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ORIGINAL ARTICLE

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Response surface analysis of electro jet drilled holes

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Abstract Modern trend towards miniaturization has given a new impetus to the development of nontraditional small hole drilling techniques. Electro jet drilling (EJD) is one such promising technique which is finding ever increasing applications in several industries including aerospace, space, medical, automobile and microfabrication (electronic and computers). The present study investigates the relationships and parametric interactions between three controllable variables on the material removal, radial overcut and hole taper in the EJD process. Experiments have been conducted on SUPERNI 263A workpieces. Applied voltage, electrolyte concentration and feed rate were selected as independent process variables. The responses have been modelled using a response surface model based on a central composite rotatable experimental design. The significant coefficients were obtained by performing analysis of variance (ANOVA) at 1% and 5% level of significance. It was found that applied voltage, electrolyte concentration and feed rate have significant effect on the material removal, radial overcut and hole taper.

Keywords Electro jet drilling · Response surface methodology · ANOVA · Radial overcut

1 Introduction

As the trend towards miniaturization continues, nontraditional micro hole drilling techniques are receiving greater attention because of the specific advantages which can be exploited during the micro hole machining operations. Recent progress made in the field of aviation (cooling holes in jet turbine blades), space, automobile, electronics and computer (printed circuit boards, inkjet printer head), medical (surgical implants), optics, miniature manufacturing and others has created a need for small and micro size holes to be drilled with high aspect ratio in extremely hard and brittle materials [1–3]. The complexity of shapes and degree of precision required on the components used in these industries need such holes to be straight, accurate and exactly positioned. Producing macro or micro holes of high aspect ratio in super alloys is beyond the capabilities of conventional machining processes. High tool wear and excessive heat generation have rendered the twist drilling unsuitable. For such cases non-conventional processes are preferred for economical hole making. Electro jet drilling (EJD) is one such non-conventional process, which possesses all the requisite capabilities in meeting the modern day demands of drilling small and micro holes [4].

EJD is an efficient advanced machining process in which a negatively charged stream of acid electrolyte is impinged on the workpiece to form a hole. The acid electrolyte (10–25% concentration) is passed under pressure (0.3–1.0 MPa) through a finely drawn glass tube nozzle. The electrolyte jet acts as a cathode when a platinum wire, inserted into the glass tube well above the fine capillary is connected to the negative terminal of a DC power supply (Fig. 1). The workpiece acts as an anode. When a suitable electric potential is applied across the two electrodes, the material removal takes place through electrolytic dissolution as the electrolyte stream strikes the workpiece. The metal ions thus removed are carried away with the flow of the electrolyte. A much longer and thinner electrolyte flow path requires much higher voltage (150–750 V) so as to effect sufficient current flow [4, 5].

The available literature mainly deals with the qualitative description of the process and its applications [1–3]. The relationship among the process influencing parameters of the EJD process and their effect on process performance are not completely known. Not much information is available in the literature, which deals with modelling and optimiza-

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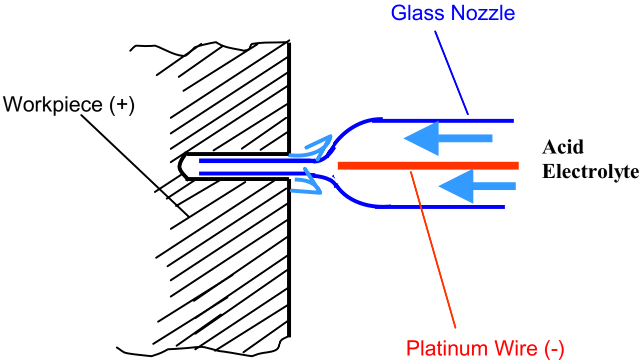

Fig. 1 Schematic diagram of the electro jet drilling process

tion of the EJD process. Sustained research is required to transform the process into a robust one for its wide scale commercial use in industries.

In the present study a central composite design (CCD) and response surface method (RSM) have been used to analyse the effect of the three parameters on the EJD process. The material removal, radial overcut and hole taper were the response parameters and were modelled by a statistical technique, known as response surface methodology (RSM).

2 EJD experimentation

Figure 2 illustrates the schematic of the experimental set-up used for drilling micro through holes in SUPERNI 263A sheets. Each work specimen of 25 × 25 × 2 mm thickness was soldered on the face of 8 mm diameter stainless steel rods, which could be rigidly held as and when required. Through holes were drilled in all experiments and each experiment was repeated three times. The mean values of the three response measurements were used as output at each set of parameters. The experiments were conducted in random order so as to remove the effects of any factors unaccounted for. For each particular run, the specified input parameters were set and controlled. The time taken for machining a hole was recorded by an electronic timer.

Table 1 Process parameters and their levels

Input factors	Level/code				
	−1.682	−1	0	1	1.682
Applied voltage (volts) A	100	190	325	460	550
Electrolyte concentration (in %) B	10	13	17.5	22	25
Feed rate (mm/min) C	0.0	0.2	0.5	0.8	1.0

Completion of the hole was signalled by the exit of the jet through the workpiece. An electronic balance (Metler, LC: 0.1 mg) was used to weigh the workpiece before and after drilling. The hole size measurements were taken using a Toolmakers microscope. A total of three diameter measurements were made at hole orientations 60° apart and their average was taken. The radial overcut was calculated on the basis of Eq. 1. Using the entry side hole diameter and exit side hole diameter measurements, the hole taper was calculated using Eq. 2.

$$overcut = \frac{d_{entry} - d_{glass\ capillary}}{2} \quad (1)$$

$$taper(\theta) = \tan^{-1}\left(\frac{d_{entry} - d_{exit}}{2t}\right) \quad (2)$$

Where d_{entry} is the hole entrance diameter, $d_{glass\ capillary}$ is the diameter of the glass capillary, d_{exit} is the hole exit diameter and t is the workpiece thickness.

2.1 Design of experiments

The traditional method of experimentation, i.e. varying one factor at a time and studying its effect, was considered time consuming and costly. Furthermore, such experiments cannot predict the presence of interactions between the different factors. With a proper designed experiment like central composite design (CCD), it is possible to determine, with a much reduced number of experiments,

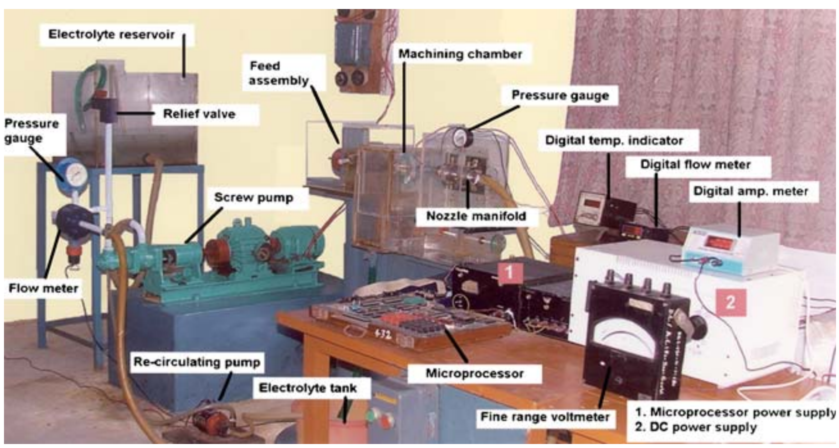

Fig. 2 Schematic of experimental setup used for the electro jet drilling technology

Table 2 Experimental conditions kept unchanged

Conditions	Value
Electrolyte	Sulfuric acid
Electrolyte pressure	0.40 MPa
Electrolyte temperature	35±1°C
Glass nozzle material	Borosilicate glass
Capillary outside diameter	0.36 mm
Cathode wire material	Platinum
Cathode wire size	1.0 mm
Inter electrode gap	25 mm

the effect of changing any one variable with the same accuracy as if only one factor has been varied at a time, and interaction effects between the factors. CCD is one type of RSM [6]. The RSM is a collection of mathematical and statistical techniques for analyzing problems in which several independent variables influence a dependent variable or response the goal being to secure the optimal response [7].

A second order central composite rotatable design with 20 runs was selected as it can handle linear, quadratic and interaction terms in the process modelling. The selected design consists of 8 factorial runs, 6 axial runs and 6 central runs. This design requires five levels of each factor in coded form: $-\propto$, –1, 0, +1, and $+\propto$. The $\propto$ is a function of k, number of independent parameters. In this design the level intervals for each factor depends on the number of factors. The levels of each factor in this CCD design were chosen as –1.682, −1, 0, +1 and +1.682 in coded form in order to have a rotatable design. Rotatability of a design means that the variation in the response predicted by a model will be constant at a given distance from the centre point of the design at which all factors are set on their middle level. Coding of factors allows the calculations to be performed independent of the units for each factor [6, 7].

2.2 Process variables

Three process variables selected for the present study are applied voltage (A), electrolyte concentration (B) and feed rate (C). Their levels in CCD are shown in Table 1. The material removal rate, radial overcut and hole taper were selected as response parameters for analysing the process performance. Other factors, which may have effects on the measures of the process performance, are set fixed (Table 2).

3 RSM model and data analysis

Empirical modelling of the EJD process can be regarded as a problem of correlating the input parameters of the process with its response parameters. This can be dealt with by means of RSM in which the dependent variable is viewed as a surface to which a mathematical model is fitted.

In the present work, RSM has been applied for developing mathematical models in the form of multiple regression equations for the quality characteristics of the hole machined by EJD. In applying the RSM, The method of least squares was used to estimate the regression coefficients in a multiple regression model [6]. The model, in terms of the observation in matrix notation is:

$$y = X\beta + \varepsilon \tag{3}$$

where y is a $(n\times1)$ vector of observation (n is the number of observations), X is an $(n\times p)$ matrix of the levels of the independent variables ($p = k + 1$, k is the number of process variables), β is a $(p\times1)$ vector of the regression coefficients and ε is an $(p\times1)$ vector of random errors. The fitted regression model is:

$$\widehat{y} = Xb \tag{4}$$

Table 3 ANOVA table of material removal rate

Source	Sum of squares	DF	Mean square	F value	Prob>F	Effect
Model	2.44	9	0.27	73.34	<0.0001	Highly significant
A	2.00	1	2.00	542.47	<0.0001	Highly significant
B	0.16	1	0.16	44.05	<0.0001	Highly significant
C	0.024	1	0.024	6.39	0.0300	Significant
A^2	2.250E–03	1	2.250E–03	0.61	0.4533	
B^2	0.058	1	0.058	15.65	0.0027	Significant
C^2	4.706E–04	1	4.706E–04	0.13	0.7286	
AB	0.17	1	0.17	46.73	<0.0001	Highly significant
AC	4.267E–03	1	4.267E–03	1.15	0.3078	
BC	8.084E–03	1	8.084E–03	2.19	0.1699	
Residual	0.037	10	3.695E–03			
Lack of fit	0.016	5	3.150E–03	0.74	0.6238	Not significant
Pure error	0.021	5	4.240E–03			
Cor total	2.48	19				

Values of "Prob>F" less than 0.0500 indicate model terms are significant. A: applied voltage; B: electrolyte concentration; C: feed rate

Table 4 ANOVA table of radial overcut

Source	Sum of squares	DF	Mean square	F value	Prob>F	Effect
Model	7.576E–03	9	8.417E–04	17.56	<0.0001	Highly significant
A	2.626E–03	1	2.626E–03	54.79	<0.0001	Highly significant
B	1.256E–03	1	1.256E–03	26.20	0.0005	Significant
C	1.448E–03	1	1.448E–03	30.22	0.0003	Significant
A^2	1.392E–04	1	1.392E–04	2.90	0.1192	
B^2	2.066E–04	1	2.066E–04	4.31	0.0646	
C^2	1.391E–03	1	1.391E–03	29.03	0.0003	Significant
AB	3.380E–04	1	3.380E–04	7.05	0.0241	Significant
AC	5.000E–05	1	5.000E–05	1.04	0.3311	
BC	4.050E–05	1	4.050E–05	0.85	0.3796	
Residual	4.792E–04	10	4.792E–05			
Lack of fit	2.019E–04	5	4.038E–05	0.73	0.6320	Not significant
Pure error	2.773E–04	5	5.547E–05			
Cor total	8.055E–03	19				

Values of "Prob>F" less than 0.0500 indicate model terms are significant. A: applied voltage; B: electrolyte concentration; C: feed rate

where b is the least square estimators of the regression coefficients β vector $(b_0, b_1, \ldots\ldots, b_k)$ which can be calculated as:

$$b = \left(XX'\right)^{-1} X'y \tag{5}$$

where XX' is a $(p\times p)$ symmetric matrix and $X'y$ is a $(p\times 1)$ column vector.

For the purpose of development of a regression equation for response parameters, the following second order response surface model [4] has been used.

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i<j=2}^{k} b_{ij} x_i x_j \pm \in_r \tag{6}$$

This assumed surface Y contains linear, squared and cross product terms of variables x_i's. The coefficient b_0 represents the response at the centre of the experiment when all the variables are 0. The b_i, b_{ii} and b_{ij} represent the coefficients of linear, quadratic and linear by linear interaction effects of the variables respectively. The difference between the observation y_i and the fitted value $\hat{y}$ is a residual $\in_r$. The modelling was started with a quadratic model including linear, squared and interaction terms with the provision that if the non-linearity was not appropriate, the model could be simplified to first order or linear model. Both the models were checked and selected in quadratic form in order to fit the data as accurately as possible. The least square method was used to compute the regression coefficients. The significant terms in the model were found by analysis of variance at 1% and 5% level of significance. These are given in Tables 3, 4 and 5 for MRR,

Table 5 ANOVA table of hole taper

Source	Sum of squares	DF	Mean square	F value	Prob>F	Effect
Model	30.62	9	3.40	26.77	<0.0001	Highly significant
A	13.39	1	13.39	105.34	<0.0001	Highly significant
B	4.23	1	4.23	33.27	0.0002	Significant
C	4.26	1	4.26	33.53	0.0002	Significant
A^2	2.59	1	2.59	20.36	0.0011	Significant
B^2	1.26	1	1.26	9.91	0.0104	Significant
C^2	0.38	1	0.38	3.03	0.1126	
AB	4.77	1	4.77	37.52	0.0001	Significant
AC	0.31	1	0.31	2.41	0.1518	
BC	2.941E–03	1	2.941E–03	0.023	0.8821	
Residual	1.27	10	0.13			
Lack of fit	0.62	5	0.12	0.96	0.5154	Not significant
Pure error	0.65	5	0.13			
Cor total	31.90	19				

Values of "Prob>F" less than 0.0500 indicate model terms are significant. A: applied voltage; B: electrolyte concentration; C: feed rate radial overcut and hole taper, respectively. The accuracy of the models have been checked by complete residual analysis including checking normal probability line of residuals, outliers T, Cook's distance and leverage [8, 9].

4 Experimental results and discussion

Experiments have been carried out on the EJD set up and the data were collected with respect to the influence of the predominant process parameters on material removal rate (MRR), radial overcut and hole taper.

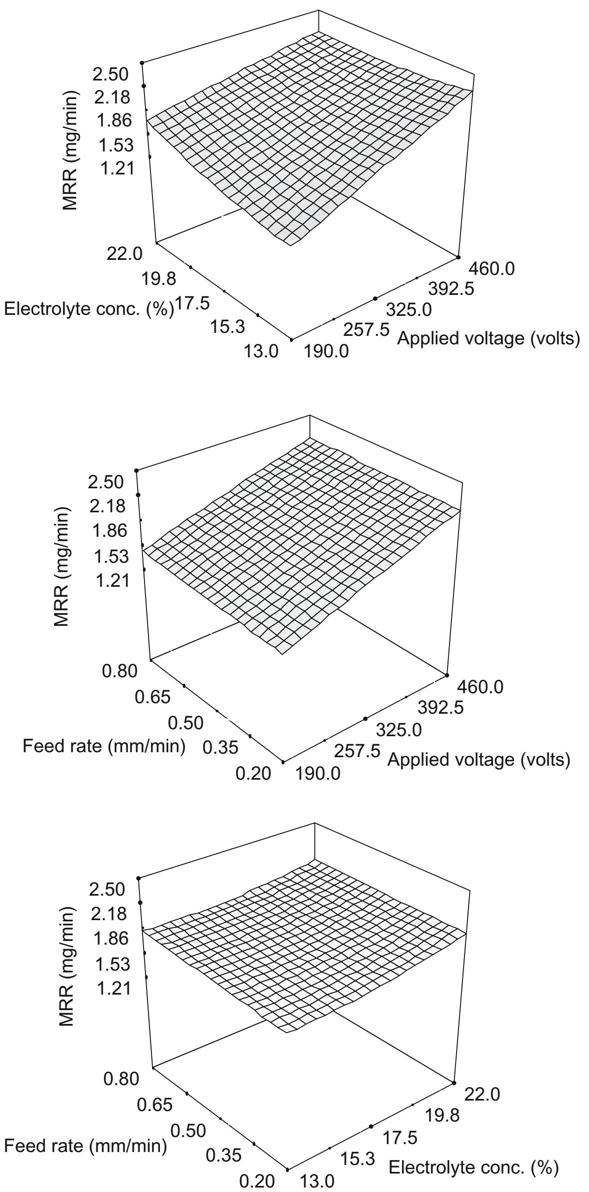

Fig. 3 3D surfaces of MRR model (interaction between different significant parameters)

4.1 Material removal rate

Applied voltage, electrolyte concentration and their interaction term have a highly significant effect on the model at 5% level of significance (Table 3) whereas these are just significant at 1% level of significance. For this model, the feed rate is significant at 5% level of significance. The response surface relating any output with two inputs can be obtained from the model. Figure 3 illustrates the response surfaces for material removal with respect to input parameters A, B and C. The main effect curve or the perturbation curve (Fig. 4) shows that any increase in applied voltage increases the machining current. Faraday law states that the MRR is proportional to the machining current. Thus increase in current increases the material removal. Linear relation of MRR with input parameters is also depicted in Fig. 4. As shown in Fig. 3 MRR increases rapidly in the high voltage range (above 350 V) as compared to low voltage range (100 to 350 V). These trends are the consequences of less dissolution efficiency at low voltage ranges because of long electrolyte flow path.

The increase in electrolyte concentration increases the material removal rate. The increase in concentration of electrolyte leads to an increase in its electrical conductivity as a result of which more current will be available in the machining zone to remove more material. Further at higher concentration, a large number of ions associated in the machining process increase the machining current and thus enhances the material removal rate. The increase in feed rate with either of the two input parameters also increases the material removal rate. The increase in feed rate reduces the inter-electrode gap and leads to smaller ohmic resistance thus resulting in enhanced flow of electrolyzing current in the gap causing high stock removal from the work surface.

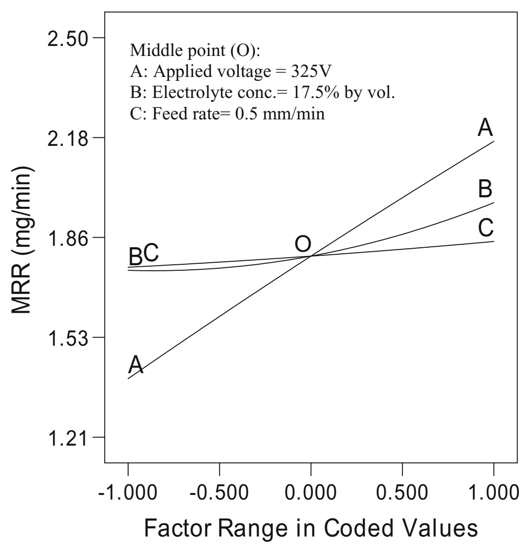

Fig. 4 Main effects of input parameters on MRR

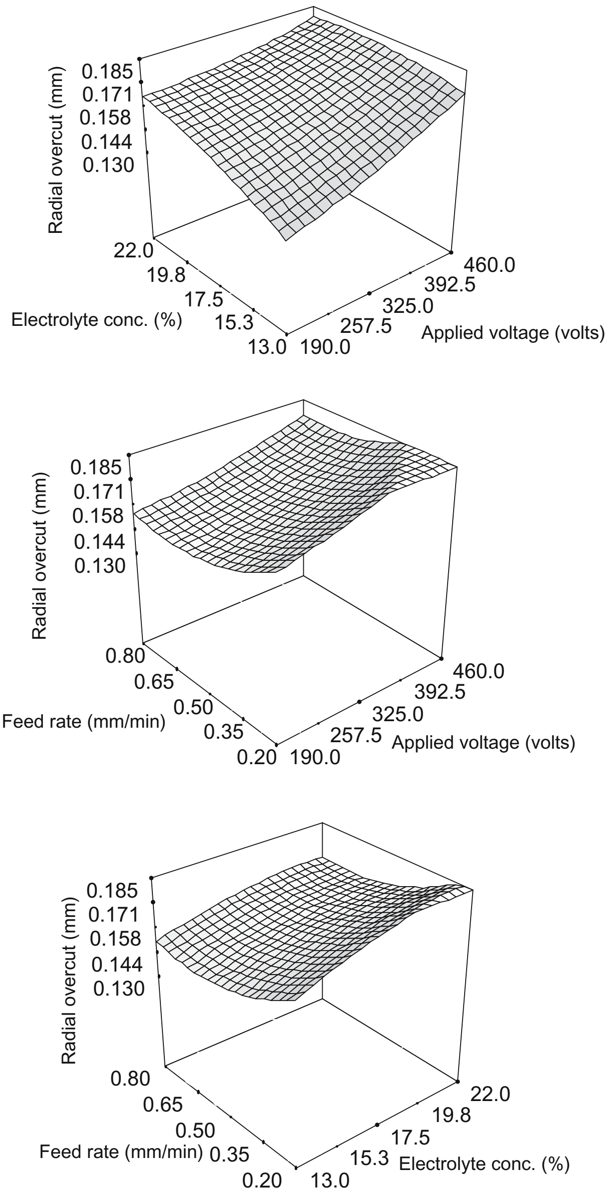

Fig. 5 3D surfaces of radial overcut model (interaction between different significant parameters)

4.2 Radial overcut

The radial overcut is an important parameter that decides the quality of the EJD hole. Applied voltage has a highly significant effect on it at 5% level of significance (Table 4). Increasing the applied voltage or electrolyte concentration results in greater radial overcut whilst higher feed rate produces a hole with less overcut (Figs. 5 and 6). For the radial overcut model, applied voltage, electrolyte concentration and feed rate are significant at 1% level of significance. The term indicating the interaction between the applied voltage and electrolyte concentration is significant at 5% level of significance. At higher voltages, i.e. at 460 V or more, radial overcut is more predominant. The availability of higher machining current with an increase in the

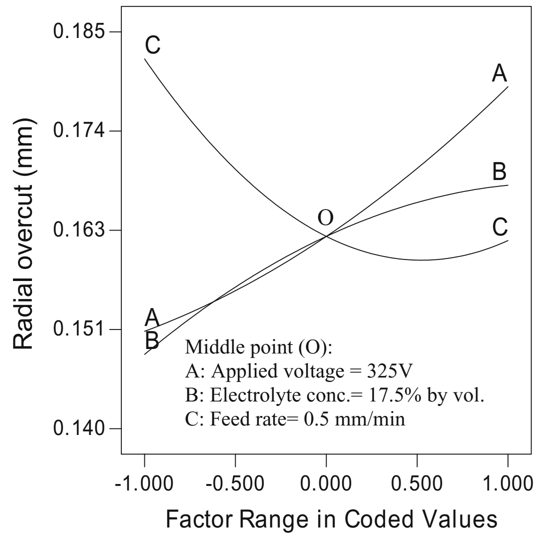

Fig. 6 Main effects of input parameters on radial overcut

applied voltage results in an increase in overcut. This increase in overcut is attributed partly to stray current effect and partly to the fact that the electro jet remains in contact with the entry side of the workpiece for a maximum period of time. An increase in feed rate with either of the two input parameters was found to have resulted in low overcut. The increase in feed rate decreases the side machining effects due to the availability of less time during which side machining occurs. The higher feed rate also reduces the exposure time during which the workpiece top surface remains in contact with the impinging electro jet thus reducing overcut to some extent.

In the case of radial overcut, applied voltage, electrolyte concentration and feed rate have a significant effect on the model (Table 4). Increasing the feed rate helps in reducing the overcut to some extent. From Table 4, it can be seen that interaction effect between the applied voltage and electrolyte concentration is significant.

4.3 Hole taper

The hole taper depends on the difference between the hole entrance diameter and hole exit diameter. From Table 5 it is revealed that the main effects of electrolyte concentration, feed rate, squared terms of applied voltage and electrolyte concentration are significant at 1% and 5% level of significance whilst the main effect of applied voltage is highly significant at 5% level of significance. The interaction term between the applied voltage and electrolyte concentration is significant at 5% level of significance. Fig. 7 illustrates the three-dimensional surfaces of the hole taper model with respect to input parameters A, B and C. Increasing the applied voltage and electrolyte concentration results in greater hole taper. The reasons for this is that the electro jet remains in contact with the entry side of the workpiece for a maximum period of time resulting in a larger hole entrance diameter than the hole exit diameter. The main effect curve

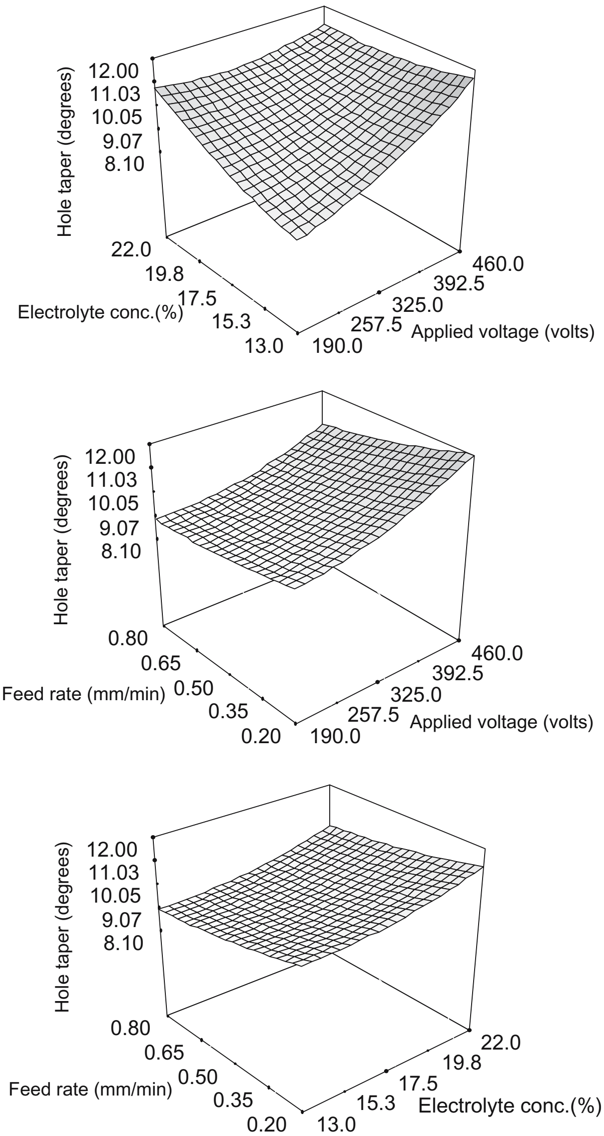

Fig. 7 3D surfaces of hole taper model (interaction between different significant parameters)

(Fig. 8) shows that at high feed rates the hole taper is reduced. However the feed rate can be increased up to a certain limit due to the use of glass nozzle in the experiment.

Low overcut and reduced hole taper are the important desirable qualities of a hole. In the present set of experiments these were achieved at 325 DC volts, 17.5% electrolyte concentration and at a feed rate of 0.5 mm/min. The quality of holes achieved at higher voltages (460 to 550 V) was poor due to higher radial overcut and hole taper. At 550 volts sparking (glow) has been seen in and around the workpiece fixture. This may be due to the fine droplets of charged electrolyte jet falling on its outwards flow after removing the stock from the workpiece. Table 6 sums up the final model of the electro jet drilling in terms of three independent coded variables.

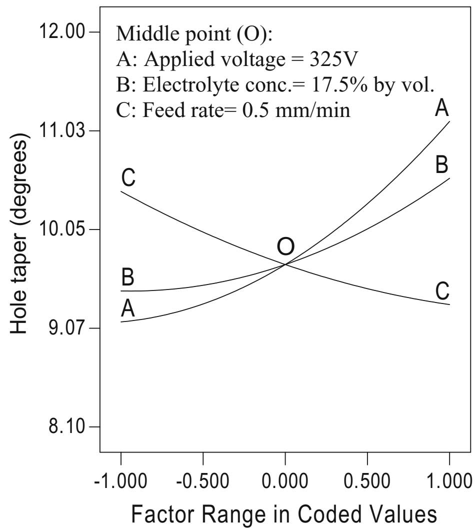

Fig. 8 Main effects of input parameters on hole taper

Table 6 Final models of electro jet drilling process in terms of three independent coded variables

Coefficient	MRR	Radial overcut	Hole taper
0	+1.79	+0.16	+9.70
β_A	+0.38	+0.014	+0.99
β_B	+0.11	+9.589E–003	+0.56
β_C	+0.042	−0.010	−0.56
β_A^2	Insignificant	Insignificant	+0.42
β_B^2	+0.063	Insignificant	+0.30
β_C^2	Insignificant	+9.825E–003	Insignificant
$\beta_{A\times B}^2$	−0.15	−6.500E–003	−0.77

5 Conclusions

The present study relates to the machining of micro holes in SUPERNI 263A by the EJD process. A set of experiments were conducted using CCD and the results were analysed using RSM. Within the specified ranges of the input variables employed the following conclusions can be drawn.

1. Applied voltage, electrolyte concentration, feed rate and interaction between the applied voltage and electrolyte concentration are the significant parameters in all the three models.
2. The increase in feed rate not only enhances the material removal but it also enables to control the radial overcut as well as hole taper. Since the fine glass nozzle, used to direct the electrolyte jet on the workpiece in the EJD process, moves inside the workpiece therefore a judicious selection of feed rate is very important for the success of the process in view of the fragile nature of the glass. The selected feed rates should be compatible with the dissolution efficiency of the work material at the applied potential level.
3. Within the overall range of test conditions employed, the optimum results, that is maximum MRR with least

radial overcut and small hole taper were achieved in the following ranges of the parameters:

- Voltage: 190−325 V
- Electrolyte concentration: 13-17.5%
- Feed rate: 0.2–0.5 mm/min.

4. Higher applied voltage, though it results in greater MRR, tends to produce holes of poor quality in terms of large radial overcut and hole taper.

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