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VARIATIONS IN SPARK DISCHARGE AREA FOR DIRECTIONAL OVERCUT IN PRECISION ELECTRICAL DISCHARGE MACHINING

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Abstract

The Electrical Discharge Machining (EDM) is established as a precision machining process when micron tolerances are required to be produced in components. For the tool makers, dimensional accuracy becomes a prime concern when complex designs and profiles are produced in the dies and moulds. In spark erosion process, sparking along the edges of tool leads to overcut in particular direction, resulting in directional overcut. In EDM, lower direction overcut is preferable to achieve higher dimensional accuracy. Therefore, optimization of directional overcut is a key concern to limit the dimensional deviations in EDM machining. The area of the tool imposed in spark erosion plays a prime role so that change in an area of the tool affects the directional overcut. The objective of present work is to investigate the influence of variations in spark discharge area along with other process parameters for optimizing the directional overcut. The variations of spark discharge area are analysed through Taguchi orthogonal array (L_{16}×4) and sequential Analysis of Variance (ANOVA) approach. The current intensity is observed as a prime parameter in precision finish-cut machining. The second order regression analysis model predicts the coefficient of correlation (R^2 value) as 94.73%, which indicates good dimensional accuracy.

Keywords: Dimensional accuracy, Directional overcut, Finish cut, Orthogonal array, Spark discharge area.

1. Introduction

The electrical discharge machining is a versatile manufacturing process, which follows electro-thermal phenomenon for material erosion. A series of plasma sparks occur between the tool electrodes and workpiece. The plasma sparks melt and vaporise the material in the form of debris and carbon residuals.

The residuals formed are flushed away immediately by the pressurised dielectric fluid. EDM is a feasible option for machining hard alloy and tools steels, which otherwise are difficult to cut under conventional machining. The intricate designs and profiles are demanding finely tuned EDM process parameters, to bring high-quality products. The EDM is leading as a widespread practice used in tool rooms for die and mould preparations, plastic injection moulds, forging dies, and automobile parts for high-precision machining [1, 2].

Electrical discharge machining is having large utility in industrial toolroom applications. EDM has drawn researchers' attention in terms of monitoring and control of the process characteristics, to find new perceptions. Radhika et al. [3] found that monitoring of EDM is an important aspect to increasing productivity and parts quality. The analysis of hybrid composites was carried through Taguchi's design of experiment. The influence of input process parameters was investigated for surface roughness, material removal rate and tool wear rate. Rao and Padmanabhan [4] used the Taguchi method to analyse the machining parameters.

The utility concept was implemented to covert multi-objective responses into a single response. The optimum parameters in the process were established for radial overcut as a performance measure. Dhanabalan et al. [5] investigated the electrical discharge machining characteristics using different electrodes such as copper, brass and aluminium. An attempt has been made to correlate thermal characteristics of multiple electrodes with titanium alloy as workpiece material. Muthukumar and Rajesh [6] applied the response surface methodology to analyze radial overcut in die sinking EDM. It is observed that current intensity and gap voltage lead to a significant effect on the radial overcut. The response surface showed that a lower level of current intensity and gap voltage can be preferred to minimize the radial overcut. Teimouri and Baseri [7] focused on overcut analysis considering tool wear.

Electrical discharge machining process was performed with a rotational electrode in the rotary external magnetic field. The various levels of tool rotational speed were followed and found that rotation of tool leads to a negative effect on overcut. Kumar et al. [8] investigated radial overcut for different types of tool material. Regular copper tool and sintered powder metallurgy copper tungsten tool were considered in experimentation. Under reverse polarity condition, it was found that the powder metallurgy copper tungsten tool resulted in minimum overcut.

Santoki and Bhabhor [9] studied the radial overcut using different tools like graphite copper and silver. The results showed that copper tool is more accurate in radial overcut. The silver tool gives better performance in certain characteristics, however, machining leads to higher cost. It was observed that current intensity significantly affects the overcut followed by a pulse on time, under positive polarity. Singh et al. [10] used rotary type single channel tube electrode in EDM for evaluating the radial overcut, for Al/Al_2O_3 composite. Using the Taguchi method, they revealed that the radial overcut is mostly affected by a combination of current intensity and pulse off time.

Khan and Yeakub [11] studied the effect of different electrode shapes on material removal, wear ratio and surface roughness for mild steel as work material. Among the various shapes, the highest material removal was observed for circular electrodes. Sohani et al. [12] investigated the effect of tool shapes along with its size factor in terms of machined features. Different shapes of electrodes such as triangular, rectangular and circular were investigated. The circular shape tool stands best in terms of higher material removal rate and lower tool wear rate, the literature it is reviewed that the radial overcut has been reported a number of times with directional overcut reporting for linear edge type geometry along with the tool size variations effect lacks.

1.1. Precision machining: Toolroom requisite

EDM is well known precise machining for producing complex profiles cavities in dies and moulds. EDM sparking is a very complex phenomenon, which takes place randomly in all directions. Due to the bottom sparking depth of cut occurs, whereas side sparking along the tool edges lead to overcut in a particular direction. Hence, from every reference tool edge, the machined cavity is larger in a particular direction, which is termed as directional overcut. In the die making process, control and monitoring of machining parameters impose excess of lead time in terms of seizing overcut.

In the tool room practices, it is observed that as the spark discharge area vary thereby the directional overcut affects, as shown in Fig. 1. The effect of variation in spark discharge areas on the depth of cut is an important aspect in correlation with directional overcut. Therefore, to enhance machining accuracy and precision, directional overcut must be optimised in terms of tunning of machining parameter settings.

1.2. Taguchi approach for directional overcut (OC)

The directional overcut along reference edge is considered an average of the difference between machined cavity dimensions (D_w) and tool dimensions (D_t) as shown in Eq. (1). The directional overcut is inversely proportional to dimensional accuracy, which means lower the directional overcut higher will be the dimensional accuracy. Different uniform square tools are selected for spark discharge area variation. In this work, the directional overcut is measured in relation to longitudinal X-axis particularly as shown in Fig. 1.

High precision tool maker microscope (Mitutoyo, Japan, least count: 0.005 mm, linear travel: 0-25 mm) is used for calibration of tool and workpiece cavity dimensions, after EDM machining. The overcut is measured at the middle of a machined cavity formed and average values are mentioned in Table 2.

$$Directional\ overcut\ (OC) = \frac{(D_w - D_t)}{2} \quad (1)$$

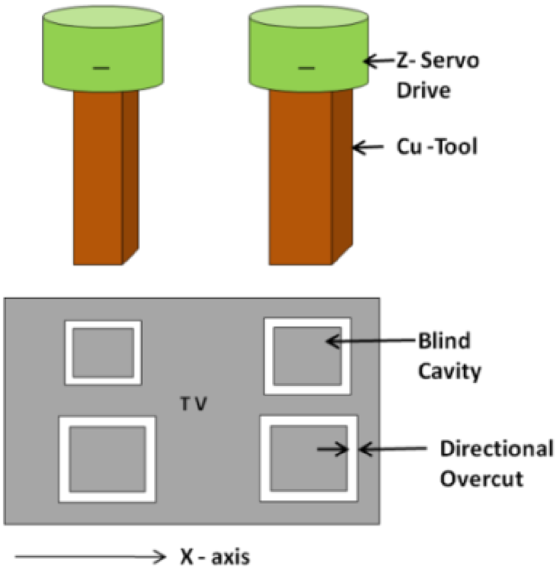

Fig. 1. Variations in spark discharge area for directional overcut.

The signal to noise ratio is considered to determine the maximum variance in the output response obtained from process data. The signal to noise ratio is means of response signal to the standard derivation of the noise [13]. For the finish cut OC analysis, 'lower the better' approach of Taguchi technique is considered in experimental investigations. The S/N ratio statistics for directional overcut with the unit dB, is given by Eq. (2) as:

$$Overcut\ S/N\ Ratio = -10\ \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (2)$$

where y_i *is* i^{th} response observation for a parametric combination and n is referred here as average overcut response.

2. EDM Experimentation

The experiments are performed on die sink EDM machine, Electronica (E-20) (supplied by Electronica Industries, India) as shown in Fig. 2. The equipment consists of CNC controlled Z servo drive, with integrated power controller unit under positive polarity. The pressure used under jet side flushing for the dielectric fluid is 0.02 N/mm^2. Furthermore, four copper tools are prepared in a square form of incremental cross-sectional area as 100, 200, 300, 400 mm² and 90 mm in height, as shown in Fig. 3.

The workpiece material AISI-D2 alloy steel is used in experimentation, which is also known as HCHCr steel. Commonly it is used in cold work dies and moulds for inner core and section blocks. The hardness of the AISI D2 tool steel is 55 HRC along with the melting temperature of alloy 1490°C [14, 15]. Chemical composition of AISI-D2 [16] are as follows: C, 1.5%; Cr, 12%; Si, 0.3%; Mn, 0.3%; Ni, 0.3%; Mo, 1.0%; V, 0.8%; Co, 0.6%; Fe, balance %.

The effect of machining process parameters on response variable helps in deciding the work interval of parameters [17]. The electrical discharge machining consists of a large number of process variables and parameters [18]. In this work, variable parameters taken into account are current intensity, pulse on time, gap voltage and spark discharge area. Considering the finish cut, four level variations of each parameter are followed as shown in Table 1. The behaviour of each process parameter significantly influences directional overcut, as observed in experimentation.

Fig. 2. Die sink EDM set-up.

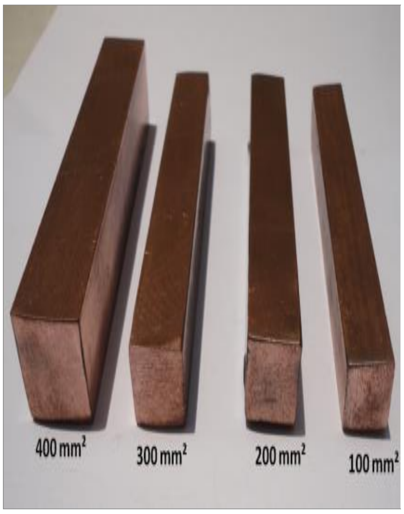

Fig. 3. Different spark discharge area Cu tools.

Table 1. EDM parameters with machining work interval.

Machine parameter	Units	Parameter levels			
Current intensity- I_p	A	3	5	7	10
Pulse on time- T_{on}	sec	0.11	0.17	0.29	0.38
Gap Voltage -V_g	V	130	135	140	145
Spark discharge area on Cu tool-A_e	mm^2	100	200	300	400
Constant parameters:					
Dielectric pressure	N/mm^2	0.02			
Density of AISI D2	gm/cm^3	7.67			
Density of Cu tool	gm/cm^3	8.94			
Duty cycle	Constant	0.9			
Tool polarity	Type	Positive			

3. Results and Discussion

Design of experimentation along with Taguchi approach is used for parametric optimisation. The robust L_{16} orthogonal array with four level variations of each parameter is employed to find out tune up parameter for finish cut machining. Analysis is performed with the help of MATLAB and Minitab17 version. Individual orthogonal array L_{16} is followed for each spark area variation and average responses in terms of directional overcut and depth of cut are mentioned in Table 2.

Table 2. Directional overcut response with variations in spark discharge area.

Experimental run L_{16}	Machining parameters			A_e :100 mm²		A_e :200 mm²		A_e :300 mm²		A_e :400 mm²	
	I_p A	T_{on} s	V_g V	OC mm	DOC mm	OC mm	DOC mm	OC mm	DOC mm	OC mm	DOC mm
1	3	0.11	130	0.036	1.16	0.008	0.44	0.004	0.53	0.033	0.34
2	3	0.17	135	0.047	1.38	0.035	0.72	0.004	0.60	0.058	0.49
3	3	0.29	140	0.050	1.45	0.036	0.79	0.044	0.69	0.071	0.56
4	3	0.38	145	0.056	1.65	0.065	0.85	0.068	0.71	0.074	0.54
5	5	0.11	135	0.058	2.30	0.069	1.08	0.088	0.74	0.125	0.65
6	5	0.17	130	0.062	2.31	0.079	1.26	0.135	0.76	0.146	0.77
7	5	0.29	145	0.074	2.51	0.085	1.27	0.160	0.93	0.176	0.95
8	5	0.38	140	0.080	3.00	0.099	1.46	0.161	0.94	0.194	1.05
9	7	0.11	140	0.085	3.39	0.137	1.48	0.168	1.15	0.204	1.14
10	7	0.17	145	0.089	3.66	0.154	1.56	0.179	1.26	0.207	1.15
11	7	0.29	130	0.098	4.69	0.159	2.12	0.180	1.36	0.208	1.29
12	7	0.38	135	0.113	4.16	0.187	2.07	0.187	1.28	0.253	1.23
13	10	0.11	145	0.165	6.16	0.213	2.27	0.204	1.41	0.269	1.51
14	10	0.17	140	0.155	5.98	0.197	1.84	0.190	1.36	0.265	1.48
15	10	0.29	135	0.207	6.48	0.242	2.56	0.286	1.52	0.330	1.82
16	10	0.38	130	0.184	6.38	0.237	2.74	0.238	1.50	0.295	1.63

3.1. Experimental data adequacy check through residual plots

Residual plot analysis is carried out to confirm the response data generated through experiments for directional overcut as shown in Fig. 4. There are three assumptions in residual plot analysis for sequential pair execution of experimental run adequacy check. These assumptions are constant variance, normality and independence consideration, in terms of residuals and fitted values. Normal probability plot shows the residuals effect by approaching towards best fit line. The plot of residuals against fit clearly shows constant variance of residuals, as uniformly spread all over. In the histogram plot, it is observed that the residuals are normally distributed. In the plot of residuals against observation order, the residuals show no treads and independent of one another [19]. Therefore, it is concluded that appropriate process spread of experimental data is gained through orthogonal array L_{16}×4 variations, for directional overcut responses.

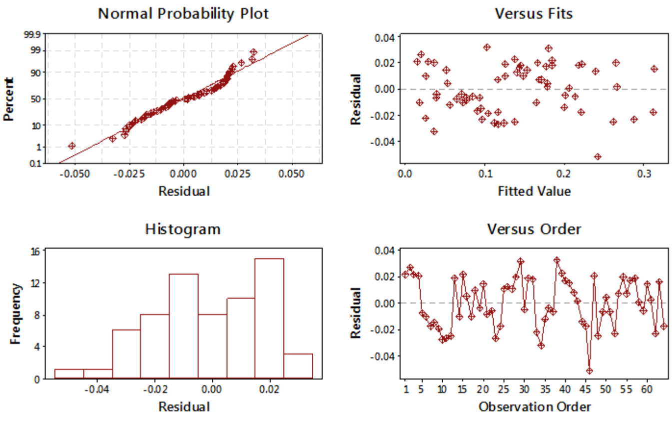

Fig. 4. Residual plot analysis for directional overcut.

3.2. Analysis of directional overcut

The comparison among directional overcut for different spark discharge areas are shown in Fig. 5. All the trends for directional overcut are observed on the similar lines. The current intensity plays a major role so that as it increases the directional overcut also increases.

As can be clearly observed that around current intensity 12 A, the trend becomes random in nature, i.e., experimental run 13 and onwards. This takes place because higher heat energy increases edge sparking, leading to variations in directional overcut. Also, recast of molten fragments takes place, as all metal fragments are not flushed away, which is exhibited by the stochastic nature at higher current intensity as shown in Fig. 5.

In EDM process, the depth of cut (DOC) for spark area variations have been investigated against the experimental run L_{16} as shown in Fig. 6. The depth of cut differs in nature marginally for different spark discharge areas. It is observed that depth of cut in case of spark discharge area 100 mm² is almost double in values compared to other cases. It means lesser the spark discharge area more is the depth of cut because higher accommodation of plasma thermal energy takes place at specific limited region. Though the process variables are same in all cases, however, more spread of energy occurs for larger region, resulting in less depth of cut. At lower values of current intensity till 7A (till experimental run 11), the nature of graphical trend is smooth, which shows that machining is stable in nature.

Figure 7 shows the estimates for directional overcut among all the spark discharge areas. The sum and average calculations of directional overcut for each spark discharge area are compared. The spark discharge area 100 mm^2 is having least overcut among all cases, which means dimensional accuracy is highest in this case. As the spark discharge area goes on increasing, the directional overcut also gradually increases due to higher edge sparking. It reveals that the spark discharge area is directly proportional to overcut responses.

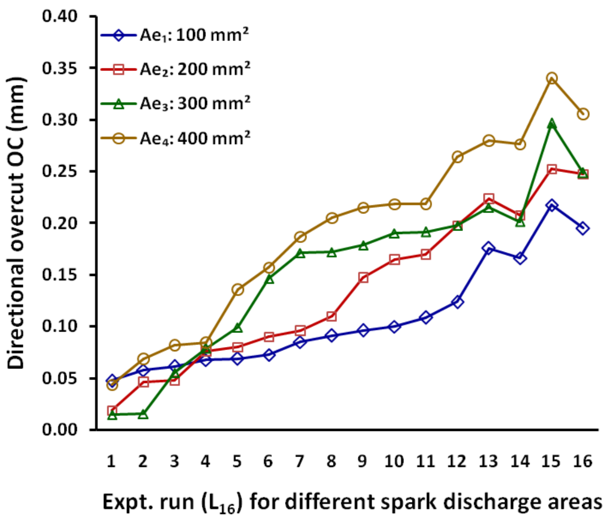

Fig. 5. Directional overcut for different spark discharge areas.

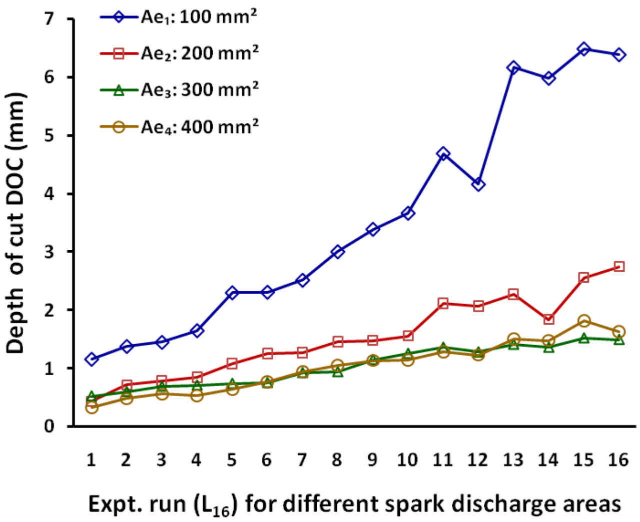

Fig. 6. Depth of cut for different spark discharge areas.

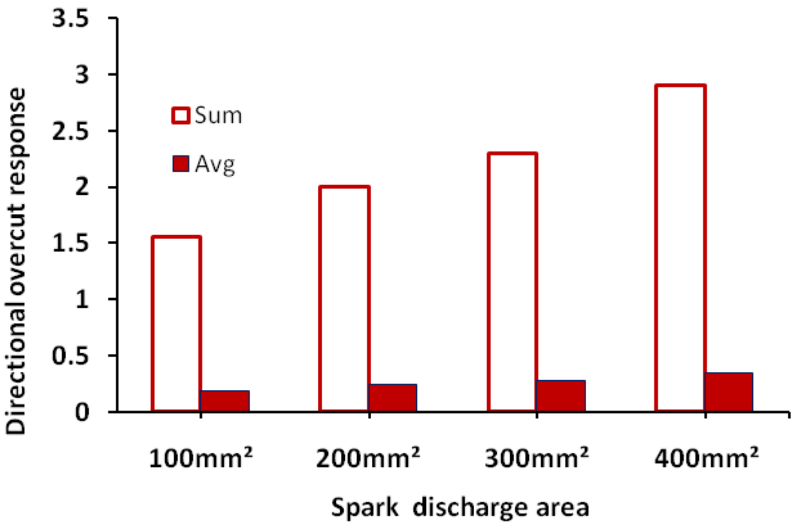

Fig.7. Sum and average overcut for different spark discharge areas.

The main effect plots for directional overcut are shown in Fig. 8. The largest spread of current intensity shows its importance in sparking process, followed by spark discharge areas. Hence, current intensity and spark discharge area are the prime important parameters to control the directional overcut. The pulse on-time and gap voltage are found to have a central mean tendency, as clearly visible. With an increase in current, the intensity of spark increases, generating more thermal energy in spark plasma [20]. As the pulse on time increases, this energy stands in the plasma section for a longer duration. Faster metal erosion takes place at higher power amperage, which leads to an increase in directional overcut.

In the experimental investigation, it is observed that as the spark discharge area increases directional overcut also increases. It is an important machining characteristic to control the EDM machining and fine-tuning of the process parameters [21]. Figure 9 shows S/N ratio plots for input process variables. Prior, as stated, lower the better approach is followed for directional overcut in precision finish cut machining. For the performance characteristic of directional overcut, the levels such as current intensity of I_p 3A, pulse on a duration of T_{on} 0.11 seconds, gap voltage of V_g 130 V and spark discharge area A_e 100 mm² are the optimally tuned finish cut EDM process parameters.

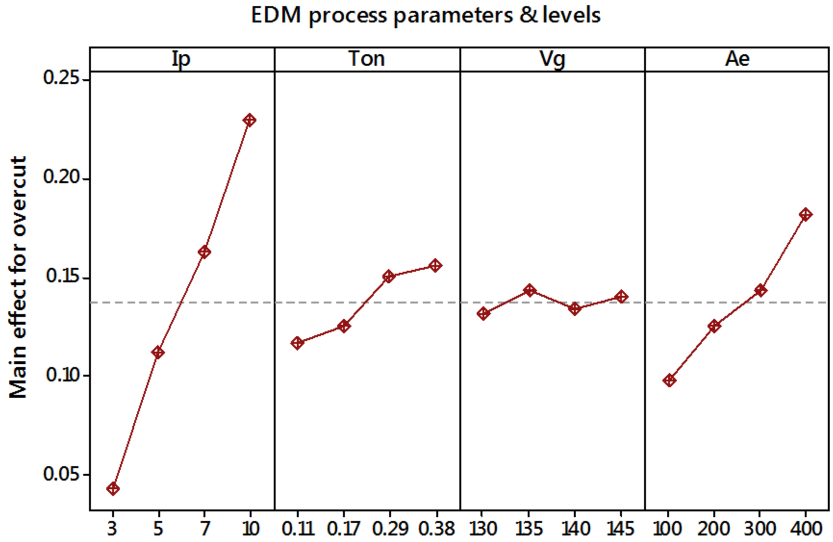

Fig. 8. Main effects plot for directional overcut.

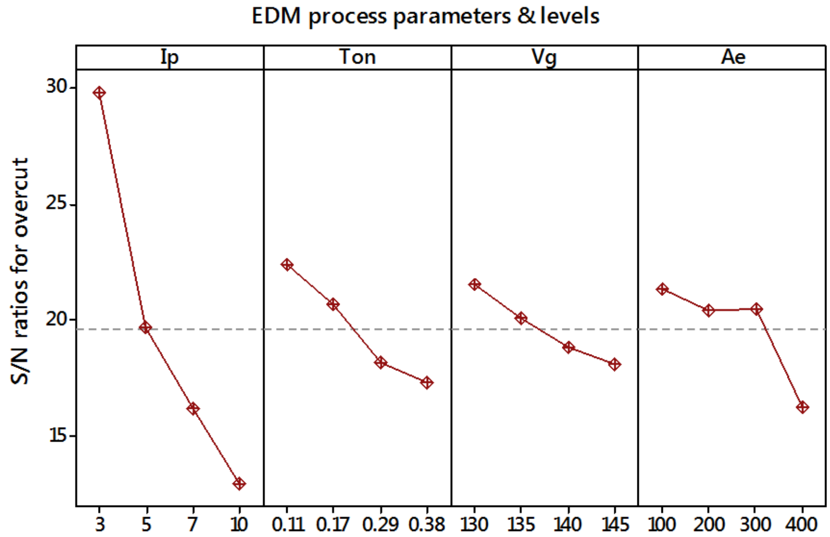

Fig. 9. S/N ratio plots for directional overcut.

3.3. Interaction plot analysis for directional overcut

Interaction plots are followed to analyse the influence of levels of one parameter in correlation to other parameters as shown in Fig. 10. Parallel lines in an interaction plot indicate smooth conduct in EDM process [22].

Similar parallel lines are observed in case of the interactions among I_p against T_{on}, V_g and A_e. The convergence of the levels shows tendency of possible interactions amongst the levels as in case of I_p against V_g and A_e. In the interaction plot, among T_{on} and V_g, heavy interactions are observed due to gap voltage effect [23], showing drastic increase in dimensional deviations for overcut response.

$$Directional\ Overcut\ (OC) = -0.73 + 0.0105\ I_p - 1.08\ T_{on} + 0.0120\ V_g - 0.000562\ A_e + 0.0181\ I_p \times T_{on} + 0.000153\ I_p \times V_g + 0.000040\ I_p \times A_e + 0.00895\ T_{on} \times V_g + 0.000307\ T_{on} \times A_e + 0.000003\ V_g \times A_e - 0.001365\ I_p^2 - 0.346\ T_{on}^2 - 0.000054\ V_g^2 \quad (3)$$

The quadratic polynomial regression analysis model is developed for directional overcut based on the experimental data input as shown in Eq. (3). The two-level parametric interactions [24] are also taken into consideration to correlate the effects of machining parameters.

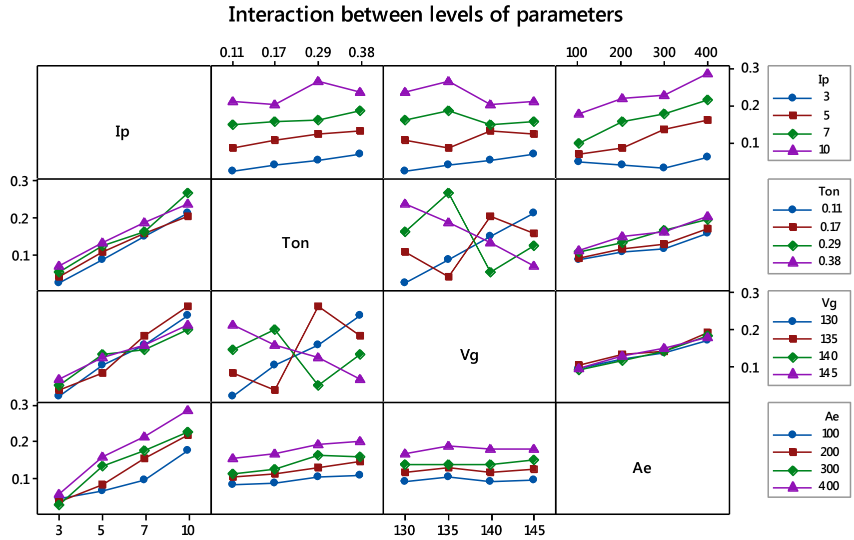

Fig. 10. Interaction plot for directional overcut.

3.4. Analysis of variance for EDM process parameters

ANOVA assist in determining the contribution of input parameters on response variable of the process. ANOVA is carried out to evaluate the significance of process variables at 95% of confidence interval [25]. Corresponding ANOVA results are shown in Table 3, where the contributions of two levels of interaction and second order of variables are also incorporated.

Table 3. ANOVA for EDM process parameters.

Source	DoF	Seq SS	Adj SS	Seq MS	F-Value	P-Value	Contribution
Regression model	14	0.3864	0.3864	0.0276	62.92	0.000	94.73%
I_p	1	0.2960	0.0000	0.2960	674.70	0.000	72.55%
T_{on}	1	0.0167	0.0004	0.0167	38.04	0.000	4.09%
V_g	1	0.0002	0.0001	0.0002	0.51	0.480	0.05%
A_e	1	0.0589	0.0004	0.0589	134.31	0.000	14.44%
$I_p \times T_{on}$	1	0.0002	0.0005	0.0002	0.54	0.464	0.06%
$I_p \times V_g$	1	0.0001	0.0001	0.0001	0.18	0.671	0.02%
$I_p \times A_e$	1	0.0087	0.0087	0.0087	19.80	0.000	2.13%
$T_{on} \times V_g$	1	0.0006	0.0006	0.0006	1.33	0.255	0.14%
$T_{on} \times A_e$	1	0.0008	0.0008	0.0008	1.88	0.177	0.20%
$V_g \times A_e$	1	0.0002	0.0002	0.0002	0.43	0.517	0.05%
I_p^2	1	0.0031	0.0035	0.0031	7.11	0.010	0.76%
T_{on}^2	1	0.0004	0.0004	0.0004	0.82	0.369	0.09%
V_g^2	1	0.0001	0.0001	0.0001	0.25	0.620	0.03%
A_e^2	1	0.0005	0.0005	0.0005	1.03	0.314	0.11%
Error	49	0.0215	0.0215	0.0004			5.27%
Total	63	0.4079					100%
R^2		94.73%		R^2- adj		93.23%	

The discharge current is the major parameter, which plays vital role with about 72.55% of the contribution, followed by spark discharge area as 14.44% and pulse on time as 4.09% for the directional overcut. Among the higher order parametric interaction of current intensity and spark discharge area ($I_p \times A_e$) is found to have a contribution of 2.13%.

The second order of current intensity (I_p^2) is also having role of 0.76%. The coefficient of correlations, R^2 and R^2-adj values of the regression analysis model are 94.73% and 93.23%, respectively, which shows that overcut model is good in statistical predictions.

3.5. Response surface plot for directional overcut

Response surfaces for two variables at the same time are analysed against directional overcut within the interval of finish cut machining. In the plot of OC against A_e & I_p, the levels I_p 3A give minimum directional overcut as shown in Fig. 11.

In the surface plot Fig. 12, it is observed that the directional overcut is maximum at pulse on time T_{on} 0.38 seconds and highest for spark discharge area A_e 400 mm². As the I_p and T_{on} increases the directional overcut increases. This takes place as stronger plasma is produced, generating more heat energy. The surface plot of OC against A_e and V_g in Fig. 13 shows the horizontal spread, which indicates that both parameters are stable in sparking process.

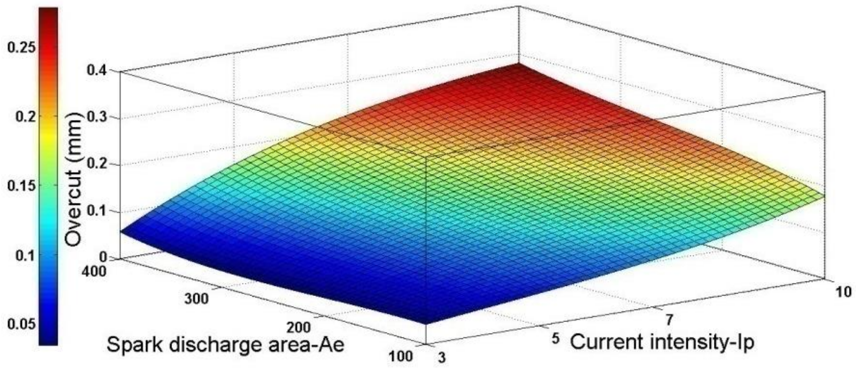

Fig. 11. Response surface for OC *Vs* A_e and I_p.

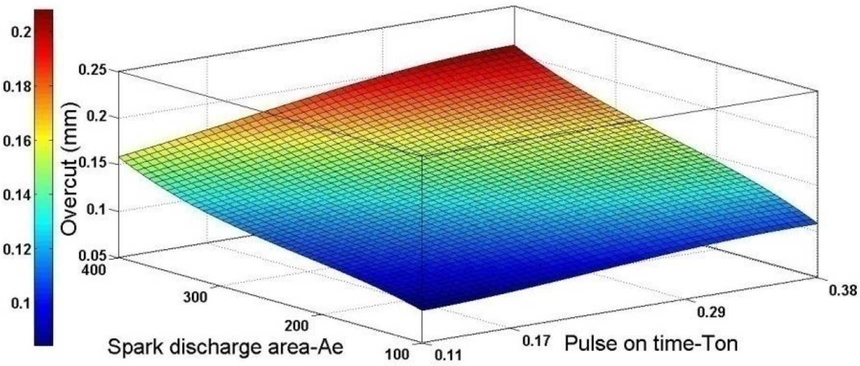

Fig. 12. Response surface for OC *Vs* A_e and T_{on}.

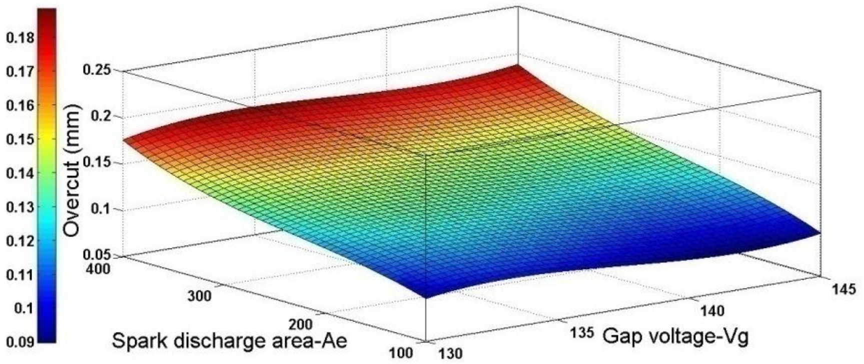

Fig. 13. Response surface for OC *Vs* A_e and V_g.

4. Conclusions

Investigations of variations of spark discharge area in finish cut EDM machining are reported in present work. Effects of spark discharge area variations for directional overcut are studied through orthogonal array L_{16} ×4 combinations. ANOVA has been carried out to study contribution of optimum EDM process parameters. Analysis of main effect and response surface plot reveal that machining parameter i.e. current intensity, pulse on time and gap voltage have found clear effect on directional overcut. Some of the findings are as follows:

- As the spark discharge area increases the directional overcut increases gradually. It reveals that more spark energy spread occurs at tool edges for larger spark discharge area. The directional overcut reduces as spark discharge area decreases, which leads to a favourable machining phenomenon in EDM.
- It is also found that the depth of cut is having a correlation with spark discharge area. As spark discharge area increases thereby, the depth of cut decreases because the spread of discharge energy takes place over the larger region.
- By analysing the experimental results, the current intensity is the most dominating parameter with about 72.55% contribution in directional overcut responses. The regression analysis model for directional overcut indicates the coefficient of correlation (R^2 value) as 94.73%, which shows good significance in statistical predictions.
- The parameter levels with current intensity as I_p 3A, pulse on time as T_{on} 0.11sec and spark gap voltage as V_g 130V are the optimum performance characteristics for dimensional accuracies in machining profiles.
- For maintaining better dimensional accuracy of finish cut EDM, lower level values of current intensity I_p 5 A and pulse on time T_{on} 0.29 seconds may be recommended, for seizing directional overcut in tool room EDM operational practices.

Nomenclatures

A_e	Spark discharge area
D_t	Dimensions of the tool
D_w	Cavity dimensions in workpiece
I_p	Current intensity
L_{16}	Orthogonal array
n	Average OC response
R^2	Coefficient of correlation
S/N	Signal to noise ratio
T_{on}	Pulse on time
V_g	Spark gap voltage
y_i	i^{th} response data of a parametric combination

Abbreviations

AISI	American Iron and Steel Institute
ANOVA	Analysis of Variance
DOC	Depth of Cut
D2	Cold Work Steel
EDM	Electrical Discharge Machining
OC	Directional Overcut

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