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Effect of Al₂O₃ powder in deionized water on metal removal rate during electro discharge machining of H11 die steel

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Abstract. The electrical discharge machining commonly used nonconventional machining process for making dies. The H11 die steels are commonly used for making forging and casting dies. In the present research, the effect of Al₂O₃ powder in de-ionized water as dielectric fluid, pulse on time, current, voltage on metal removal rate (MRR) have been investigated. The result shows that MRR increases with increase in pulse on time and current. Also, The MRR increases with the presence of Al₂O₃ powder in de-ionized water.

Keywords. Al₂O₃ powder, de-ionized water, MRR, H11 die steel

1. Introduction

Now a days, various machining processes are employed to achieved the finish product from the raw material in production the manufacturing industries [1]. Due to the enormously demands for new alloy having improve mechanical/ thermal/ tribological properties in aerospace and automotive industries, EDM process has grown enormously [2]. The EDM process is an excellent alternative machining process for making the finish products using high strength conductive materials and ceramics with high dimensional accuracy [3]. During the EDM machining, the material erosion takes place due to electric sparking between the work piece and the electrode [4]. The Kerosene / EDM oil / deionized water are the commonly used dielectric fluid for EDM [5].

The AISI H11, AISI H13, AISI D1, AISI D2, AISI D3, AISI P20 etc. die steels are commonly used for making hot-work forging dies, press forging dies and die-casting dies [6]. Conventional machining of die materials requires high wear resistance tool. Hardness and toughness of these materials requires non-conventional machining. Now days, due to global competitiveness, manufacturing industries are gives attention towards the quality of finish products with high productivity. The MRR is significantly affected on the selection of cutting conditions. To maximize the MRR during the EDM machining, EDM conditions should be selected properly.

In the past, numerous researchers made attempt to investigate the influence of EDM machining condition on MRR and selection of optimal machining conditions for maximum MRR during electric discharge machining.
Chow et al. [7] investigated the effect of SiC powder mixed in kerosene during the micro-slit machining of Ti alloy by EDM. Result revealed that material MRR and surface finish increases with the presence of SiC powder in kerosene. Lin and Lin [8] optimized the EDM conditions during electrical discharge machining using grey relational analysis (GRA) with Taguchi methodology and fuzzy methodology. The pulse on time, discharge current and duty factor have been considered as EDM conditions. The GRA has been found more accurate approach to optimize the EDM conditions. Kansal et al. [9] employed response surface methodology (RSM) for the optimization of EDM machining variables for minimum surface roughness and maximum MRR using Powder mixed dielectric fluid. The surface roughness and maximum MRR are taken as output responses. The result revealed that MRR and surface finish increases in the presence of silicon powder in dielectric fluid during the EDM process.

Kanlayasiri and Boonmung [10] studied the influence of machining parameter on surface finish during wire cut EDM of SKD11 cold die steel. The pulse-on time and current are found most influencing factors that affects the surface roughness. Chiang [11] developed prediction models for surface finish, MRR and electrode wear ratio using RSM during EDM machining of Al$_2$O$_3$+TiC mixed ceramic. The pulse on time and discharge current are found most significant parameters that affect electrode wear ratio and surface finish. Also, as the current, voltage and duty factor increases, the MRR also increases. Habib et. al. [12] used RSM to study the influence of EDM conditions with kerosene/ SiC mixed dielectric fluid on MRR. The results revealed that gap voltage, pulse on time and peak current are observed significant parameters that affect the MRR. Rao et al. [13] used artificial neural network and genetic algorithm to study the effect of EDM conditions on surface finish during the machining of 15CDV6, Ti6Al4V, M-250, and HE15 materials. Also, an attempt is made to develop model in terms of EDM conditions. A comparison has also been made between the predicted results and experimental results. The results revealed that developed model has high prediction ability to predict the new values of surface roughness with different combination of EDM conditions.

Chattopadhyay et al. [14] investigated the impact of machining variables on surface roughness during rotary EDM process of copper-steel system with kerosene as dielectric fluid using Taguchi methodology. The peak current and pulse on time are found main influencing factor for surface finish. Ahmed and Lajis [15] employed response surface methodology for the optimization of the EDM conditions during the machining of Inconel 718. The surface roughness and MRR are considered as response. For MRR, peak current was identified as main influencing machining variable while minimum surface roughness is achieved at minimum value of peak current and pulse on time. Shashikant et al. [16] developed empirical relationship between process variables and MRR using RSM during EDM process of EN19 steel. The process variables have been optimized for maximum MRR. The current, voltage, pulse off-time, and their interactions are found significant while pulse on-time has been found insignificant variable for MRR.

Rengasamy et al. [17] investigated the effect of wt % ZrB$_2$ as reinforcement in Al 4032 alloy on mechanical properties and tool wear during the EDM machining of Al 4032/ ZrB$_2$ based MMCs. It has been revealed that compressive strength increases with increases in wt% of ZrB$_2$. Also, pulse on time is found insignificant parameter for tool wear. Satpathy et al. [18] used topsis methodology for the optimization of EDM parameters for minimum TWR and maximum MRR during the EDM machining of AlSiC- 20% SiC reinforced metal matrix composite. It is observed from the result that the MRR decreases with increase in pulse on time. Tamang et al. [19] investigated the influence of EDM conditions on overcut and taper angle in drilling of AISI305 stainless steel using brass electrode. The results revealed that as the current and pulse on time increases, the overcut also increases while taper angle increases with increase in value of current. Bains et al. [20] investigated the effect of magnetic field assisted EDM parameters on micro hardness and recast layer thickness of work-piece during the EDM machining of Al/SiC based MMC using Cu/Gr/W based electrode. It has been found that magnetic field decreases the micro hardness and recast layer thickness of workpiece. Barenji et al. [21] studied the influence of EDM
variable on MRR and TWR in machining of AISI D6 tool steel using circular copper electrode. It has been observed that as the value of pulse on time and current increases, the MRR also increases.

The review of published literature presented above indicates that lot of research work is carried out to study the influence of EDM parameters (pulse on time, pulse of time, voltage and current) for minimum TWR. Very fewer efforts have been made to investigate the effect of dielectric fluid on TWR and MRR. The H11 hot die steels are commonly used die steel for making different purpose dies. Thus, there is a lot of scope to explore this material. In this research RSM based on face centered design (FCD) has been used to investigate the effect of pulse on time, current, voltage and type of dielectric fluid (de-ionized water and Al₂O₃ mixed de-ionized water) on MRR. An attempt has also been made to develop prediction models for MRR in terms of EDM machining conditions.

2. Design matrix for experimentation

In the present research, pulse on time, current, voltage, and types of dielectric fluid have been considered as an EDM machining condition. Among these machining conditions, current, voltage, and pulse on time have been considered as numeric factor while types of dielectric fluid has been as category EDM parameter. The table 1 shows the EDM parameters and values of parameters while table 2 shows the design matrix according to face centered design based RSM for experimentation and measured values of MRR.

| Parameters       | Units | Type                  | Levels   |
|------------------|-------|-----------------------|----------|
| Voltage          | Volts | Numeric               | -1 200   |
| Current          | Amp   | Numeric               | 10 500   |
| Pulse on time    | µs    | Numeric               | 80 1250  |
| Type of dielectric | Categoric | De-ionized water/ Al₂O₃ |  |

Table 2. Design matrix and measured values of MRR

| Std order | Voltage (Volts) | Current (Amp) | Pulse on time (µs) | Type of Dielectric | MRR (mm³/min) |
|-----------|-----------------|---------------|--------------------|--------------------|---------------|
| 1         | 20              | 10            | 50                 | deionized water    | 0.865         |
| 2         | 50              | 10            | 50                 | deionized water    | 3.527         |
| 3         | 20              | 20            | 50                 | deionized water    | 4.374         |
| 4         | 50              | 20            | 50                 | deionized water    | 6.527         |
| 5         | 20              | 10            | 125                | deionized water    | 0.994         |
| 6         | 50              | 10            | 125                | deionized water    | 3.882         |
| 7         | 20              | 20            | 125                | deionized water    | 4.317         |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 8 | 50 | 20 | 125 | deionized water | 6.828 |
| 9 | 20 | 15 | 88  | deionized water | 3.522 |
|10 | 50 | 15 | 88  | deionized water | 5.895 |
|11 | 35 | 10 | 88  | deionized water | 3.218 |
|12 | 35 | 20 | 88  | deionized water | 6.472 |
|13 | 35 | 15 | 50  | deionized water | 4.379 |
|14 | 35 | 15 | 125 | deionized water | 4.714 |
|15 | 35 | 15 | 88  | deionized water | 4.881 |
|16 | 35 | 15 | 88  | deionized water | 4.992 |
|17 | 35 | 15 | 88  | deionized water | 4.737 |
|18 | 35 | 15 | 88  | deionized water | 4.837 |
|19 | 20 | 10 | 50  | de-ionized water/ Al$_2$O$_3$ | 1.838 |
|20 | 50 | 10 | 50  | de-ionized water/ Al$_2$O$_3$ | 4.327 |
|21 | 20 | 20 | 50  | de-ionized water/ Al$_2$O$_3$ | 5.174 |
|22 | 50 | 20 | 50  | de-ionized water/ Al$_2$O$_3$ | 7.147 |
|23 | 20 | 10 | 125 | de-ionized water/ Al$_2$O$_3$ | 1.886 |
|24 | 50 | 10 | 125 | de-ionized water/ Al$_2$O$_3$ | 4.915 |
|25 | 20 | 20 | 125 | de-ionized water/ Al$_2$O$_3$ | 5.483 |
|26 | 50 | 20 | 125 | de-ionized water/ Al$_2$O$_3$ | 7.928 |
|27 | 20 | 15 | 88  | de-ionized water/ Al$_2$O$_3$ | 4.397 |
|28 | 50 | 15 | 88  | de-ionized water/ Al$_2$O$_3$ | 6.858 |
|29 | 35 | 10 | 88  | de-ionized water/ Al$_2$O$_3$ | 4.482 |
|30 | 35 | 20 | 88  | de-ionized water/ Al$_2$O$_3$ | 7.273 |
|31 | 35 | 15 | 50  | de-ionized water/ Al$_2$O$_3$ | 5.683 |
3. Experimentation and measurement

All drilling operations have been carried out on AISI H11 hot die steel samples of dimension 30 mm x 30 mm x 10 mm using ELEKTRA EMS 5535 EDM machine. The copper rods of 12 mm diameter and 3 cm length have been used as an EDM tool. The de-ionized water having electric resistivity 0.25 MΩ cm and de-ionized water with Al₂O₃ (2 gm/L) have been used as dielectric fluids. The MRR of machined samples have been evaluated using Equation 1.

\[
MRR = \frac{W_{iw} - W_{fw}}{\rho \times T}
\]

(1)

Where,

- \(W_{iw}\) = Initial weight of workpiece
- \(W_{fw}\) = Final weight of workpiece
- \(\rho\) = Density of AISI H11 steel
- \(T\) = Machining time

The weights of samples have been measured using Sartorius LA-1200S precision scale having accuracy of 0.001 g. The final values of MRR are presented in Table 2.

4. Result and discussion

The objective of present research is to investigate the impact of EDM parameters and Al₂O₃ in dielectric fluid on MRR during the machining of AISI H11 steel. For this purpose, the experimental results along with design matrix have been input into the design expert software 8.0.4.7.

4.1 Development of empirical relationship between EDM conditions and MRR.

4.1.1 Diagnosis of assumptions of ANOVA. The figure 1 shows the normal probability plot for residuals. It is used to validate the first assumption of ANOVA i.e. assumption of normal distribution [22]. It has been revealed from the figure that mostly residuals are laying on a straight line i.e. the residuals for MRR are normally distributed. The figure 2 shows residuals versus the predicted plot for MRR. It is used for the validation of second assumption of ANOVA i.e. assumption of constant variance [23]. There is no predefined pattern is observed, so data is following second assumption of ANOVA.
Figure 1. Normal probability plot for residuals of MRR

Figure 2. Plot between of residuals and predicted MRR

4.1.2 ANOVA for MRR. In this research, ANOVA is conducted at the confidence level of 95%. The reduce ANOVA table for MRR after the forward elimination method is given in table 3.
Table 3 represents that the “Prob. > F” for MRR empirical model is 0.0001 which is lower than 0.05, that shows the MRR empirical model is significant, that implies the terms in the model affects the MRR. In the same manner, the “Prob. > F” for current, pulse on time, voltage, type of dielectric fluids and interaction of voltage & current; voltage & pulse on time and second order term of pulse on time, current & voltage are smaller than 0.05 so these are the significant terms for MRR prediction model.

The “Prob. > F” for lack-of-fit is 0.2537 which is larger than 0.05, so it is insignificant, which is required. The $R^2$ value and adjusted $R^2$ value are 0.991 and 0.988 respectively, which is almost close to each other. Adequate precision is equal to 72.11 which indicate adequate model discrimination.

### Table 3. Reduce ANOVA for MRR

| Source                  | Sum of squares | Degree of freedom | Mean square | F-Value | p-value Prob> F |
|-------------------------|----------------|-------------------|-------------|---------|----------------|
| Model                   | 96.151         | 9.000             | 10.683      | 326.639 | 0.0001         |
| A-Voltage (Volts)       | 31.210         | 1.000             | 31.210      | 954.223 | 0.0001         |
| B-Current (Amp)         | 49.893         | 1.000             | 49.893      | 1525.449| 0.0001         |
| C-Pulse on time (µs)    | 0.392          | 1.000             | 0.392       | 11.977  | 0.0019         |
| D-Type of dielectric    | 7.891          | 1.000             | 7.891       | 241.274 | 0.0001         |
| AB                      | 0.247          | 1.000             | 0.247       | 7.537   | 0.0108         |
| AC                      | 0.159          | 1.000             | 0.159       | 4.867   | 0.0364         |
| A^2                     | 0.786          | 1.000             | 0.786       | 24.045  | 0.0001         |
| B^2                     | 0.191          | 1.000             | 0.191       | 5.837   | 0.0230         |
| C^2                     | 1.010          | 1.000             | 1.010       | 30.879  | 0.0001         |
| Residual                | 0.850          | 26.000            | 0.033       |         |                |
| Lack of Fit             | 0.725          | 20.000            | 0.036       | 1.742   | 0.2537         |
| Pure Error              | 0.125          | 6.000             | 0.021       |         |                |
| Cor Total               | 97.002         | 35.000            |             |         |                |
| Std. Dev.               | 0.1809         |                   | R-Squared   | 0.991233|                |
| Mean                    | 4.8549         |                   | Adj R-Squared| 0.988199|                |
| C.V. %                  | 3.7251         |                   | Pred R-Squared| 0.984421|                |
| PRESS                   | 1.5111         |                   | Adeq Precision| 72.11287|                |

4.1.3 MRR prediction empirical model. The MRR prediction empirical models with deionized water and deionized water/Al$_2$O$_3$ are given in Equations 2 and 3 respectively.

$\begin{align*}
\text{(MRR)} &= -9.517 + 0.211 \times V + 0.60 \times I + 0.052 \times \text{Pulse on time} - 0.0016 \times I \times V + 0.0002 \times V \times \text{Pulse on time}^2 \\
\text{Pulse on time} &= 0.0017 \times V^2 - 0.0075 \times I^2 - 0.0003 \\
\text{(MRR)} &= -8.58 + 0.211 \times V + 0.60 \times I + 0.052 \times \text{Pulse on time} - 0.0016 \times I \times V + 0.0002 \times V \times \text{Pulse on time}^2 \\
\text{Pulse on time} &= 0.0017 \times V^2 - 0.0075 \times I^2 - 0.0003 
\end{align*}$

(2) (3)
4.2 Impact of EDM conditions on MRR
The figure 3 represents the effect of types of dielectric fluid on metal removal rate at V 35 volts, current 15 ampere and pulse on time 88 µs.

**Figure 3.** Effect of type of dielectric fluid on MRR

From the figure it cleared that the addition of Al₂O₃ powder in deionized water increases the MRR. The Al₂O₃ powder in deionized water increases the electrical conductivity and gap between the workpiece & tool, which further increases the MRR [24]. Also, the Al₂O₃ powder creates a bridge between the workpiece and electrode gap which further scatter discharge energy. The scatter energy generates a minor crater and debris. The MRR is accelerated due to easily drain of minor debris from the gap.

**Figure 4.** 3D Plot for MRR in terms of V and current with deionized water
The figures 4 and 5 shows the 3D plots for MRR in terms of current and voltage at constant pulse on time 88µs with deionized water and deionized water/Al₂O₃ respectively.

**Figure 5.** 3D Plot for MRR in terms of voltage and current with deionized water/Al₂O₃

From the both plots it has been revealed that MRR increases with increase in voltage and current with both types of dielectric fluid. At the current increases. The spark energy increases with increase in current, which further increase the pulsation energy with faster melting of workpiece. This leads to increase in MRR of workpiece [25]. Also, with increase in voltage, the pulsation energy also increases, which further increases the amount of MRR.

**Figure 6.** 3D Plot for MRR with pulse on time voltage and deionized water
Figure 7. 3D Plot for MRR with pulse on time, voltage and deionized water/Al₂O₃

The figures 6 and 7 shows the 3D plots for MRR in terms of voltage and pulse on time with deionized water and deionized water/Al₂O₃ respectively at constant current 15 ampere. From the plots it is cleared that MRR initially increases up to a certain value of pulse on time after that MRR continuously decreases with increase in pulse on time. As the pulse on-time increases, the amount of discharge energy at the interface of workpiece and tool also increase, which expands the plasma channel. This give rise to enlargement of heat source radius, consequently increase the MRR up to a certain value of pulse on time. After that further increase in pulse on time, plasma channel becomes wilder and spark energy centralization decreases which leads to decrease in MRR [24].

From the all plots it is cleared that the maximum MRR is obtained at higher value of current, voltage and some certain value of pulse on time with deionized water/Al₂O₃ dielectric fluid. At low current, low voltage and low pulse on time, Al₂O₃ powder prevents the formation of plasma channels which reduces the MRR. Also, at high current, high voltage and high pulse on time, ideal plasma channel is generated which increase discharge energy but at the same time Al₂O₃ powder increases the gap quantity and makes the spark more unfailing therefore MRR decreases [24].

5. Optimization and conformation run

The optimum solutions for MRR are shown in table 4. The maximum MRR 8.02174 mm³/min has been obtained at 50 volts, 20 ampere current, 93 µs pulse on time with deionized water/Al₂O₃ dielectric fluid.

A set of three experiments have been conducted to validate the developed MRR models. The table 4 indicates the comparison between the experimental and predicted values of MRR. The absolute % error between the predicted MRR and experimental MRR are obtained within 5 %, which shows the excellent prediction ability of developed models.
Table 4. Optimum value and conformation run

| S.No. | Voltage (volts) | Current (Amp.) | Pulse on time (µs) | Types of dielectric | MRR (mm³/min) | % Absolute error |
|-------|----------------|----------------|-------------------|---------------------|---------------|-----------------|
| 1     | 49.63          | 20             | 93                | De-ionized water/Al₂O₃ | 8.022         | -2.387          |
| 2     | 50             | 20             | 78                | Al₂O₃               | 7.828         | -3.231          |
| 3     | 50.00          | 20             | 98                | De-ionized water    | 7.112         | 4.823           |

6. Conclusion
The aim of the present research is to study the influence of EDM parameters and Al₂O₃ in dielectric on MRR during the EDM machining of AISI H11 hot die steel. Also, an attempt is made to develop MRR prediction models in terms of EDM parameters with different types of dielectric using RSM. The following major conclusions have been derived:

1. The pulse on time, current, voltage, and types of dielectric shows the significant effect on MRR.
2. The interaction of current and voltage & voltage and pulse on time have been also found significant model term that affects the MRR.
3. The R² square value 0.9912 shows that developed model has excellent MRR prediction ability.
4. The quadratic variation for MRR has been obtained with current, voltage and pulse on time.
5. The MRR initially increases with increase in pulse on time up to a certain value of pulse on time after that MRR continuously decreases with increase in pulse on time. Also, MRR continuously increases with increase in voltage and current.
6. The higher MRR is achieved with deionized water/Al₂O₃ dielectric fluid for all the values of voltage, current and pulse on time.
7. The maximum MRR 8.02174 mm³/min has been obtained at 50 volts, 20 ampere current, 93 µs pulse on time with deionized water/Al₂O₃ dielectric fluid.
8. The conformation run shows the excellent predicted ability of the developed MRR prediction models.

In this research empirical relationship has been developed only for MRR. The work can be extended by considering more responses like TWR, surface roughness etc. and more EDM parameters such as temperature, shape of electrode, type of tools, etc.

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