff -0.81*TS -4.99*Ton^2 +1.58*TS^2 - 2.13*Ton*TS$.
3. Desirability function in combination with response surface methodology has been used for single response optimization. Optimal setting for MRR are 35Amp IP, 7.5µs Ton, and 2.01µs Toff.

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