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# An Experimental Investigation and Optimization of Electrical Discharge Drilling for Small Hole Drilling with High Aspect Ratio

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**Abstract:** ***Electric discharge drilling (EDD) is a thermo erosion process used to produce micro/small holes in hard and composite materials. EDD is mostly used to drill small holes in products for several applications such as fuel injector, dental and medical devices, turbine blades cooling channels etc. In present work, small holes of diameters ($\phi$) 0.5 mm and 1mm are drilled in Die steel using tubular electrodes of copper and brass. Using Taguchi' design of experiment method, process parameters namely discharge current (Ip), pulse on time (Ton), pulse-off time (Toff) and electrode material are investigated and optimized for different hole geometries using electrodes of $\phi$ 1 mm & 0.5 mm. In EDD process, drilling capability and diametric over cut (DOC) are the performance characteristics under investigation. Using Grey relational analysis (GRA), both performance characteristics are optimized simultaneously.***

**Keywords:** Electric discharge drilling, hole drilling with high aspect ratio, drilling capability, diametric over cut, Taguchi method, Grey relational analysis

## 1. Introduction

Micro-holes are integral part of several components especially micro devices such as micronozzles, micro-electro mechanical system (MEMS), inkjet printer nozzles, medical equipments, and aerospace applications such as drilling in turbine blades for cooling purpose etc. [1,2].

Drilling of high aspect micro holes in high temperature resisting super alloys using conventional drilling process is not possible. High tool wear and frequent tool breakage is major problem in conventional drilling [3]. With the advancement in technology, new non-contact machining methods are developed for drilling micro holes with high aspect ratio such as micro-EDM, femto second and excimer laser machining and LIGA technology etc. Micro-holes less than 200µm were produced in diesel fuel injection nozzles using micro-EDM [4]. Micro-EDM is highly preferred over other processes because of its comparatively better drilling rate, ability to machine hard and composite materials, burr free surface etc.

Electrical discharge drilling (EDD) is a modified electrical discharge machining (EDM) process to produce high aspect macro or micro holes with tight tolerance in hard and composite conductive materials.EDD employs rotating tubular electrode of small diameter ($\phi$ 0.2 mmto 3mm) for drilling. In case of tubular electrodes, the dielectric fluid is pumped through the hollow cavity of the electrode at very high pressure under the work material and tool electrode. The combination of very high dielectric pressure, rotation of electrode and servo controlled feed of electrode magnifies the material removal rate in EDD as compared to die sinking EDM. Due to high drilling rate in EDD, it is also known as fast drill EDM [5].

Figure 1 shows the schematic setup of EDD process. The principle of material removal in EDD is similar to EDM, where the material erodes due to melting and vaporization caused by high heating under repeated sparks [6]. In EDD, cylindrical electrode is fed toward the work material with the help of servo motor that maintains the constant gap between the work surface and tool electrode. Primary sparking takes place between the work surface and bottom of the electrode resulting the material erosion at the bottom of tool electrode and hence hole drilling takes place. High pressure dielectric fluid flushes the eroded particles out of the spark gap. Secondary sparks occurs between the sides of the drilled surface and eroded particles resulting into over cut at the top of the drilled hole as shown in Figure 2.

In EDD process, there are several controlling factors affecting the performance characteristics such as discharge current, pulse on time, pulse off time, type of dielectric fluid, fluid pressure, electrode rotational speed etc. Several investigations have carried out to study the influence of these controlling factors to obtain burr free micro holes with high aspect ratio in different work materials [7].[8] Compared the drilling performance of CuW and graphite electrodes of diameter 300µm for Ti6AI4V work material. CuW electrode melts up to 50% in drilling a depth of 5.5mm, while graphite electrode melts upto 400% in drilling a depth of 0.5 mm. In micro hole drilling in nickel-based super alloy using copper tubular electrode, material removal rate (MRR)is mostly influenced by peak current, duty factor and electrode rotation, but depth averaged surface roughness (DASR) was influenced by peak current and pulse on-time. MRR and electrode wear rate (EWR) increases with increasing voltage and discharge current. Brass electrode results in better MRR as compared to tungsten carbide electrode [9]. Using EDD, burr free micro holes with high aspect ratio and tight tolerance can be obtained only if the drilling is performed at optimal parameters for a given work material.

In present work, Taguchi's design of experimental approach is utilised to investigate the process parameters on two performance characteristics namely drilling capability (DC) and diametric overcut (DOC) while EDD in die steel. Brass and Copper tubular electrodes are selected in two geometries (diameter 0.5mm and 1 mm) for the analysis of drilling hole of two geometries i.e. hole diameter 0.5mm and 1mm. Along with electrode material, three other process parameters namely Discharge current (Ip), Pulse-on time (Ton) and Pulse-off time (Toff) are also investigated. Grey relational analysis is used to obtain single optimal parameters setting for maximum DC and minimum DOC.

## 2. Experimental Details

### 2.1 EDD setup and work material

In present work, experiments are performed on 3-axis electric discharge drilling machine (ED-25), where x-y movement of work table is manually controlled while electrode feed (z-axis) is servo controlled. Figure 3 depicts the experimental setup used for present experimentation. The present machine tool have variable parameters in following range; discharge current (Ip);1-9 amp., pulse-on time(Ton); 1-9µs, pulse-off time (Toff); 1-9µs and electrode rotational speed;130-160 rpm. Distilled water as a dielectric fluid is supplied at a pressure of 6 MPa through hollow electrode.In present machine tool, tubular electrode of maximum length 400mm and diameter ranging between 0.2mm to 3mm can be used.

In present work, tubular electrodes of Copper and Brass with diameter 1 mm and 0.5 mm are used for drilling holes in rectangular die steel plate having thickness of 13mm.The composition of die steel constitutes Cr; 12.5 %,C; 1.5 %,Mn; 0.6%, Si; 0.6%, Co; 1%, Mo; 0.9%, V; 1.10%, Ni; 0.3% and remaining Fe. The density and hardness of die steel are 7.7 g/cm$^3$ and 680 HV respectively.

### 2.2 Performance characteristics

In present experimentation, two performance namely drilling capability (DC) and diameter overcut (DOC) are measured. Drilling capability is taken as the ratio of drilling rate to that of electrode wear rate.

DC: drilling rate(DR) /electrode wear rate (EWR)

Where; DR: rate of drilling blind hole in workmaterial (mm/min.); EWR:rate of electrode wear in drilling a blind hole in a given work material (mm/min.). Length of electrode wear is calculated using a reference point on work surface and scale given on z-axis. The electrode wear rate is calculated by measuring the difference between length of electrode before and after drilling in a given time.

DOC represents the geometrical deviation in holes drilled at different parameters. DOC is calculated as difference in diameter of upper side of drilled hole and the outer diameter of tubular electrode. To calculate diameter of drilled hole, stereo microscope (magnification; 90 times) is used.

## 3. Selection of Process Variables and Experimental Design

Screening experiments were performed to select important process parameters and their effective range for experimentation using design of experiment approach. Screening experiments depicts that electrode material (Cu and Br)have noticeable influence on performance characteristics. Also, electrode geometry (i.e. diameter) show significant variation on performance characteristics correspond to same setting of input parameters. Low electrode rotation speed of 130 rpm resulted in high sparking and erosion; while at 160 rpm, minimum sparking was observed that makes the drilling process difficult. Therefore, in present work, a constant rotational speed of 145 rpm is taken for electrode. Based on screening experimentation, four process variables namely electrode material, Ip, Ton and Toff are selected. In present work, the effective variable range for Ip, ton, Toff is found as 3-9 Amp, 2-8 µs, 3-7µs respectively. Table 1 shows the selected process parameters and their values.

For electrode material, two levels are selected (i.e. Cu and Br) while Ip, Ton and Toff are kept at three levels. Therefore, a mixed orthogonal array ($L_{18}$) is used for experimentation as listed in Table 2. To evaluate the influence of electrode geometry (i.e. diameter) on performance characteristics, electrodes with two diameters 0.5 mm and 1 mm are selected. For both electrode geometries, experiments are performed according to the experimental plan mentioned in Table 2.

## 4. Results and Discussions

Experiments are performed randomly as per experimental design given in Table 2. Figure 4 shows the actual holes drilled in die steel. The influence of process variables and other important findings are discussed as follow.

Using $L_{18}$ orthogonal array mentioned in Table 2, holes are drilled and performance characteristics are calculated for two type of hole geometries (diameter 0.5 mm & 1mm) as listed in Table 3. Using Taguchi's methodology, process parameters are analysed for two performance characteristics.

Using Taguchi method, response tables are prepared to calculate the influence of each level of selected process parameters on performance characteristics. The average effect on drilling capability at level 1 of work material and Ip for 1 mm electrode is calculated as:

$A_{1=}$ (1.68+1.77+4.57+0.59+0.87+0.81+0.303+0.31)/9 =1.2926

$B_1$= (1.68+1.77+4.57+1.90+1.78+1.31)/6 =2.1683

Using this methodology, response tables for DC and DOC are obtained for holes drilling of 1mm and 0.5 mm as listed in Table 4 and 5 respectively.

### 4.1 Drilling capability (DC)

Fig 5 (a & b)and Fig 6 (a-b) show the mean effect plots for DC and DOC for electrodes of $\phi$ 1mm and $\phi$ 0.5mm electrode.

Figure 5 (a & b) shows the similar effect of process parameters on DC for both electrode geometries of diameter 1mm and 0.5mm. Comparing electrode geometry of diameter 1mm and 0.5mm, it can be observed that electrode of diameter 1mm results in higher DC as compared to electrode of diameter 0.5mm for all process parameters. It implies that electrode with larger diameter results into faster drilling with lower EWR.

Figure 5 (a & b) shows that copper electrode has better drilling capability as compared to brass electrode. DC is the ratio of drilling rate to EWR. In present experimentation, drilling rate was found better for brass electrode but at the same time EWR is very high in brass electrode as compared to copper electrode. Therefore, DC is lower for brass electrode.

Increasing Ip, DC decreases for both electrode geometries (1mm and 0.5mm). Increasing Ip, increases the rate of ionisation of spark gap results into high heat generation. With increasing heat generation, EWR increases remarkably as compared to drilling rate, thereby decreases DC. Increase in Ton value, increases the spark frequency which increases the melting of work material and electrode. Figure 6a &6b shows the wear in copper electrode (of diameter 1mm) atlow and high value of Ip respectively.

DC shows decreasing and then increasing trend with increasing value of Toff for 1mm electrode while in case of 0.5 mm electrode, D C increases with increasing Toff. Increase in Toff increases the time between two consecutive sparks, thereby flushing of melted and eroded particles becomes easier and quicker. At high Toff, EWR decreases due to more cooling effect of dielectric and hence DC increases.

DC is a "higher the better" type of characteristic, therefore based on response graph in Figure 5 (a & b), the highest value of DC can be obtained correspond to the parameter combination of $A_1$ (Cu), $B_1$ (3 amp.), $C_3$ (8μs) and $D_3$ (7μs) for both the electrode geometries of ϕ 1mm and ϕ 0.5mm.

### 4.2 Diametric overcut (DOC)

Figure 7 (a-b) represents the influence of process parameters on DOC for electrode of diameter 1mm and 0.5 mm. Comparing the Fig 7(a) and 7 (b), dissimilar effect of process parameter on DOCis observed for electrodes of different diameters.In case of drilling with electrode of diameter 1mm, Cu gives low DOC while for electrode of diameter 0.5 mm, Br gives low DOC. Figure 8 shows the magnified view of drilled hole using stereo microscope. DOC shows increasing trend with increasing Ip, but the ratio of increase in DOC is different for electrodes of two geometries.

Increasing Ip and Ton increases the primary and secondary sparking that over melts the upper side of hole and hence increases the diametrical over cut. Figure 9 shows the cu section of drilled hole using electrode of diameter 1 mm. Figure 9 shows the deterioration of top side of hole due to over melting caused by secondary sparking. Increasing Toff decreases the secondary sparing between work material and electrode that decreases the DOC.

DOC is "lower the better" type characteristic. The lower DOC can be obtained correspond to the parameters combination of $A_1$ (Cu), $B_1$ (3 amp.), $C_1$ (2μs) and $D_3$ (7μs) and $A_2$ (Br), $B_1$ (3 amp.), $C_1$ (2μs) and $D_3$ (7μs) for electrode geometries of ϕ 1mm and ϕ 0.5mm respectively.

## 5. Optimization of Multiple Performance Characteristics

DC is "higher the better" and DOC is 'lower the better" type of performance characteristics. Using Taguchi's methodology, it is difficult to optimize multi performance characteristics. In order to optimize DC and DOC simultaneously, grey relational analysis (GRA) can be utilized along with Taguchi method. The grey theory proposed by Deng (1982) has been proven to be useful for dealing with the problems with poor, insufficient and uncertain information. For multi characteristics optimization, GRA involves following steps (Lu et al., 2009; Chiang et al., 2009; Jangra et al. 2011):

- Conduct the experiments at different settings of parameters based on the orthogonal array.
- Normalize the mean values.
- Perform the grey relational generating and calculate the grey relational coefficient.
- Calculate the grey relational grade by using the weighing factor for the performance characteristics.
- Analyse the experimental results using the grey relational grade and statistical analysis of variance (ANOVA).
- Select the optimal levels of process parameters.

**Data pre-processing**

Data pre-processing is the first step in GRA. Data pre-processing involves transforming an original sequence into a comparable sequence. A series of various units must be transformed to dimensionless quantities. Experimental results are thus normalized in a range of 0–1. Usually, each series is normalized by dividing the data in the original series by their average.

Let the original reference sequence and sequence for comparison be represented as $x_o(k)$ and $x_i(k)$, $i$=1, 2, . . ., $m$; $k$ =1, 2, . . ., $n$, respectively, where $m$ is the 18 number of experiment to be considered, and $n$ is the 2 number of observation data. Data pre-processing converts the original sequence to a comparable sequence. Several methodologies of pre-processing data can be used in Grey relation analysis, depending on the characteristics of the original sequence

Drilling capability (DC) is a "larger-the-better" type of characteristic, therefore original sequence is normalized as given below:

$$x_i^*(k) = \frac{x_i^o(k) - min\, x_i^o(k)}{max\, x_i^o(k) - min\, x_i^o(k)} \quad (1)$$

Diametric overcut (DOC) is "smaller-the-better" type of characteristic; therefore, the original sequence is normalized as below:

$$x_i^*(k) = \frac{max\, .x_i^o(k) - x_i^o(k)}{max\, x_i^o(k) - min\, x_i^o(k)} \quad (2)$$

The notations $x^*_0(k)$ and $x^*_i(k)$refers sequence and comparability sequence, respectively. Table 6 shows the normalized data for DC and DOC.

The grey relational coefficient is calculated to express the relationship between the best (reference) and actual values. The grey relational coefficient is expressed using equation as given:

$$\gamma_{0,i}(k) = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{oi}(k)+\zeta.\Delta_{max}} \quad (3)$$

$$0<\gamma_{0,i}(k) \leq 1$$

Where
$\Delta_{oi}(k)$ = deviation sequence of reference sequence $x^*_o(k)$ and comparability sequence$x^*_i(k)$, i.e. $\Delta_{oi}(k) = | x^*_o(k) - x^*_i(k) |$ is the absolute value of the difference between $x^*_o(k)$and $x^*_i(k)$,
$\Delta_{min}$ =min. min.$\Delta_{oi}(k)$,
$\Delta_{max}$ =max. max.$\Delta_{oi}(k)$,

$\zeta$ is the distinguishing coefficients $\zeta \in |0, 1|$. $\zeta$ is taken as 0.5 in this study. The purpose of defining this coefficient is to show the relational degree between the reference sequences $x^*_o(k)$ and the comparability 18 sequences$x^*_i(k)$. where$i$ = 1, 2, 3…., $m$ and $k$ =1, 2,…., $n$ with $m$=18 and $n$=2 in this study.

Using Table 6, the deviation sequence $\Delta_{01}$ for data of ϕ 1 mm can be calculated as follows:
$\Delta_{o1}(1) = | 1.0000 - 0.331019 | = 0.668981$,
$\Delta_{o1}(2) = | 1.0000 - 0.804878 | = 0.195122$,

Similarly calculation has been performed for electrode of diameter 0.5 mm.
Using Table 7 and Eq. (3), the grey relational coefficient for geometry of ϕ 1 mm can be calculated as follows:

$$\gamma(x^*_o(1).x^*_1(1)) = \frac{0.0000 + 0.5 \times 1.0000}{0.668981 + 0.5 \times 1.0000} = 0.427723,$$

$$\gamma(x^*_o(2).x^*_1(2)) = \frac{0.0000 + 0.5 \times 1.0000}{0.195122 + 0.5 \times 1.0000} = 0.719298,$$

Similar calculation re performed for all 18 sequences for both electrode geometries of diameter 1mm and 0.5mm as listed in Table 8.

Grey Relational Grade
The grey relational grade is a weighting-sum of the grey relational coefficients. The overall evaluation of multiple performance characteristics is based on the grey relational grade. It is defined as follows:

$$\Gamma_{0,i} = \sum_{k=1}^{n} w_k \gamma_{0,i}(k), \quad i = 1,2,\ldots..m \quad (4)$$

$w_k$represent the weight of the $k^{th}$ machining characteristics, and $\sum_{k=1}^{n} w_k = 1$.

Table 8 shows the grey relational grade (GRG) for 18 sequences.

### 5.1 Optimization of process parameters

Optimization of the multiple performance characteristics can be converted into optimization of single grey relational grade. To separate out the effect of each process parameters on the grey relational grade at different levels, response graph for grey relational grade is constructed using the Taguchi methodology as shown in Figure 10 (a & b).

Basically, the larger the grey relational grade, the better is the multiple performance characteristics. The parameters combination of $A_2$ (Brass) $B_1$(3 amp.) $C_1$ (2μs) $D_2$ (7μs) and $A_1$ (copper) $B_1$(3 amp.) $C_1$ (2μs) $D_2$ (7μs) gives highest value of the grey relational grade for the electrodes of diameter 1mm and 0.5mm respectively.

The optimal values of the performance characteristics (DC and DOC) are predicted. In order to predict the optimal values of the machining characteristics, only significant parameters are included which affect the machining characteristics under 95% confidence levels. The optimal values are predicted by using equation 5.

$$\eta_{opt.} = \eta_m + \sum_{i=1}^{q}(\eta_i - \eta_m). \quad (5)$$

Where, $\eta_m$ = total mean of the machining characteristic under consideration;
$\eta_i$ = mean values of the optimum level and q = number of factors that significantly and affects the machining characteristics.

Analysis of variance (ANOVA) is performed on GRG data to analyse the significant parameters as listed in tables 9 and 10. From ANOVA tables only one process parameter namely discharge current (B) is found most significant affecting the GRG values under 95% confidence level (because $p \leq 0.05$) for both electrodes of diameter 1mm and 0.5 mm.

Using Tables 4 and 5 and equation (5), the optimal values for DC and DOC are predicted and confirmatory experiments are performed correspond to optimized parameters setting. Table 11 shows the predicted values and confirmatory values of DC and DOC.

## 6. Conclusions

In present work, the electrical discharge drilling process is used to drill holes of small diameter and high aspect ratio in die steel material. Based on screening experimentation, four process variables namely electrode material, Ip, Ton and Toff are selected for Taguchi's design of experiment method. For electrode material, two levels are selected (i.e. Cu and Br) while Ip, Ton and Toff are kept at three levels.

Two performance characteristics namely drilling capability (DC) and diameter overcut (DOC) are calculated. To evaluate the influence of electrode geometry (i.e. diameter) on performance characteristics, same experiments are performed with electrodes of two diameters 1 mm and 0.5mm.

Result shows that electrode with larger diameter results into faster drilling with lower EWR. Copper electrode shows better drilling capability as compared to brass electrode. Increasing Ip, DC decreases for both electrode geometries (1mm and 0.5mm). Increase in Ton value, increases the spark frequency which increases the melting of work material and electrode. At high Toff, EWR decreases due to more cooling effect of dielectric and hence DC increases.

In case of drilling with electrode of diameter 1mm, Cu gives low DOC while for electrode of diameter 0.5 mm, Br gives low DOC. DOC shows increasing trend with increasing Ip, but the ratio of increase in DOC is different for electrodes of two geometries. Increasing Ip and Ton increases the primary and secondary sparking that over melts the upper side of hole and hence increases the diametrical over cut. Increasing Toff decreases the secondary sparing between work material and electrode that decreases the DOC.

In order to optimize DC and DOC simultaneously, grey relational analysis (GRA) is utilized along with Taguchi method. The parameters combination of $A_2$ (Brass) $B_1$(3 amp.) $C_1$ (2μs) $D_2$ (7μs) and $A_1$ (copper) $B_1$(3 amp.) $C_1$ (2μs) $D_2$ (7μs) gives highest value of the grey relational grade for the electrodes of diameter 1mm and 0.5 mm respectively. Using Grey relational analysis along with Taguchi method, the problem of multi characteristics optimization can be solved easily.

## 7. Acknowledgment

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**Figures:**

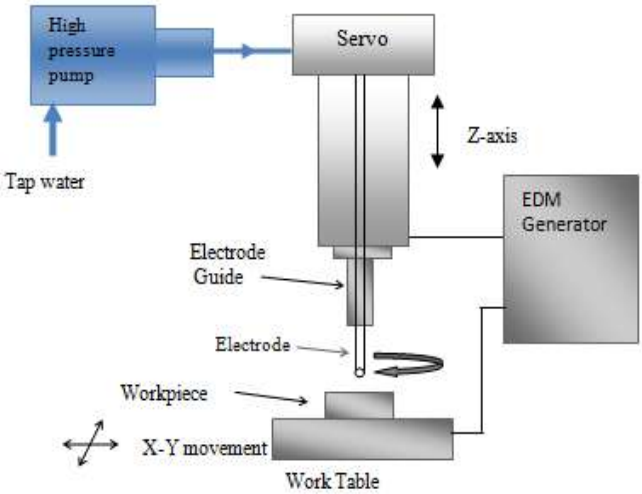



**Figure 1:** Schematic diagram of electric discharge drilling machine (Modified in Yilmaz et al. 2010)

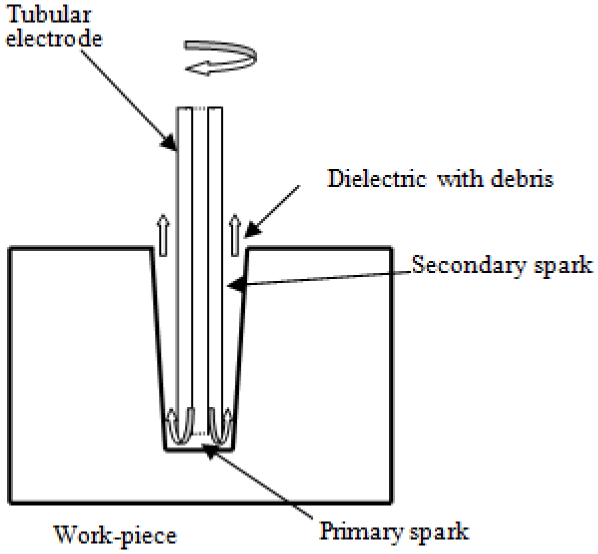



**Figure 2:** Schematic diagram of primary and secondary spark

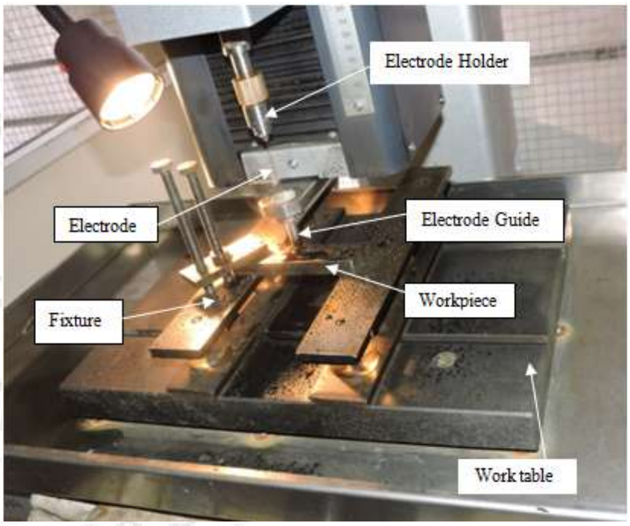



**Figure 3:** Detailed EDD setup

**Figure 4:** Specimen after EDD

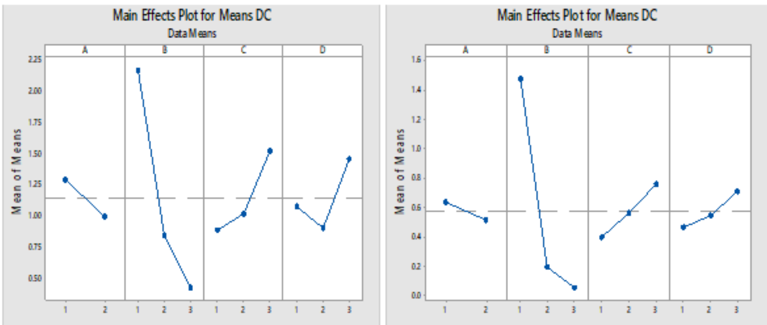



**Figure 5:** (a) Mean value of DC for 1 mm electrode **Figure 5:** (b) Mean of DC for 0.5 mm electrode

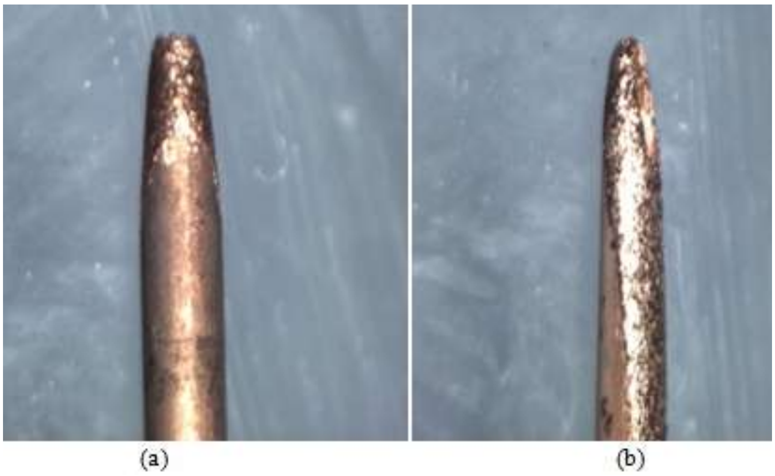



**Figure 6:** Electrode after drilling (a): Ip: 3 amp, Ton: 5 µs; Toff; 5µs (b) Ip: 6 amp, Ton: 8 µs; Toff; 5µs; Magnification 90x, zoom at 2

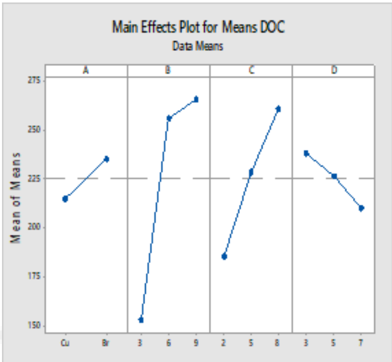



**Figure 7:** (a) Mean DOC for 1mm electrode

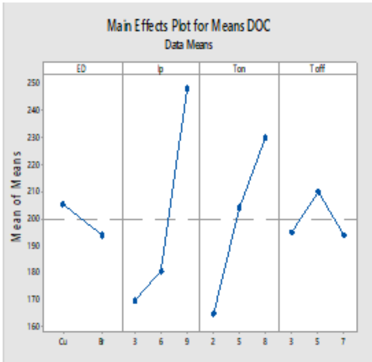



**Figure 7:** (b) Mean of DOC for 0.5mm electrode

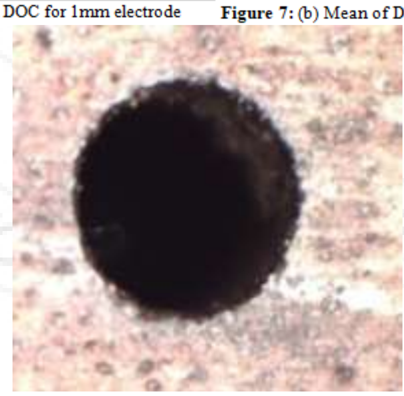


**Figure 8:** Top view of drilled hole using stereo microscope

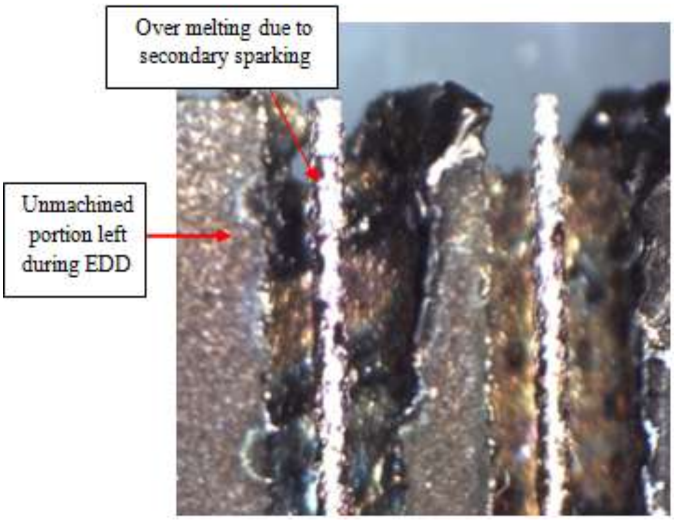
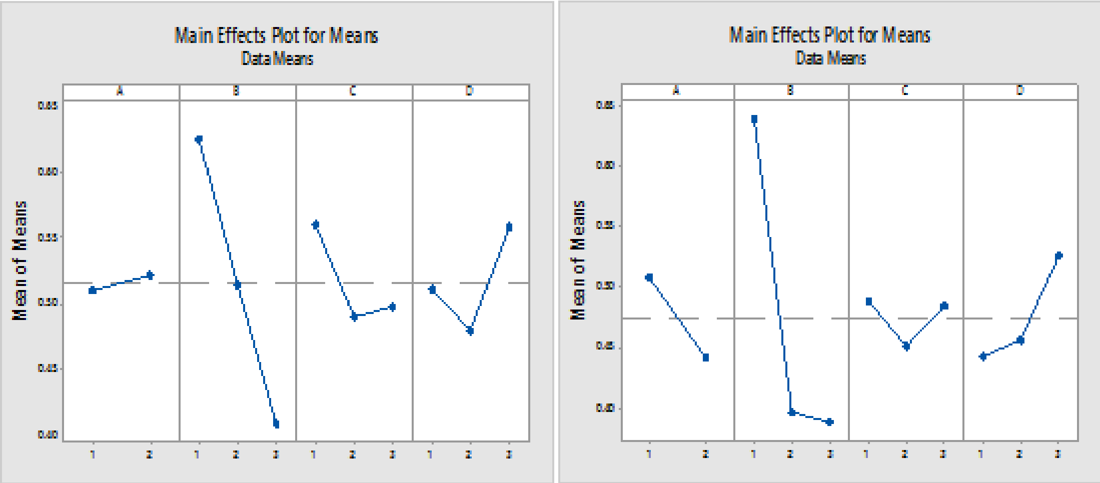



**Figure 9:** Cut section of hole drilled by tubular electrode




(a) (b)

**Figure 10:** Response graph for GRG (a) for electrode of diameter 1 mm (b) for electrode of diameter 0.5 mm

**Table**

**Table 1:** Process parameters and their levels

| Process parameter | Symbol | Levels | | |
|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 |
| Electrode material | A | Cu | Br | --- |
| Discharge Current (Ip), Amp. | B | 3 | 6 | 9 |
| Pulse on time (Ton), µs | C | 2 | 5 | 8 |
| Pulse-off time (Toff), µs | D | 3 | 5 | 7 |

**Table 2:** Experimental Design

| Exp. No | Work Material | Ip (Amp) | Ton (µs) | Toff (µs) |
|---|---|---|---|---|
| 1 | Cu | 3 | 2 | 3 |
| 2 | Cu | 3 | 5 | 5 |
| 3 | Cu | 3 | 8 | 7 |
| 4 | Cu | 6 | 2 | 3 |
| 5 | Cu | 6 | 5 | 5 |
| 6 | Cu | 6 | 8 | 7 |
| 7 | Cu | 9 | 2 | 3 |
| 8 | Cu | 9 | 5 | 5 |
| 9 | Cu | 9 | 8 | 7 |
| 10 | Br | 3 | 2 | 3 |
| 11 | Br | 3 | 5 | 5 |
| 12 | Br | 3 | 8 | 7 |
| 13 | Br | 6 | 2 | 3 |
| 14 | Br | 6 | 5 | 5 |
| 15 | Br | 6 | 8 | 7 |
| 16 | Br | 9 | 2 | 3 |
| 17 | Br | 9 | 5 | 5 |
| 18 | Br | 9 | 8 | 7 |



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**Table 3:** Mean values for DC and DOC

| Experiment No. | Trail No. | Electrode ϕ 1 mm | | Electrode ϕ 0.5 mm | |
|---|---|---|---|---|---|
| | | DC | DOC µm | DC | DOC µm |
| 1 | 3 | 1.68 | 165 | 0.90 | 120 |
| 2 | 7 | 1.77 | 185 | 1.68 | 150 |
| 3 | 8 | 4.57 | 220 | 2.70 | 90 |
| 4 | 9 | 0.59 | 155 | 0.16 | 270 |
| 5 | 6 | 0.87 | 200 | 0.10 | 245 |
| 6 | 4 | 0.81 | 215 | 0.104 | 295 |
| 7 | 5 | 0.303 | 210 | 0.073 | 185 |
| 8 | 2 | 0.31 | 255 | 0.025 | 270 |
| 9 | 1 | 0.73 | 245 | 0.024 | 310 |
| 10 | 18 | 1.90 | 125 | 1.13 | 140 |
| 11 | 16 | 1.78 | 145 | 1.23 | 180 |
| 12 | 15 | 1.31 | 180 | 1.22 | 240 |
| 13 | 17 | 0.63 | 155 | 0.12 | 190 |
| 14 | 11 | 0.92 | 170 | 0.29 | 257 |
| 15 | 12 | 1.24 | 190 | 0.409 | 280 |
| 16 | 14 | 0.25 | 180 | 0.034 | 210 |
| 17 | 13 | 0.46 | 270 | 0.088 | 270 |
| 18 | 10 | 0.52 | 330 | 0.105 | 350 |

**Table 4:** Response table for Drilling Capability (DC) for electrodes of ϕ 1 mm and ϕ 0.5mm

| | Electrode ϕ 1mm | | | | Electrode ϕ 0.5 mm | | | |
|---|---|---|---|---|---|---|---|---|
| Level | A | B | C | D | A | B | C | D |
| 1 | 1.292 | 2.168 | 0.892 | 1.080 | 0.6406 | 1.4766 | 0.4028 | 0.4685 |
| 2 | 1.001 | 0.843 | 1.018 | 0.900 | 0.5140 | 0.1971 | 0.5688 | 0.5496 |
| 3 | -- | 0.428 | 1.530 | 1.460 | -- | 0.0581 | 0.7603 | 0.7138 |

**Table 5:** Response table for diametric overcut (DOC) for electrodes of ϕ 1 mm and ϕ 0.5mm

| | Electrode ϕ 1mm | | | | Electrode ϕ 0.5 mm | | | |
|---|---|---|---|---|---|---|---|---|
| Level | A | B | C | D | A | B | C | D |
| 1 | 205.6 | 170.0 | 165.0 | 195.0 | 215.0 | 153.3 | 185.8 | 238.3 |
| 2 | 193.9 | 180.8 | 204.2 | 210.0 | 235.2 | 256.2 | 228.7 | 226.7 |
| 3 | -- | 248.3 | 230.0 | 194.2 | -- | 265.8 | 260.8 | 210.3 |

**Table 6:** Data Pre processing on mean value of DC and DOC

| Sr. No | **Electrode ϕ 1 mm** | | **Electrode ϕ 0.5 mm** | |
|---|---|---|---|---|
| | DC | DOC | DC | DOC |
| Reference sequence Comparability Sequence | 1.000 | 1.000 | 1.000 | 1.000 |
| 1 | 0.331019 | 0.804878 | 0.327354 | 0.884615 |
| 2 | 0.351852 | 0.707317 | 0.618834 | 0.769231 |
| 3 | 1 | 0.536585 | 1 | 1 |
| 4 | 0.078704 | 0.853659 | 0.050822 | 0.307692 |
| 5 | 0.143519 | 0.634146 | 0.028401 | 0.403846 |
| 6 | 0.12963 | 0.560976 | 0.029895 | 0.211538 |
| 7 | 0.012269 | 0.585366 | 0.018311 | 0.634615 |
| 8 | 0.013889 | 0.365854 | 0.000374 | 0.307692 |
| 9 | 0.111111 | 0.414634 | 0 | 0.153846 |
| 10 | 0.381944 | 1 | 0.413303 | 0.807692 |
| 11 | 0.354167 | 0.902439 | 0.450673 | 0.653846 |
| 12 | 0.24537 | 0.731707 | 0.446936 | 0.423077 |
| 13 | 0.087963 | 0.853659 | 0.035874 | 0.615385 |
| 14 | 0.155093 | 0.780488 | 0.099402 | 0.357692 |
| 15 | 0.229167 | 0.682927 | 0.143871 | 0.269231 |
| 16 | 0 | 0.731707 | 0.003737 | 0.538462 |
| 17 | 0.048611 | 0.292683 | 0.023916 | 0.307692 |
| 18 | 0.0625 | 0 | 0.030269 | 0 |

**Table 7:** Deviation sequence

| | Electrode ϕ 1 mm | | Electrode ϕ 0.5 mm | |
|---|---|---|---|---|
| Deviation sequences | $\triangle_{01}(1)$ DC | $\triangle_{01}(2)$ DOC | $\triangle_{01}(1)$ DC | $\triangle_{01}(2)$ DOC |
| No. 1, *i* =1 | 0.668981 | 0.195122 | 0.672646 | 0.115385 |
| No. 2, *i* =2 | 0.648148 | 0.292683 | 0.381166 | 0.230769 |
| No. 3, *i* =3 | 0 | 0.463415 | 0 | 0 |
| No. 4, *i* =4 | 0.921296 | 0.146341 | 0.949178 | 0.692308 |
| No. 5, *i* =5 | 0.856481 | 0.365854 | 0.971599 | 0.596154 |
| No. 6, *i* =6 | 0.87037 | 0.439024 | 0.970105 | 0.788462 |
| No. 7, *i* =7 | 0.987731 | 0.414634 | 0.981689 | 0.365385 |
| No. 8, *i* =8 | 0.986111 | 0.634146 | 0.999626 | 0.692308 |
| No. 9, *i* =9 | 0.888889 | 0.585366 | 1 | 0.846154 |
| No. 10, *i* =10 | 0.618056 | 0 | 0.586697 | 0.192308 |
| No. 11, *i* =11 | 0.645833 | 0.097561 | 0.549327 | 0.346154 |
| No. 12, *i* =12 | 0.75463 | 0.268293 | 0.553064 | 0.576923 |
| No. 13, *i* =13 | 0.912037 | 0.146341 | 0.964126 | 0.384615 |
| No. 14, *i* =14 | 0.844907 | 0.219512 | 0.900598 | 0.642308 |
| No. 15, *i* =15 | 0.770833 | 0.317073 | 0.856129 | 0.730769 |
| No. 16, *i* =16 | 1 | 0.268293 | 0.996263 | 0.461538 |
| No. 17, *i* =17 | 0.951389 | 0.707317 | 0.976084 | 0.692308 |
| No. 18, *i* =18 | 0.9375 | 1 | 0.969731 | 1 |

**Table 8:** Grey relational coefficients and GRG

| **Sr. No.** | **Electrode ϕ 1 mm** | | | **Electrode ϕ 0.5 mm** | | |
|---|---|---|---|---|---|---|
| | DC | DOC | Grey relation grade | DC | DOC | Grey relation grade |
| 1 | 0.427723 | 0.719298 | 0.573511 | 0.426386 | 0.8125 | 0.619443 |
| 2 | 0.435484 | 0.630769 | 0.533127 | 0.56743 | 0.684211 | 0.625821 |
| 3 | 1 | 0.518987 | 0.759494 | 1 | 1 | 1 |
| 4 | 0.351792 | 0.773585 | 0.562689 | 0.345023 | 0.419355 | 0.382189 |
| 5 | 0.368601 | 0.577465 | 0.473033 | 0.339766 | 0.45614 | 0.397953 |
| 6 | 0.364865 | 0.532468 | 0.448667 | 0.340112 | 0.38806 | 0.364086 |
| 7 | 0.336082 | 0.546667 | 0.441375 | 0.337453 | 0.577778 | 0.457616 |
| 8 | 0.336449 | 0.44086 | 0.388655 | 0.333416 | 0.419355 | 0.376386 |
| 9 | 0.36 | 0.460674 | 0.410337 | 0.333333 | 0.371429 | 0.352381 |
| 10 | 0.447205 | 1 | 0.723603 | 0.46011 | 0.722222 | 0.591166 |
| 11 | 0.436364 | 0.836735 | 0.63655 | 0.476496 | 0.590909 | 0.533703 |
| 12 | 0.398524 | 0.650794 | 0.524659 | 0.474805 | 0.464286 | 0.469546 |
| 13 | 0.354098 | 0.773585 | 0.563842 | 0.341501 | 0.565217 | 0.453359 |
| 14 | 0.371773 | 0.694915 | 0.533344 | 0.35699 | 0.43771 | 0.39735 |
| 15 | 0.393443 | 0.61194 | 0.502692 | 0.368697 | 0.40625 | 0.387474 |
| 16 | 0.333333 | 0.650794 | 0.492064 | 0.334166 | 0.52 | 0.427083 |
| 17 | 0.344498 | 0.414141 | 0.37932 | 0.338734 | 0.419355 | 0.379045 |
| 18 | 0.347826 | 0.333333 | 0.34058 | 0.340198 | 0.333333 | 0.336766 |

**Table 9:** ANOVA for grey relational grade for electrode ϕ 1 mm

| Source | DF | Seq SS | Adj SS | Adj MS | F-value | p-value |
|---|---|---|---|---|---|---|
| A | 1 | 0.000621 | 0.000621 | 0.000621 | 0.16 | 0.694 |
| B | 2 | 0.140567 | 0.140567 | 0.070283 | 18.54 | 0.000 |
| C | 2 | 0.017211 | 0.017211 | 0.008605 | 2.27 | 0.154 |
| D | 2 | 0.018583 | 0.018583 | 0.009291 | 2.45 | 0.136 |
| Error | 10 | 0.037918 | 0.037918 | 0.003792 | | |
| Total | 17 | 0.214900 | | | | |

**Table 10:** ANOVA for grey relational grade for electrode ϕ 0.5 mm

| Source | DF | Seq SS | Adj SS | Adj MS | F-value | p-value |
|---|---|---|---|---|---|---|
| A | 1 | 0.020026 | 0.020026 | 0.020026 | 1.44 | 0.258 |
| B | 2 | 0.244876 | 0.244876 | 0.122438 | 8.80 | 0.006 |
| C | 2 | 0.004949 | 0.004949 | 0.0024 | 0.18 | 0.840 |
| D | 2 | 0.023978 | 0.023978 | 0.011989 | 0.86 | 0.451 |
| Error | 10 | 0.139062 | 0.139062 | 0.013906 | | |
| Total | 17 | 0.432891 | | | | |

**Table 11:** Predicted and Confirmatory values of DC and DOC using GRA approach

| Electrode Geometry | Performance Characteristics | Optimal parameters | Predicted values | Experimental value |
|---|---|---|---|---|
| ϕ 1 mm | DC | $A_2B_1C_1D_3$ | 2.16 | 1.98 |
| | DOC | | 170 µm | 130 µm |
| ϕ 0.5 mm | DC | $A_1B_1C_1D_3$ | 1.47 | 1.39 |
| | DOC | | 153.3 µm | 144 µm |



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