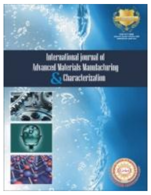

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Study of Micro Hole Characteristics on Al 1100 During MEDM – an Empirical Approach

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A B S T R A C T

Dependency of dimensional characteristics of micro structures on machining conditions in a process like micro EDM (μEDM) has been widely reported by various researchers. In this paper, attempt to generate empirical models that give idea about the accuracy level of the micro holes drilled on Al 1100 sheets during micro ED drilling using tungsten rods of 300μm diameter as electrode has been made. Dimensional accuracy of the holes has been quantified in terms of radial overcuts at top and bottom side and taper angle of the micro hole. The models have been generated using non-linear regression based on Gauss Newton method. The data required for the model generation has been generated from experiments conducted on the basis of Taguchi method using L16 orthogonal array with Gap voltage, Capacitance, Pulse ON time, Aspect ratio and Electrode rotation as input parameters. The prediction based on the generated models has been verified with randomly selected set of experiments and are found to be in reasonably good agreement with the experimental results.

Introduction

Electro discharge machining is a thermo electric process, which has the capability to machine any conductive materials regardless of their mechanical and chemical properties. The process capability of electro discharge machining in the field of miniaturization was first demonstrated by Kurafuji and Masuzawa in 1968 [1]. Promising applications are not limited to the machining of hard materials for micro moulds, but also include the production of difficult to make features such as fuel injection nozzles, spinneret holes for synthetic fibres, electronic and optical devices, micro mechatronic actuator parts, and micro tools for producing these devices [2-3].Even though the energy transfer mechanism has been complex and is difficult to visualize, a number of attempts has been made to develop models for the same. Theoretical micro EDM models based on thermal concepts has been developed by researchers for the prediction of responses like micro crater dimension [4-6], surface roughness [7], profile generation [8] etc.

The effect of different machining process parameters in micro EDM on dimensional quality of the micro holes generated has been reported by many researchers. Machining parameters like voltage, capacitance [9], peak current, pulse ON time [10, 11] etc. has been reported to have effect on dimensional quality of micro entities during micro EDM. Effects of electrode polarity, rotation [12], thermal and electrical properties of work piece material [13, 14] have also been reported. Other than overcut and taper angle, qualitative studies like circularity, surface roughness of micro holes were also a done by researchers [14, 15].

Even though modelling for energy transfer mechanism has been attempted by many researchers, relatively less work has been done in the development of mathematical models that predict the quality of the micro hole generated by micro EDM process. So the objective of this paper is to develop mathematical models that predict the values for radial overcut at top and bottom side of the micro hole and taper angle which are detrimental to the quality and accuracy of micro holes. The data for developing mathematical models have been used from the prior work published by the same authors in [16].

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Details of Experimentation

Parameter Selection

Three electrical and two non-electrical parameters are considered in this study, which are Gap voltage (V), Capacitance (C), Pulse ON time (t_{ON}), Aspect ratio (l/d) and Electrode rotation (R). Each parameter is considered with 4 levels and values pertaining to each parameter level are tabulated in Table I. All parameters except aspect ratio are set on the micro machine tool through graphical user interface. The variation of aspect ratio is done by performing through-hole drilling using electrode of same diameter on sheets of different thickness. For experimental planning, L16 orthogonal array which can accommodate five factors with four levels has been used and “smaller the better” condition (SB) has been used for calculating Signal to noise ratios (S/N ratios) of all response characteristics [17].

TABLE I. PARAMETERS AND THEIR LEVELS

Parameter		Levels			
		1	2	3	4
V	(V)	75	100	125	150
C	(pF)	33	100	1000	10000
t_{ON}	(µs)	20	40	60	80
(l/d)	-	0.93	1.26	1.76	2.36
R	(rpm)	0	500	1000	1500

Response selection

Radial overcut at top and bottom ends and taper angle of the micro hole have been selected as the response characteristics to quantify the quality of micro holes. Radial overcut at both top and bottom has been calculated by deducting the radius of the electrode used for drilling from the radius value of the micro hole at top and bottom. Taper in a micro hole drilled occurs due the diameter variation of the hole from entrance to exit. Fig. 1 (a-b) shows the schematic diagram of top and bottom radial overcuts and taper angle measurements.
The mathematical formulas used for the calculation of these responses are shown below:

Radial overcut at top and bottom:

$$OC_{top/bottom} = \left(\frac{D_{top/bottom} - D_{electrode}}{2} \right) \quad (1)$$

Taper Angle in degrees:

$$\theta = \tan^{-1}\left(\frac{D_{top} - D_{bottom}}{2t} \right) \quad (2)$$

where,

$OC_{top\ or\ bottom}$	=	Radial Overcut at top or bottom
θ	=	Taper angle
$D_{top/bottom}$	=	Diameter of the micro hole at top/bottom
$D_{electrode}$	=	Diameter of the Electrode used
T	=	Thickness of the work piece

Experimental procedure

The experiments are conducted at different conditions as per experiment design using Hyper 15 C brand table top type micro machine tool (Fig. 1(c)). Each experiment has been repeated three times. Aluminium sheets of thicknesses 0.28mm, 0.38mm, 0.53mm and 0.71mm are used as work piece material and pure tungsten rod of diameter of 300µm diameter is used as electrode. The aluminium work piece cut into required dimension are placed flat and perfect using a spirit level and positioned properly using magnetic pins. The electrodes used for drilling has been cut into pieces using a foil based micro EDM technique (Fig. 1(d))[16]. The micro holes and electrodes after machining are visually inspected and the top and bottom diameters of the micro holes have been measured using Sipcon’s vision measurement system. Fig. 2 and Table II show the selective images of micro holes generated during experimentation and the details for each of the response characteristic respectively.

Empirical Modelling

The modelling has been done using the mean values of output responses viz. top and bottom radial overcuts and taper angle. The general expression for the mathematical models has been formulated as under:

$$y = A(X_1)^{a_1}(X_2)^{a_2}(X_3)^{a_3}(X_4)^{a_4}(X_4)^{a_5} \quad (3)$$

where;
y = response variable,
X_1, X_2… = predictors or parameters considered,
a_1, a_2… = power indices of respective predictors or parameters and A = constant.

The above non-linear equation can be converted into linear form by logarithmic transformation as shown below:

$$\log y = \log A + a_1 \log X_1 + a_2 \log X_2 + a_3 \log X_3 + a_4 \log X_4 + a_5 \log X_5 \quad (4)$$

Equation (4) can be re written as,

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 \quad (5)$$

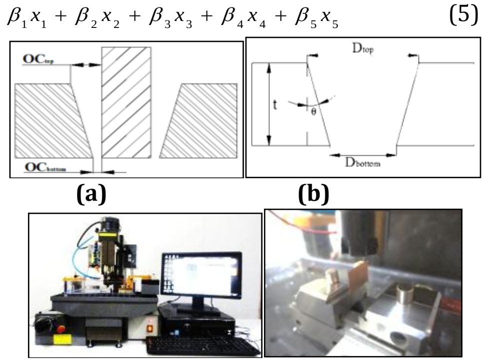


Figure 1. Schematic diagrams showing (a) Top and Bottom radial overcuts, (b) Taper angle, (c) Micro machine tool, (d) Electrode cutting using copper foil.where;

$\hat{y}$ = true value of the response variable on a logarithmic scale,

x_1,x_2,x_3,x_4,x_5 = logarithmic transformations of input parameters,

β_0, β_1, β_2, β_3, β_4, β_5 = corresponding parameters to be estimated.

Gauss Newton method can be used to estimate the parameters of the first order model shown above using the response values and the input parameter value sets used for experiment design. The equation obtained has been cross checked by mathematical models generated using trial version of Minitab 16 software. The empirical relations obtained for each of the response are shown in Table III. Adequacy of the models has been checked by calculating Mean error (E_{mean}), Standard deviation (σ_{dev}) and Average percentage error ($\%E_{avg}$). The equations used are shown below:

Mean Error $$E_{mean} = \frac{1}{N}\sum_{i=1}^{n}\left(y_i - y_{exp}\right)$$

(6)

Standard deviation $$\sigma_{dev} = \sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(y_i - \mu\right)^2}$$

(7) Average % Error

$$\%E_{avg} = \frac{1}{N}\sum_{i=1}^{n}\left(\frac{y_i - y_{exp}}{y_i}\right)\times 100 \qquad (8)$$

where;
y_i = response value generated using the model
y = corresponding response value obtained through experiment
μ = average of response values obtained using model
$= \frac{1}{N}\sum_{i=1}^{n} y_i$
N = number of observations

Table IV shows the results of error analysis done on the mathematical models developed. It has been observed that the values of E_{mean} and σ_{dev} are low for all the models. This shows that the models are satisfactory for predicting radials overcuts and taper angle. The limitation of these models is none of these models are applicable for a machining condition with stationary electrode. So the adequacy check has been performed after avoiding those set of readings which are obtained at condition of zero rpm of electrode.

The models have been validated by conducting experiments based on randomly selected machining parameters and comparing the response characteristics measured with those predicted by the mathematical models. It has been observed that the models for top and bottom and overcut showed more accuracy in predicting the response values. Prediction of taper angle using the model has not found to be satisfactory. Calculation of taper angle depends on top and bottom diameters of the micro holes machined which are already affected by noise and thus both of them could be slightly erroneous. So the dependence of taper angle on such two entities could be the reason for relatively inaccurate prediction of the same.

Fig 3 to 5 shows the variation of each of the response characteristic value generated using the models formulated with respect to machining parameters considered in this study. The gap voltage and capacitance have been varied considering the remaining parameters – pulse ON time, Aspect Ratio and Electrode rotation – at its minimum and maximum values considered for this study. In case of electrode rotation, the lowest value has been considered as 500rpm as the condition of stationary electrode (ZERO rpm) cannot be included in the type of equations modelled in this study. Simple lines and dotted lines shown in the graphs corresponds to plots of data generated using machining parameter combination with minimum and maximum values of pulse ON time, aspect ratio and electrode rotation respectively.

From Fig. 3, it has been observed that top radial overcut increases with increase in gap voltage and capacitance. The response has observed to be the maximum when all the parameters are at their maximum values and observed to decrease with decrease in capacitance and gap voltage for a set of pulse ON time, aspect ratio and electrode rotation. The increase in top overcut with increase in gap voltage may be because of the increased ionization effect that happens inside the discharge channel which leads to increase in discharge channel width. The longer sustainability of the discharge column at higher discharge energies could also be a reason [18]. With a longer duration of discharge, the electrons released from the negative poles will collide with the neutral particles in the dielectric fluid, resulting in greater ionization effect. The greater the number of electrons and ions colliding with the work piece, the bigger the micro hole expansion. As it becomes difficult to remove all the debris from the hole using side flushing, there is more chance of increasing the width of discharge channel in addition to secondary sparking like short circuiting and arcing during micro ED drilling [14]. It has also been observed that increase in electrode speed also lead to increase in top radial overcut. This could be because of the secondary sparking caused by the debris particles movement facilitated by electrode rotation in the upward direction through the hole.

In the case of bottom radial overcut, maximum response has been observed when all the parameters are maximum and is observed to decrease with decrease in the non-electrical parameters and pulse ON time for a capacitance value (Fig. 4). It has been observed that the electrode wear has been the maximum at low discharge conditions. At lower gap voltage conditions, the time required for machining is very high, which will lead to more exposure of electrode to machining condition. Also at lower voltage conditions, the spark gap will be on the lower side, soflushing will be difficult issue. So, excessivemachining time and arcing because of debris accumulation may be the reason for high electrode wear at low gap voltage conditions [14, 19].

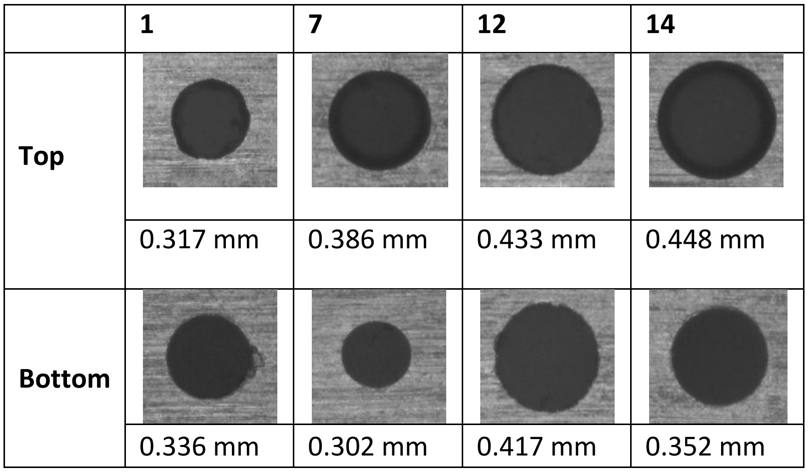


Figure 2. Micro Holes drilled on 0.28mm thick Aluminium sheet.

TABLE II. SIGNAL TO NOISE RATIOS AND MEAN VALUES FOR THE RESPONSE CHARACTERISTICS

Exp No.	V	C	t_{ON}	l/d	R	η_{OCtop}	Mean OC_{top}	$\eta_{OCbottom}$	Mean OC_{bottom}	η_{θ}	Mean θ
1	75	33	20	0.93	0	40.099	0.0098	34.654	0.019	-4.996	-1.773
2	75	100	40	1.26	500	23.900	0.0628	28.813	0.036	-13.092	4.11
3	75	1000	60	1.76	1000	22.481	0.0703	34.909	0.007	-17.002	6.861
4	75	10000	80	2.36	1500	22.122	0.0780	30.879	0.026	-12.457	4.175
5	100	33	40	1.76	1500	23.392	0.0617	26.179	0.029	-12.319	3.576
6	100	100	20	2.36	1000	23.140	0.0695	31.486	0.002	-15.132	5.426
7	100	1000	80	0.93	500	26.747	0.0450	37.51	0.010	-17.262	7.223
8	100	10000	60	1.26	0	36.094	0.0157	39.854	0.010	1.555	0.829
9	125	33	60	2.36	500	22.562	0.0737	29.475	0.025	-12.175	3.933
10	125	100	80	1.76	0	36.659	0.0147	42.974	-0.001	-5.29	1.711
11	125	1000	20	1.26	1500	25.603	0.0478	28.626	0.031	-8.201	2.536
12	125	10000	40	0.93	1000	23.518	0.0660	24.658	0.058	-4.552	1.636
13	150	33	80	1.26	1000	21.447	0.0842	25.711	0.051	-14.154	4.936
14	150	100	60	0.93	1500	23.926	0.063	34.524	0.016	-19.881	9.579
15	150	1000	40	2.36	0	35.662	0.016	33.483	-0.013	-8.208	2.325
16	150	10000	20	1.76	500	22.061	0.0778	23.389	0.067	-1.784	1.171

TABLE III. EMPIRICAL MODELS DEVELOPED FOR RESPONSE CHARACTERISTICS

Response Variable	**Mathematical Model**
Top radial Overcut	$OC_{top} = 0.006 \times V^{0.331} \times C^{0.015} \times t_{ON}^{0.131} \times (\frac{l}{d})^{0.356} \times R^{0.011}$
Bottom radial Overcut	$OC_{bottom} = \frac{4.631 \times 10^{-7} \times V^{1.934} \times C^{0.159} \times t_{ON}^{0.216} \times (\frac{l}{d})^{0.252}}{R^{0.006}}$
Taper angle	$\theta = \frac{2.513 \times t_{ON}^{0.574} \times R^{0.337}}{V^{0.674} \times C^{0.089} \times (\frac{l}{d})^{0.720}}$

TABLE IV. RESULTS FOR ERROR ANALYSIS ON MATHEMATICAL MODELS

	OC_{top}	OC_{bottom}	θ
E_{mean}	-0.0029	-0.0005	-0.0417
σ_{dev}	0.0076	0.0157	1.8202
$\%E_{avg}$	-4.6007	-15.1018	-5.4840

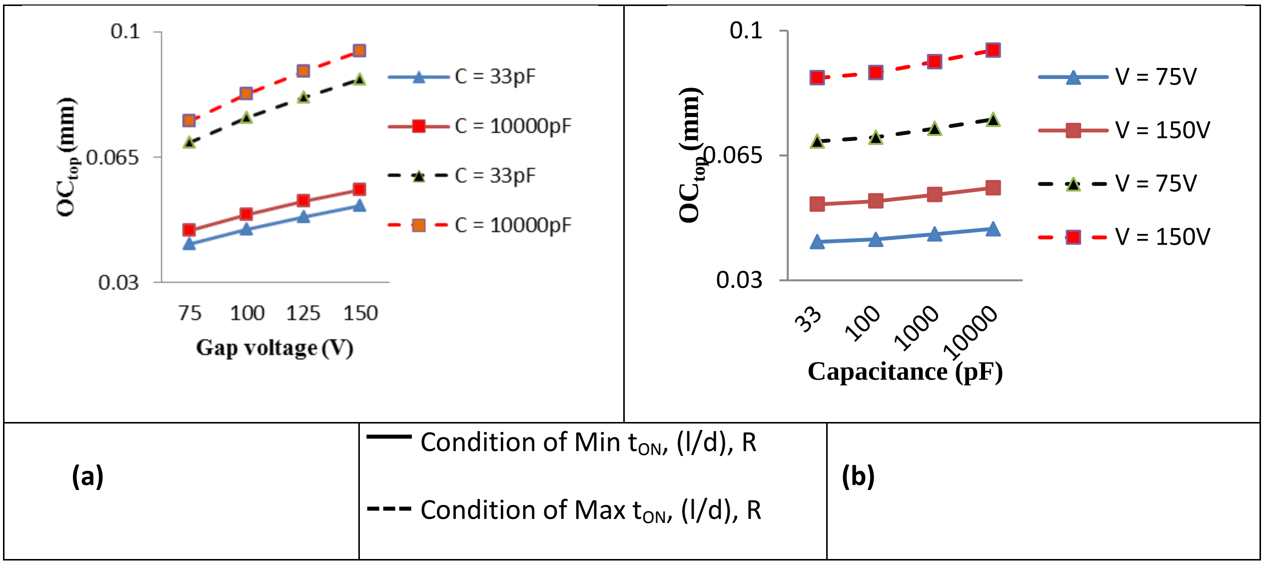
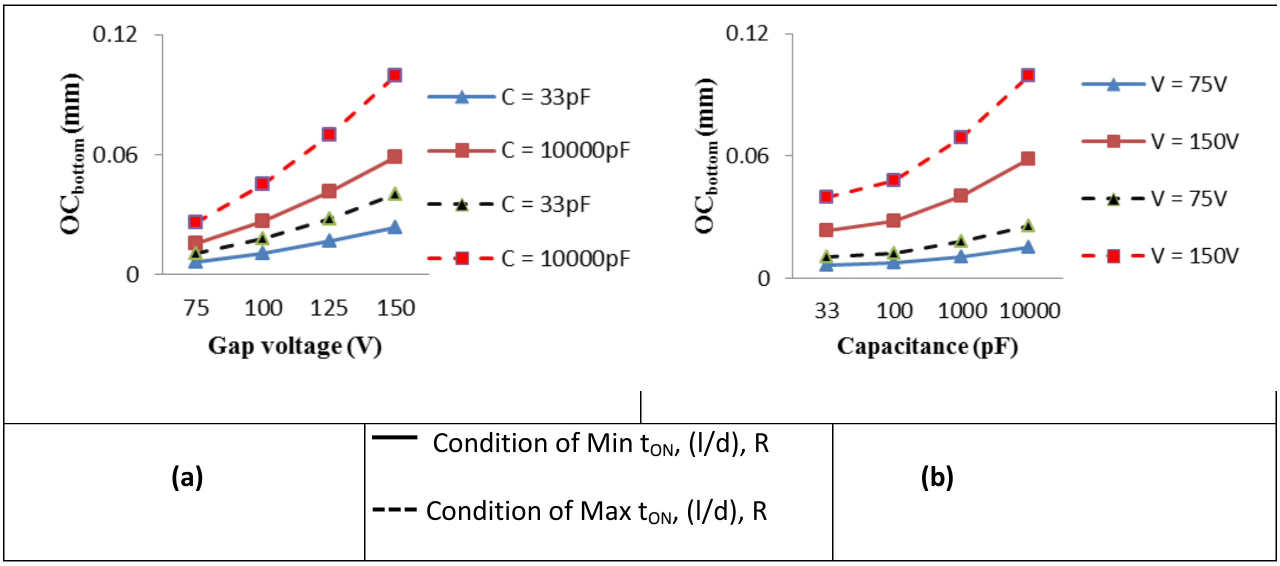


Figure3. Effect of gap voltage and capacitance on Top radial overcut



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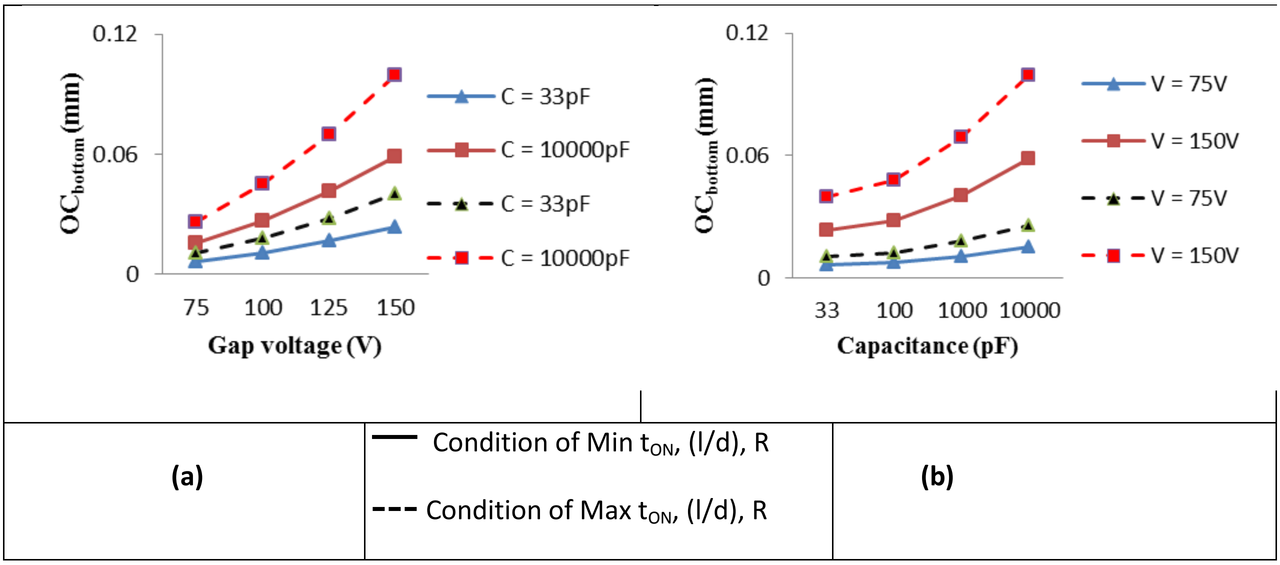

Figure 5.Effect of gap voltage and capacitance on Taper angle.

machining time and arcing because of debris accumulation may be the reason for high electrode wear at low gap voltage conditions [14, 19]. So by the time the electrode pass through the sheet, the size of the electrode will be small and the micro hole end at the bottom side will also be small. This will lead to lesser bottom radial overcuts at lower discharge energies. When the hole is completely drilled, the condition of secondary discharge will be the least as most of the debris particles will go out of the hole through the bottom side. So micro hole expansion because of debris particle presence will be the least at the bottom.

Maximum value for taper angle has been observed when the pulse ON time, aspect ratio and electrode rotation are at their maximum values for a constant gap voltage and capacitance and is seemed to decrease with increase in gap voltage and capacitance. When a hole is drilled to a certain depth, the debris ejected from the working area begins to attach and accumulate on the surface of the electrode [8]. Discharges occur between the debris and the inner side of the hole. The gaseous bubbles generated by these secondary discharges push the debris further along the axis of electrode feed. Most of the debris would eventually be driven out of the hole due to secondary discharges that result in a larger diameter at the top. At the end of the operation, the debris would easily get ejected through the hole exit; the occurrence of secondary discharges reduces, resulting in the taper towards bottom side. From Fig. 5, it is clear that the response decreases with increase in gap voltage and capacitance. So relatively low electrode wear at low discharge conditions could also be a reason for higher taper angle at low discharge conditions.

Conclusions

Attempt to develop mathematical models which the quality defining factors for micro hole machined using micro EDM process like top an d bottom radial overcuts and taper angle has been made. Error analysis on the models gave positive results. The experiments conducted by randomly selected machining conditions for the purpose of validation of the models gave reasonably accurate results.

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