Analysis of the Influence of EDM Parameters in Micro Hole Drilling of Titanium Wrought Alloy

Gosavi Vaibhav Y.*, Phafat Nitin G.
Department of Mech Engg, JNEC, Aurangabad, 431003, India.

* Corresponding author. Tel.: +919579442391; email: vaibhavgosavi10@gmail.com
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Abstract: The selection of adequate manufacturing conditions is one of the most important aspects to take into consideration in the Electrical Discharge Machining (EDM) of hard to cut metals, as these conditions are the ones those have decisive effect on important machining characteristics as: Material Removal Rate (MRR), Electrode Wear Rate (EWR) and the machining accuracy as: Overcut (OC), Taper (T). In this work, a study was carried out on the influence of the factors as: Current (I), Capacitance (C), Pulse on time (Ton) and Pulse off time (Toff) over the listed technological characteristics. The experiments were performed on titanium wrought alloy (VT-20) machined with hollow brass electrode. Accordingly, to obtain the optimal machining conditions techniques like Design of Experiments (DOE) and ANOVA were used. The Experimental results showed that using appropriate machining parameters; the diameter variation between entrances and exit of micro hole can be improved. Considerable amount of re-solidified material and burr were observed at high values of current which leads to secondary discharge and made significant effect on electrode wear. It was also observed that lower range of current and pulse on time gives better topographical condition for micro holes.

Key words: Micro EDM, ANOVA, Secondary discharge.

1. Introduction

Technological advances have facilitated many development in MEMS, electrical, medical, aerospace and other industries in recent years. As the devices in these industries are getting smaller, requirement of high precision machining techniques is being increasing. Nowadays, micro-machining processes are playing important role in satisfying these requirements. Among these processes, Micro Electrical Discharge Machining (Micro-EDM) is one of the most widely used machining processes in micro machining industry [1, 2]. It is contact less process hence, this technique is widely used to fabricate micro scale structure and components. Deep micro hole have a wide range of applications in industry. Common example include fuel injection nozzles, spinnerets nozzle holes, drug delivery orifices, inkjet printer nozzle, ejection pins or core for mould inserts, machining of micro cutting tools, biomedical filters and so on [3–8]. In this process the metal is removed from the work piece as a result of erosion caused by rapidly recurring spark discharge taking place between the electrode (tool) and workpiece. The thermal energy released is used for the material removal by melting and evaporation based on thermodynamic bulk boiling phenomenon [9]. It means that the EDM is basically a thermal process and the electric current supplied is an important factor. It has been reported in several studies that the process is time consuming, therefore difficult to apply for mass production [10, 11]. Electrode wear is another problem in EDM drilling, particularly in case of smaller and higher aspect ratio micro holes [11]. Moreover, a common problem of micro EDM during machining of deep micro holes is the circulation of dielectric and removal of debris from inter-electrode gap which increases overcut and result into tapered hole [12]. In this work, a study focused on the EDM drilling of titanium wrought alloy, whose field of applications is being increasing in aerospace industry. Consequently, an analysis on the influence of capacitance, current, pulse on time and off time over technological variables as the material removal rate, electrode wear rate, overcut and taper was performed. This was done with Design of Experiment (DOE) and techniques such as multiple linear regression analysis. Mathematical models were created, that made it possible to explain the variability associated with each of the technological variables studied in this work.

2. Experimentation

Experiments were performed for through micro hole machining using charmills robodrill machine shown in Fig 1. Rotary hollow tubular copper electrode of diameter 500 μm was fed downward into the workpiece under servo control. The EDM oil was circulated as a dielectric fluid and injected through the tubular electrode. The electro-conductive titanium wrought alloy (VT-20) was selected for study as, it has drawn special attention in aerospace industry, due to its excellent properties. [13]

Fig. 1. Micro EDM machine

Central composite half design (CCD) with 31 run was used to design experiments with an alpha value of 2. The working ranges of selected process variables were determined to fix their levels and to develop the design matrix. This was achieved by conducting preliminary experiments by using one variable at a time approach for the selection of parameter ranges. A large number of trial runs have been conducted at different machining parameters. The upper level of a factor was coded as +2 and the lower level as -2, the coded values for intermediate values were calculated from the following equation:

$$X_i = \frac{X - Xmin}{Xmax - Xmin} \quad \dots (1)$$

where, Xi is the required coded value of a variable X, X is any value of the variable from Xmin to Xmax, Xmin is the lower limit of the variable and Xmax is the upper limit of the variable.

$$X_1 = \frac{\ln C - \ln 0.26}{\ln 0.32 - \ln 0.26}, X_2 = \frac{\ln I - \ln 19}{\ln 20 - \ln 19}, X_3 = \frac{\ln T_{on} - \ln 16}{\ln 20 - \ln 16}, \quad X_4 = \frac{\ln T_{off} - \ln 16}{\ln 20 - \ln 16} \quad \ldots (2)$$

The coded values for intermediate levels have been calculated using equation (2). The selected process parameters of the experiment with their limits, units and notations, are given in Table 1.

Table 1. The Arrangement of Channels

	Unit	-2	-1	0	+1	+2
Capacitance (C)	μF	0.15	0.22	0.26	0.32	0.38
Current (I)	A	8	15	19	26	32
Pulse on time (Ton)	μsec	8	12	16	20	24
Pulse off time (Toff)	μsec	8	12	16	20	24

Experiments were conducted as per the design matrix and effect of process parameters on individual response was analyzed. MRR and EWR are used to evaluate machining performance while OC and T were used to evaluate machining accuracy. In this work, the MRR and EWR values were calculated by the weight difference of the workpiece and electrode, before and after undergoing the EDM process. The overcut of the micro-holes is the distance between the diameter of the machine hole and the electrode diameter that was measured with optical microscope. As the hole became taper, the overcut was taken from the average of entrance and exit side of the micro-holes. Difficulty in removing debris from inter electrode gap increases with increasing aspect ratio that causes secondary discharge and arching to side walls of holes. As a result the hole entrance becomes larger than exit. Taper angle of micro hole is measured as:

$$\Theta = \tan^{-1} \frac{(D_{top} - D_{bottom})}{2h} \quad \ldots (3)$$

where, Θ is taper angle, D_{top} is entrance diameter, D_{botton} is exit diameter and h is machining depth. [14]

3. Result and Discussion

Results are drawn based on experimental observations and analysis carried out with optical microscope images and the effect of selected process parameters on output is discussed. As EDM is thermal erosion process, increase in discharge energy accelerates thermally activated wear mechanisms. The discharge energy (E) per pulse can be expressed as

$$E = V_p I_P T_{on} \frac{1}{T_{on} + T_{off}} \quad \ldots (4)$$

$$E = V_p I_P \eta \quad \ldots (5)$$

where, V_p = the voltage of a single pulse, I_p = the current of single pulse, T_{on} = pulse on time, T_{off} = the pulse off time and η = duty cycle.

Therefore, the gap voltage, current and the duty ratio greatly influence the micro EDM process [15]. Pulse on time is duration that allows the current to flow per cycle. Total discharge energy (E) is proportionate to the amount of energy applied during this on time. Equation (5) indicates that along with voltage and current, duty cycle is also proportional to discharge energy, but this parameter is not perfectly independent of pulse off time. Since the pulse off time is needed sufficiently depending on power of a single pulse.

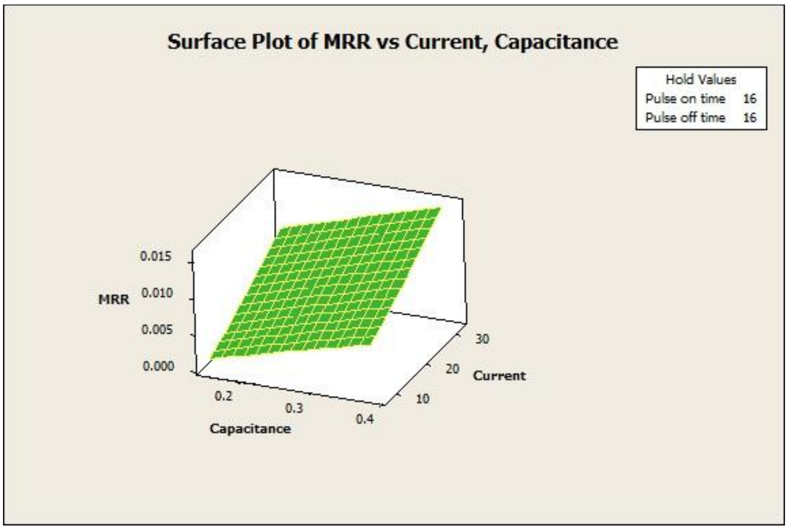
$$E = \frac{1}{2} C V^2 \quad \text{... (5)}$$

where, C = capacitance and V = gap voltage.

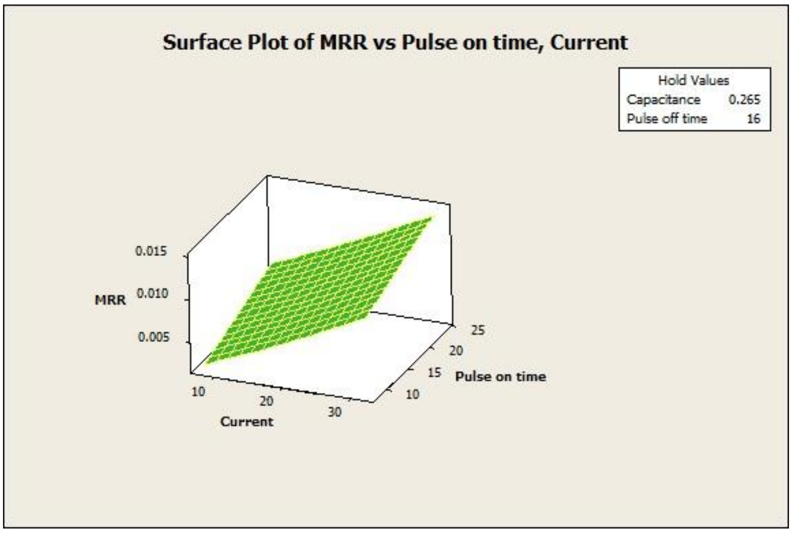
Capacitor controls pulse frequency of charging and dis-charging. Therefore, the performance of the micro-EDM is also influenced by the capacitance [16].

3.1. Analysis of Material Removal Rate

The effect of different process variables on MRR is shown in Fig. 2 (a) and (b) with response surface plots. It was observed that with the increase in capacitance, current and pulse on time MRR increases, while it decreases with increase in pulse off time. The increase in MRR with the increase in discharge current is due to the fact that the spark discharge energy goes beyond the dielectric strength to facilitate the action of melting and vaporization, and progressing the large impulsive force in the spark gap, thereby increasing the MRR. Therefore, the larger current results in deeper craters which increases the material removal.



(a)



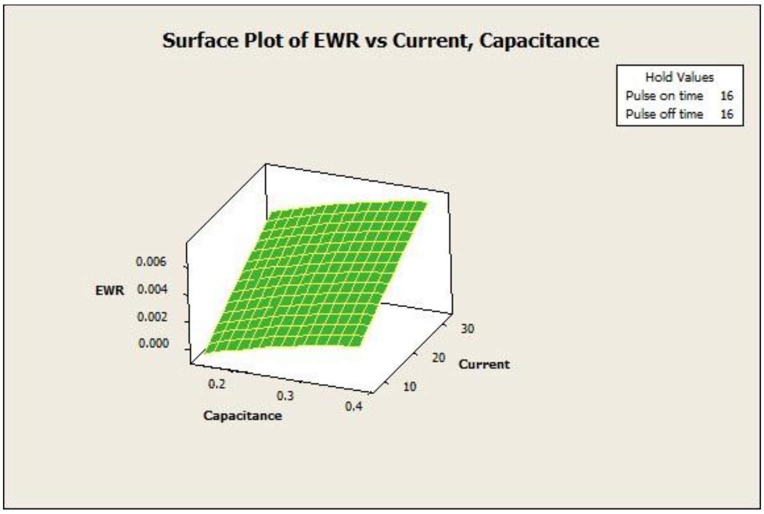
(b)

Fig. 2. Response surface plots for the interaction effects of input parameters on MRR

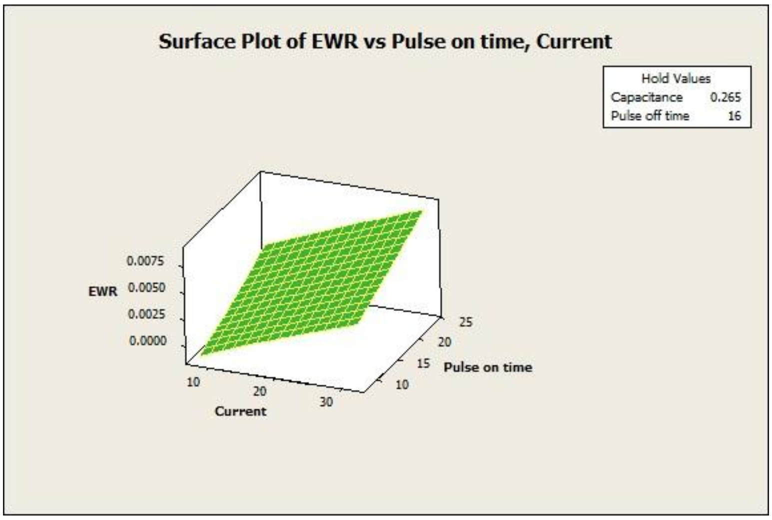
Proportional increase in MRR was observed with increase in capacitance. Premature sparking due to the change in capacitance results into variation in MRR. Pulse off time is the waiting interval time period during two pulses, it is the duration of time in which no machining takes place and it allows the melt material to vaporize and to escape from machining zone, hence increase in pulse off time results into decrease in MRR.

3.2. Analysis of Electrode Wear Rate

The effect of different process variables on EWR is shown in Fig. 3 (a) and (b) with response surface plots. It was observed that EWR increases initially with increase in capacitance and then decreases at higher capacitance. This is because, at low capacitance the time to charge the capacitor to full storage of energy is less. Hence time to charge capacitor is less compared to the time taken by electrode to achieve sparking gap. Whereas at high capacitance, the time to charge capacitor is higher and it is greater compared to the time taken to achieve the sparking gap. It result into variation of EWR with respect to capacitance. Proportional increase in EWR was observed with increase in, current and pulse on time, while it decreases with increase in pulse off time. Machining time reduces drastically with increase in discharge energy at the same time large amount of electrons are removed from electrode surface that result into simultaneous electrode wear.



(a)



(b)

Fig. 3. Response surface plots for the interaction effects of input parameters on EWR

Electrode wear mainly due to the high density electron impingement (electrical) and its thermal effect as well as due to the mechanical vibrations (shocks) generated by metal particles from the work material. Imperfections in the microstructure of electrode material also leads to electrode wear. The EDM process has byproducts such as debris and gaseous bubbles which fill the discharge gap, causing changes of gap conditions. Abnormal sparks such as arcing and short circuit results due to concentration of debris in this narrow discharge zone, resulting in extensive electrode wear.

In deep hole drilling, the electrode wear is comparatively higher than conventional micro EDM. The reason behind increase in electrode wear is due to increase in difficulty to remove the debris from machining zone with increase in aspect ratio. If debris are not removed properly, they causes secondary discharge in inter-electrode gap as a result electrode wears with increase in secondary discharge. Fig 4 show electrode wear due to secondary discharge in case of deep hole drilling.

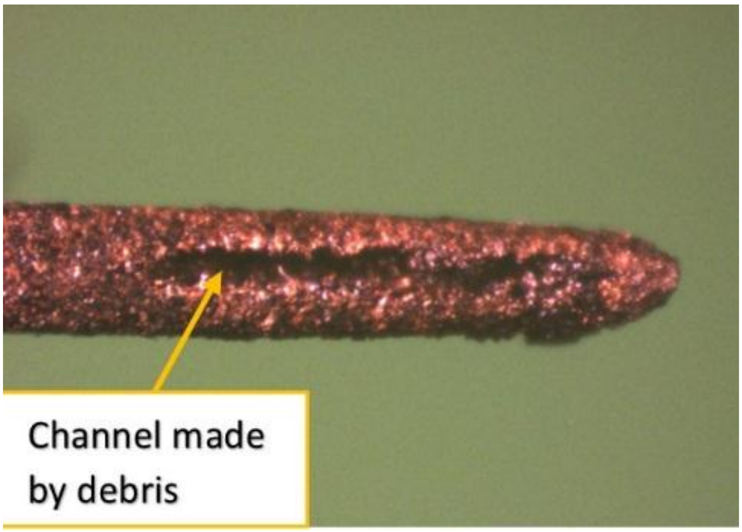
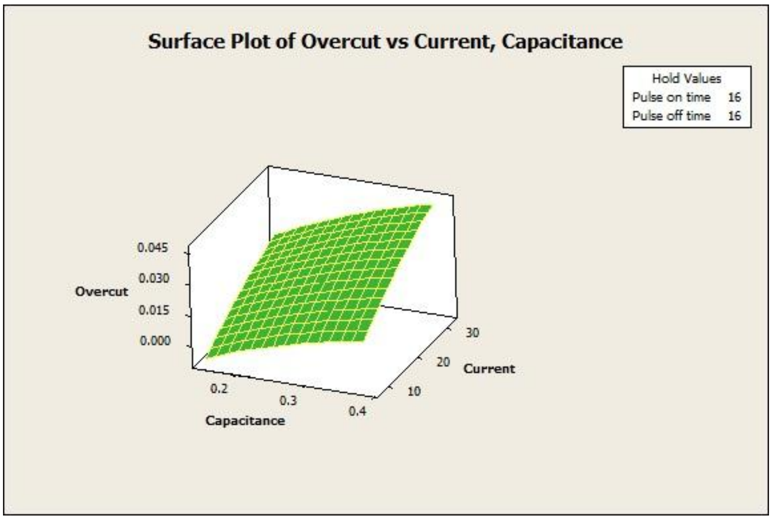


Fig. 4. Electrode wear due to secondary discharge

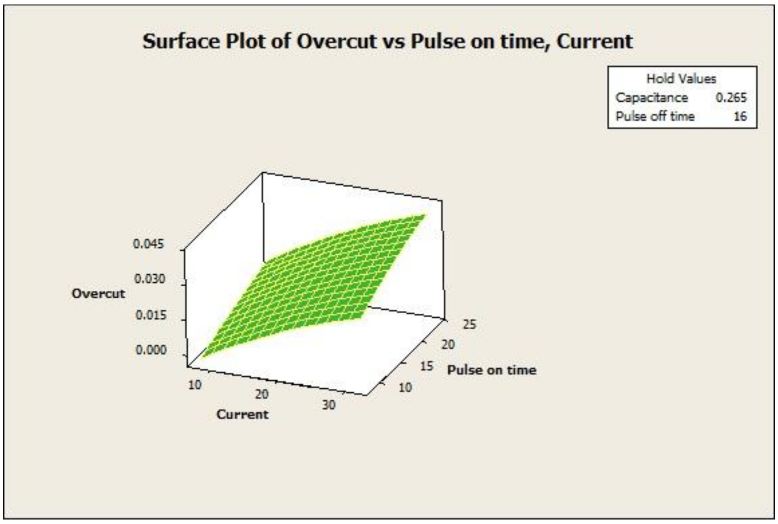
It can be seen that debris made channel inside the electrode to escape from machine zone under the dielectric pressure but with increased depth, flushing pressure become insufficient to remove debris and causes electrode wear. So with increase in discharge energy secondary discharge increases and results in electrode wear.

3.3. Analysis of Overcut

The effect of different process variables on overcut is shown in Fig. 5 (a) and (b) with response surface plots. It was observed that overcut increases initially with increase in capacitance and then decreases at higher capacitance. Proportional increase in overcut was observed with increase in current and pulse on time, while it decreases with increase in pulse off time. During the micro EDM drilling of small and high aspect-ratio micro-holes, the evacuation of debris becomes difficult from small working zone. The difficulty level increases with the increase of aspect ratio. If the debris cannot be removed from the machined zone appropriately, it causes secondary sparking and arcing at the side walls of micro holes. This phenomenon becomes dominant when the discharge energy is higher which results into deeper craters that increase the overcut. Overcut is less at low current, as at low current, erosion of material is less. As spark energy is low, the crater formed on the workpiece is small in depth and hence results in good dimensional accuracy. With increased pulse duration, more material is removed within shorter time and some debris does not get sufficient time to move out of inter-electrode gap, causes secondary spark and arching to side wall, results into increased overcut.



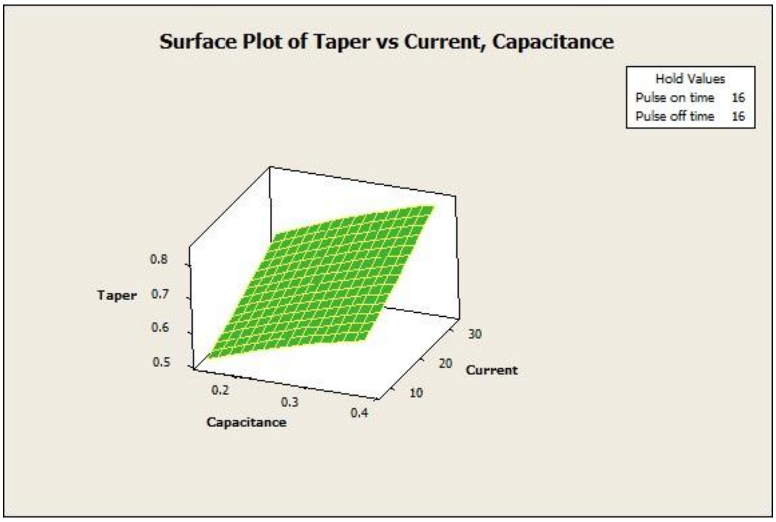
(a)



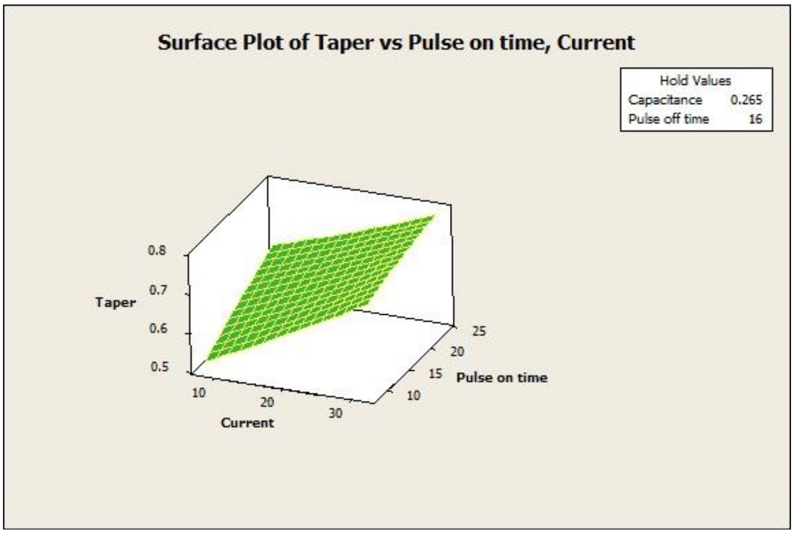
(b)

Fig. 5. Response surface plots for the interaction effects of input parameters on overcut

3.4. Analysis of Taper



(a)



(b)

Fig. 6. Response surface plots for the interaction effects of input parameters on taper

The effect of different process variables on taper is shown in Fig. 6 (a) and (b) with response surface plots. It was observed that with the increase in capacitance, current and pulse on time taper increases while it decreases with increase in pulse off time. The main reason for tapered hole is secondary sparking and arcing at the side walls of micro-holes. This phenomenon causes the entrance of micro holes to be larger and smaller hole at exit side. Smaller hole can be observed at exit side, as at the end of the drilling operation, the dielectric fluid escape through the hole exit. This reduces the total number of erosion particles suspended in the dielectric and hence reduces lateral secondary erosion. Also with increased discharge energy, electrode wears rapidly and takes hemispherical shape at the end. The tapered shape of electrode get replicated over workpiece which result into tapered hole. Therefore, the larger discharge energy results into increased taper.

4. Development of Mathematical Model

RSM is used to obtain the regression equation for MRR, EWR, OC and T that are influenced by process parameters namely capacitance, current, pulse on time and pulse off time. Using the experimental results obtained against all the set experimental conditions and ANOVA was followed, the following first order (linear) model has been developed for selected technological characteristics. Final model equations for MRR, EWR, OC and T in terms of coded values are:

$$\ln(MRR) = -0.0076 + 0.0256X_1 + 0.0003X_2 + 0.0002X_3 - 0.0001X_4 \quad \dots (6)$$

$$\ln(EWR) = -0.0070 + 0.0106X_1 + 0.0002X_2 + 0.0002X_3 - 0.00005X_4 \quad \dots (7)$$

$$\ln(Overcut) = -0.0385 + 0.099X_1 + 0.0012X_2 + 0.0009X_3 - 0.0003X_4 \quad \dots (8)$$

$$\ln(Taper) = 0.312 + 0.619X_1 + 0.0074X_2 + 0.0056X_3 - 0.00279X_4 \quad \dots (9)$$

These are the first order model. By substituting above equations into equation (2), the model finally can be expressed as:

$$\mathrm{MRR} = 1.161\mathrm{X}_1^{0.1233}\mathrm{X}_2^{0.001148}\mathrm{X}_3^{0.001121}\mathrm{X}_4^{0.000578} \quad \dots (10)$$

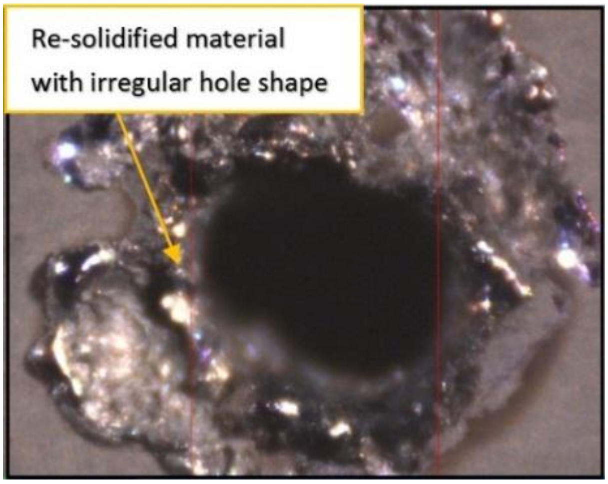
$$\mathrm{EWR} = 1.0617\mathrm{X}_1^{0.051}\mathrm{X}_2^{0.001}\mathrm{X}_3^{0.001}\mathrm{X}_4^{0.0002} \quad \dots (11)$$

$$\mathrm{Overcut} = 445583.08\mathrm{X}_1^{0.4812}\mathrm{X}_2^{0.0038}\mathrm{X}_3^{0.0041}\mathrm{X}_4^{0.0015} \quad \dots (12)$$

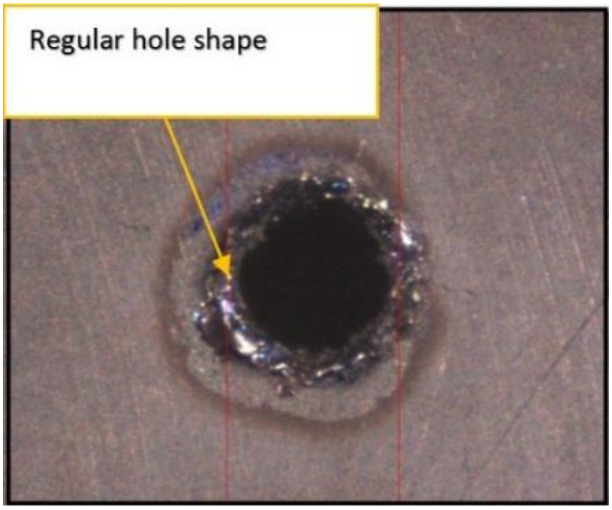
$$\mathrm{Taper} = 68.1301\mathrm{X}_1^{2.9816}\mathrm{X}_2^{0.0238}\mathrm{X}_3^{0.025}\mathrm{X}_4^{0.0125} \quad \dots (13)$$

5. Analysis Based on Optical Microscope Images

The effect of parameters on micro-hole shape can be clearly observed from images of machined holes under different parametric combination. After analyzing all images, the effect of each parameter has been identified individually and it was found that, lower range of peak current and pulse on time, gives better topographical condition of micro holes. Fig. 7 shows Images of machined micro holes under two different parametric combination.



(a) 0.26 μF/ 8 A/ 8 μs/ 8 μs



(b) 0.26μF/ 32 A/ 16 μs/ 16 μs

Fig. 7. Holes shapes at high and low values of current, using 500 μm diameter brass electrodes.

The poorer surface quality of the micro holes was obtained at higher current values, which results in a surface characterized by a relevant amount of irregularities and debris. On the other side, for the lower values of current, the surface results to be more regular and with less burrs. This could be due to the more aggressive parameter combination adopted for the machining and improper flushing out of debris that increases the probability of obtaining micro-holes with rougher edge. Moreover, due to insufficient time allowed for flushing of the debris from machined zone causes the debris particles to re-solidify near to the micro holes edge. Fig. 7 (a) shows that, the surface of micro hole has relatively less burrs and re-solidified material on the micro holes edge. On the other side, micro holes executed with higher current value Fig. 7 (b) are characterized by a considerable amount of re-solidified material and burrs on both the edge as well as the inner surfaces of the micro holes. This phenomenon could be due to the dimension of the debris removed by each electrical discharge. As brass has a much lower melting point than other electrode material, it is possible to state that more material was melted and removed, therefore larger debris and melted material could float and re-solidified in the working zone.

6. Conclusion

This work deals with the micro hole machining under different parameter combinations with micro EDM. The influence of operating parameters on the final output was investigated. Based on the findings, the conclusions can be drawn as:

1. In the case of MRR, the most influential factor was current, followed by the capacitance, the pulse on time, while the pulse off time was relatively insignificant at the considered confidence level. The MRR increased, as would logically be expected, when current and pulse on time were increased, while an increase in pulse off time brought about a decrease in MRR.

2. In the case of EWR, it was seen that the current was the most influential, followed by capacitance, the pulse on time and the pulse off time. It was found that with increase in secondary discharge, electrode wear increases. Due to insufficient flushing condition in high aspect ratio drilling, it was found that debris made channel and cause electrode wear.

3. In the case of the overcut, the most influential factors were current, followed by the capacitance, the pulse on time and the pulse off time. With increase in current and capacitance increase in overcut was observed.

4. Finally, in case of taper, it was observed that the most influential factor was once again current, followed by the pulse on time, the capacitance and the pulse off time. The experiments with higher electrode wear value shows higher overcut as a result of tapered shape attained by electrode during the machining.

5. From the observations, lower range of peak current and pulse on time, gives better topographical condition of micro holes.

Acknowledgment

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Vaibhav was born in Satana district in Maharastra, India. He has obtained Bachelor of engineering and Master's Degree in Production and manufacturing Engineering from KKWIEER, Nasik and JNEC, Aurangabad, Maharastra, India in the year 2012 and 2015 respectively. He has 3 year experience and working as assistant professor in JNEC, Aurangabad, Maharastra, India. His area of interest is advance manufacturing processes and micro machining.

Nitin was born in Akola district in Maharastra, India. He has obtained Bachelor of engineering and Master's Degree in Industrial Engineering from VNIT, Nagpur, and Ph.D.(Mechanical Engineering) from Aurangabad, India in the year 2006 and 2014 respectively. He has 20 years of experience and working as associate professor in JNEC, Aurangabad, Maharastra, India. His area of interest is advance manufacturing processes and micro machining.