Scholars Journal of Engineering and Technology (SJET) **ISSN 2321-435X (Online)**
Sch. J. Eng. Tech., 2015; 3(4B):447-462 **ISSN 2347-9523 (Print)**
©Scholars Academic and Scientific Publisher
(An International Publisher for Academic and Scientific Resources)
www.saspublisher.com

Research Article

An Experimental Investigation on AISI 316 Stainless Steel for Tool Profile Change in Die Sinking EDM Using DOE

Abhijeetsinh V Makwana[1*], Kapil S Banker[2]
[1]PG Scholar, Department of Mechanical Engineering, Shankersinh Vaghela Bapu Institute of Technology, GTU Ahmedabad, Gujarat, India
[2]Assistant Professor, Department of Mechanical Engineering, Shankersinh Vaghela Bapu Institute of Technology, GTU Ahmedabad, Gujarat, India

***Corresponding author**
Abhijeetsinh V Makwana
Email: abhijeetmakwana720@gmail.com

Abstract: The objective of research is to study the influence of Process parameters and electrode shape configuration on the Machining characteristics of die sinking EDM. The present work aims to study the effect of different electrode shapes (Circular, rectangular and triangular) With constant cross sectional area of 280 mm^2 on material removal rate (*MRR*), surface roughness (*SR*) and Electrode wear rate (EWR) for AISI 316 Stainless steel workpiece material and pure copper As electrode material. Detailed analysis of structural features of machined surface is done by using Scanning Electron Microscope (SEM) to understand the mode of heat affected zone (HAZ), recast layer thickness and micro cracks which alternatively affects structure of machined workpiece and hence tool life. The optimization of the parameters of the EDM machining will be carried out by using the taguchi's method for design of experiments (DOE). The main objective of this analysis is to identify the Optimum electrode shapes in terms of higher MRR, minimum EWR and excellent surface characteristics. The optimum tool shape for higher MRR, lower EWR and excellent SR is circular, followed by rectangular and Triangular cross sections.
Keywords: Design of experiments (DOE), Electrical discharge Machining (EDM), Electrode Shape Configuration, Taguchi method, Parameter analysis, Signal to Noise Ratio (S/N).

INTRODUCTION

Die sinking electrical discharge machining (EDM) is one of the most widely used techniques for the fabrication of die and mold cavities which are finally used for mass production of metals and polymer products by replication such as die casting, injection molding, etc. In any replication process, it is expected that the quality mold will faithfully duplicate its shape and surface texture. Inaccurate duplications cause problems in assemblies, operations as well as lower the aesthetic view. In die sinking EDM the electrode produces exactly its opposite shape on the work material. Electrical energy is used to generate electrical sparks and material removal mainly occurs due to localized melting and vaporization of material which is carried away by the dielectric fluid flow between the electrodes. The performance of this process is mainly influenced by many electrical Parameters like, current, voltage, polarity, and pulse on time, pulse of time, electrode gap and also on non-electrical parameters like work and tool material, dielectric fluid pressure. All these electrical and non electrical parameters have a significant effect on the EDM output parameters. In the EDM process, material is removed from the workpiece by generating high-frequency electrical sparks through a thin dielectric layer between the electrode and the workpiece surface. However, the gap between the electrode and the work piece is very small (typically 5~100 µm), and thus debris tends to accumulate in the machining area. Unless this debris is efficiently removed, it causes a breakdown of the insulating properties of the dielectric layer and therefore induces a secondary discharge phenomenon, i.e. multiple electrical sparks within the same region of the machined surface. The secondary discharge phenomenon leads to a serious degradation of the surface roughness of the machined component and must therefore be suppressed by assigning suitable values to the EDM machining parameters to maintain the gap size at its designated value throughout the entire machining operation. In present day‘s scenario, EDM is used as a standard technique for manufacturing production tooling out of hardened materials for production of dies and moulds. Due to rapid tool wear involved; many electrodes are often required for machining each cavity. Tool wear affects machining accuracy and demand for frequent tool replacement adding to around 50% of tooling cost. Alternatively use of rapid tooling technique minimizes the electrode development lead-time and reduces the tooling cost considerably. Therefore, design, development and manufacturing of EDM electrode play a very vital role in EDM technology. A lot of published EDM research work relates to parameter optimization for a particular work tool interface or to determine best tool material for a particular work material. Many innovative electrode material and designs have also been tried. The objective of this review paper is to report and review the research work carried out by researchers in the field of EDM electrode design and manufacturing.

LITERATURE REVIEW

In this paper few selected research paper related to Die-sinker EDM and the studies carried out in these papers are mainly concerned with the different electrode shape configuration and EDM input parameters such as current, voltage, pulse on time, duty cycle, etc. and how these affect the machining characteristics like MRR, SR, TWR, HAZ, Recast layer thickness and Micro Cracks etc.

D. Gurguí *et al*. [1] investigated Influence of the Process Parameters to Manufacture Micro-cavities by Electro Discharge Machining (EDM). In this research the application of the conventional EDM process to manufacture micro cavities with the objective to obtain how the process parameters could effects on the result. As a result the dimensions and shape of the micro-cavities were analyzed. Finally the results provide recommendations of operating conditions for better micro-cavities manufacturing in stainless steel 316L.

T. Muthuramalingam *et al*. [2] has studied the Application of Taguchi-grey multi responses optimization on process parameters in electro erosion. This multi response optimization of the electrical discharge machining process has been conducted with AISI 202 stainless steel with different tool electrodes such as copper, brass and tungsten carbide. Gap voltage, discharge current and duty factor have been used as electrical excitation parameters with different process levels. Taguchi L27 orthogonal table has been assigned for conducting experiments with the consideration of interactions among the input electrical process parameters. Material removal rate, electrode wear rate and surface roughness have been selected as output parameters. From the experimental results, it has been found that the electrical conductivity of the tool electrode has the most influencing nature on the machining characteristics in EDM process.

M Manohar *et al*. [3] conducted experimental study to assess the effect of electrode bottom profile while machining Inconel 718 through EDM Process. Electrodes used were of copper rods of 12mm diameter. Experimental study was carried out to demonstrate that electrodes of convex and concave bottom profile can be used effectively for EDM of Inconel 718 material. From the experimental results, it has been found that Electrodes of convex bottom profile perform better than flat or concave profiled electrodes in terms of lesser recast-layer, better surface finish for plain surface machining and closer geometry and MRR for hole drilling. EWR is the least in the case of concave profile electrodes, preceded by convex profile electrodes and the flat profile electrode has the highest EWR.

Mohammadrezashabgard *et al*. [6] conducted experimental investigation and 3D finite element prediction of the white layer thickness, heat affected zone and surface roughness in EDM process. The experiments were carried out under the designed full factorial procedure to validate the numerical result. Inputs were pulse on time and pulsed current and workpiece used AISI H13 tool steel. Final result shows that the pulse on time leads to higher white layer thickness, depth of heat affected zone and SR.

Rajmohan T *et al*. [9] conducted Optimization of Machining Parameters in Electrical Discharge Machining (EDM) of 304 Stainless Steel using copper as a tool material. Input and output parameters were Pulse on Time, Pulse off Time, Voltage, Current and Material Removal Rate. Using taguchi's L9 OA and also using ANOVA technique. They finally concluded that the current and pulse off time are the most significant machining parameter for MRR in EDM of 304 Stainless Steel.

T. M. Chenthil Jegan *et al*. [10] has studied Determination of Electro Discharge Machining Parameters in AISI 202 Stainless Steel Using Grey Relational Analysis. Input and output parameters were Discharge Current, Pulse on Time, Pulse off Time and Material Removal Rate, Surface Roughness. The result shows that Discharge Current was the main parameter affecting the MRR. Hence by properly adjusting the control factors, work efficiency and product quality can be increased.

M. S. Sohani *et al*. [13] studied Investigations into the effect of tool shapes with size factor consideration in sink electrical discharge machining (EDM) process. He presents paper with the application of response surface methodology (RSM) for investigating the effect of tool shapes such as triangular, square, rectangular, and circular with size factor consideration along with other process parameters like discharge current, pulse on-time, pulse off-time, and tool area. Also The RSM-based mathematical models of material removal rate (MRR) and tool wear rate (TWR) have been developed using the data obtained through central composite design. He finally concluded that the best tool shape for higher MRR and lower TWR is circular, followed by Triangular, rectangular, and square cross sections. From the parametric analysis, it is also observed that the interaction effect of discharge current and pulse on-time is highly significant on MRR and TWR, whereas the main factors such as pulse off-time and tool area are statistically significant on MRR and TWR.

MATERIALS AND METHODS

The pure copper with 99.96 % is used as a tool material because of its higher MRR and less TWR and yields a better surface finish. The pure copper tools with constant cross sectional area of 280mm^2 and different shapes like triangular, rectangular, and circular are used to erode a stainless steel 316 workpiece. The tool material is a pure electrolytic copper (99.9% Cu). The physical and mechanical properties of electrolytic copper are as follows: electrical resistivity—16.7nΩm, and thermal conductivity—393 W/m K.. Fig. 1 & 2 shows the photograph of the tools and workpiece used for the experiments.

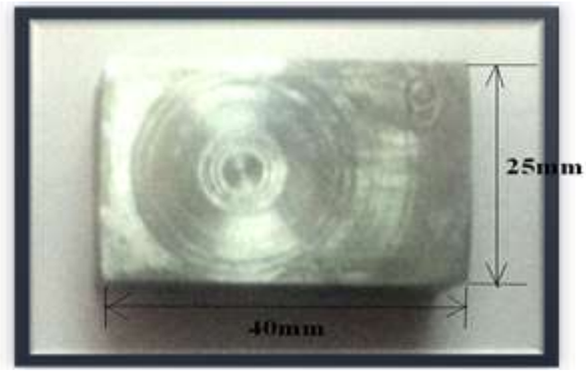


Fig.1: Raw material SS 316 plates as per required dimensions

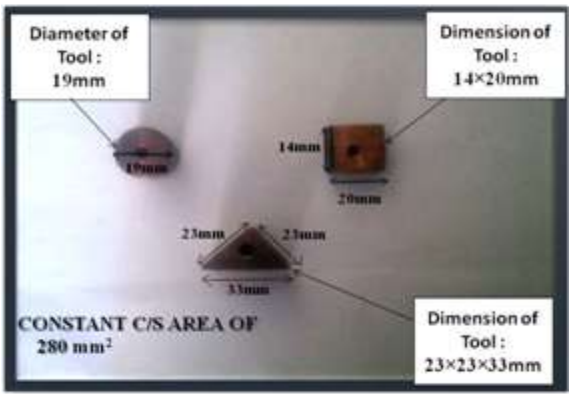


Fig. 2: Raw material pure copper (electrode shapes) as per required dimensions

Table 1: Properties of SS 316 workpiece material and pure copper electrode

Property	SS 316	Copper
Composition (Wt %)	C: 0.017, p:0.030, Mg:1.240, Cr:16.540, Ni:10.120, Si:0.440, S:0.021, Mo:2.100	Cu:99.960, Fe:0.018, Sb:0.002, Pb:0.000, Zn:0.002, P:0.001
Specific gravity (g/cm^3)	7.99	8.96
Melting point (°C)	1385	1083
Hardness (HRB)	80	100

EXPERIMENT DETAILS

In the present investigation, the experiments were performed in an "S25 Sparkonix" EDM machine. The impulse flushing of kerosene (dielectric fluid) was employed throughout the experimental investigations. The schematic diagram of the experimental setup is shown in Fig. 1.

Fig.3 Experimental Setup (S25 Sparkonix EDM)

DESIGN OF EXPERIMENTS

A systematic approach to investigate a system or a process, Introduced by R.A. Fisher in England in the early 1920's and then standardized by Dr. Genichi Taguchi.

Table 2 FACTORS & THEIR LEVELS

FACTORS	LEVEL 1	LEVEL 2	LEVEL 3
Current	10	15	20
Pulse on Time	6	8	7
Pulse off Time	5	7	6

Table 3 TAGUCHI'S L9 ORTHOGONAL ARRAY

SR NO.	CURRENT (Amp.)	PULSE ON TIME (μs)	PULSE OFF TIME(μs)
1	10	6	5
2	10	8	7
3	10	7	6
4	15	6	7
5	15	8	6
6	15	7	5
7	20	6	6
8	20	8	5
9	20	7	7

FINAL EXPERIMENTS AS PER DOE TABLE

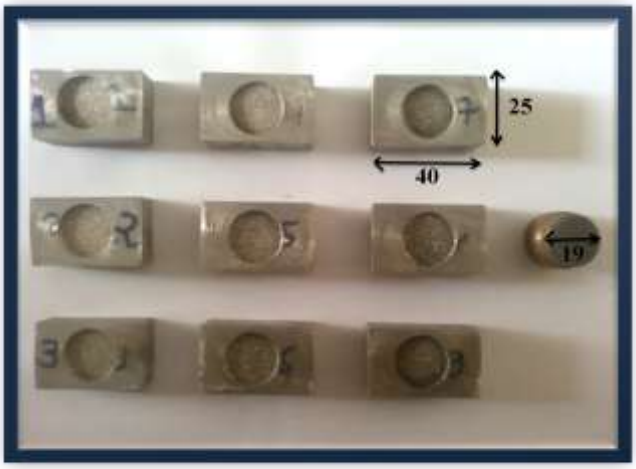


Fig.4 with Circular Tool

Fig.5 with Triangular Tool

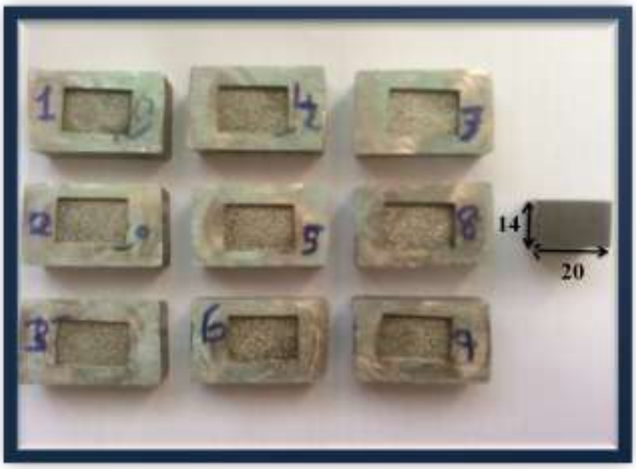


Fig.6 with Rectangular Tool

CALCULATION OF MRR (mm^3/min) & EWR (gm/min)

$$MRR = \frac{Wi - Wf}{\rho \times t}$$

$$EWR = \frac{Ti - Tf}{t}$$

Where,
W_i =Weight of workpiece before machining (in gm.)
W_f = Weight of workpiece after machining (in gm.)
ρ = density of work piece material. (In gm/mm^3)
t = time consumed for machining. (In minutes)
T_i =Weight of tool before machining (in gm.)
T_f = Weight of tool after machining (in gm.)

CALCULATION OF SR (µm)

Fig.7 Surface Roughness Tester

RESPONSE MEASURES

Table.4 Measured MRR, EWR & SR

SR NO.	SHAPE	I	T_{ON}	T_{OFF}	MRR (mm^3/min)	EWR (gm/min)	SR (µm)
1	○	10	6	5	44.826	0.001505	10.9022
2		**10**	**8**	**7**	48.532	**0.000804**	19.2010
3		**10**	**7**	**6**	31.398	0.001164	**9.8011**
4		15	6	7	51.612	0.004197	12.2055
5		15	8	6	71.592	0.004155	17.0260
6		15	7	5	72.769	0.002857	23.7787
7		20	6	6	75.926	0.006925	16.3809
8		**20**	**8**	**5**	**91.615**	0.006125	18.6624
9		20	7	7	85.368	0.007463	21.4050
10	△	10	6	5	29.991	0.003263	11.4422
11		10	8	7	30.594	0.001975	19.2414
12		10	7	6	37.051	0.002867	10.1080
13		15	6	7	54.891	0.005771	13.0221
14		15	8	6	49.601	0.003840	17.7259
15		15	7	5	56.105	0.003537	23.7922

16		20	6	6	66.168	0.004780	16.8874
17		20	8	5	68.513	0.008403	18.7841
18		20	7	7	59.513	0.005343	21.5472
19		10	6	5	34.672	0.001843	11.4351
20		10	8	7	29.076	0.001549	19.2241
21		10	7	6	38.305	0.003273	10.0102
22		15	6	7	52.830	0.005769	12.9151
23		15	8	6	66.129	0.007092	17.5571
24		15	7	5	70.236	0.004944	23.6810
25		20	6	6	87.590	0.009331	16.8705
26		20	8	5	77.446	0.006711	18.6921
27		20	7	7	73.734	0.004178	21.4420

RESULT & DISCUSSION

In this chapter, the optimization of the parameters of the EDM machining will be carried out by using the taguchi's method for design of experiments (DOE). The objective of the analysis is to identify the Optimum electrode shapes in terms of higher MRR, minimum EWR and excellent surface finish.

FOR MRR

Table-5: Response Table for Signal to Noise Ratios for MRR, Larger is better

Level	**Electrode shape**	**Current**	**Pulse on time**	**Pulse off time**
1	35.64	31.01	34.42	35.14
2	33.66	35.56	34.84	34.81
3	34.83	37.56	34.87	34.19
Delta	1.98	6.56	0.46	0.95
Rank	**2**	**1**	**4**	**3**

From Response table 5 for Signal to noise ratio larger is better for MRR, it is seen that 1 rank is given to current so current is most significant for MRR, followed by electrode shapes and pulse on time, pulse off time are less significant. In 1 Rank having 37.56 is larger S/N ratio for level 3 so, I.e. 20 A is more significant.

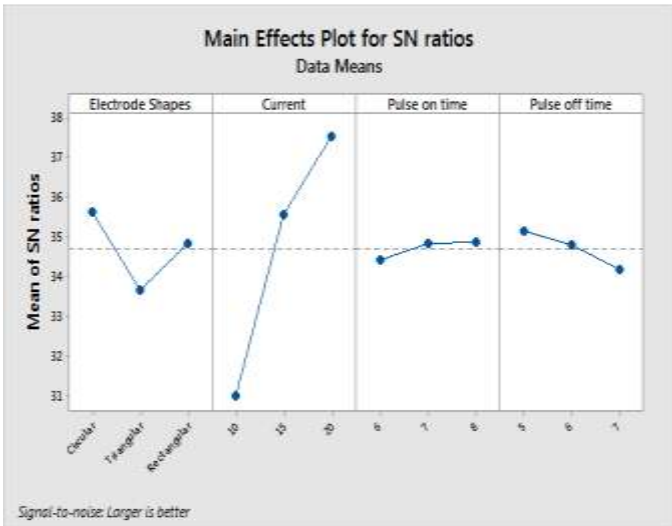


Fig.8: Main Effects Plot For SN Ratio for MRR

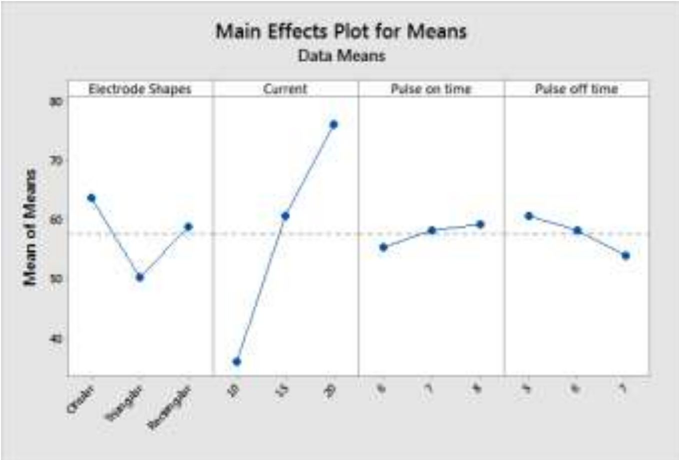


Fig.9: Main Effects Plot for Means for MRR

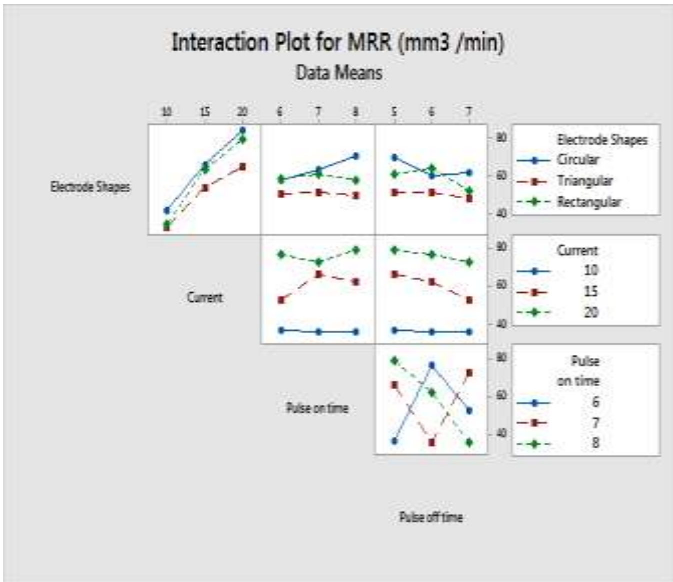


Fig.10: Interaction Plot for MRR

FOR EWR

Table- 6: Response Table for Signal to Noise Ratios for EWR, Smaller is better

Level	Electrode shape	Current	Pulse on time	Pulse off time
1	50.34	54.70	47.57	48.46
2	47.79	46.89	48.98	47.60
3	47.35	43.89	48.93	49.43
Delta	2.99	10.81	1.41	1.83
Rank	2	1	4	3

From Response table 6 for Signal to noise ratio Smaller is better for EWR, it is seen that 1 rank is given to current so current is Most significant for EWR, followed by electrode shapes and pulse on time, pulse off time are less significant. In 1 Rank having 43.89 is Smaller S/N ratio for level 3 so, I.e. 20 A is more significant.

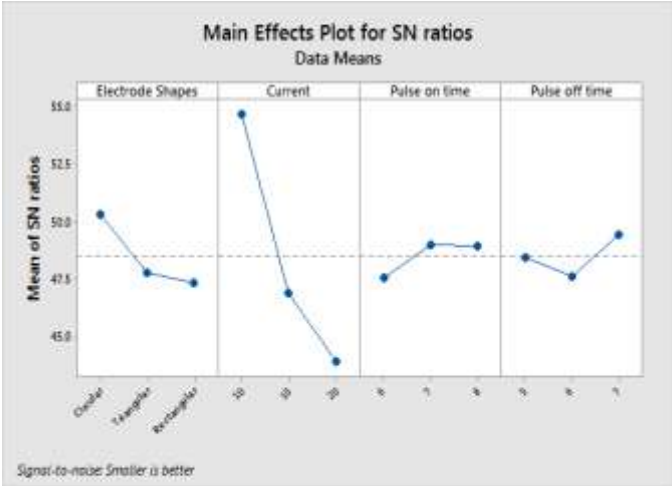


Fig.11 Main Effects Plot For SN Ratio for EWR

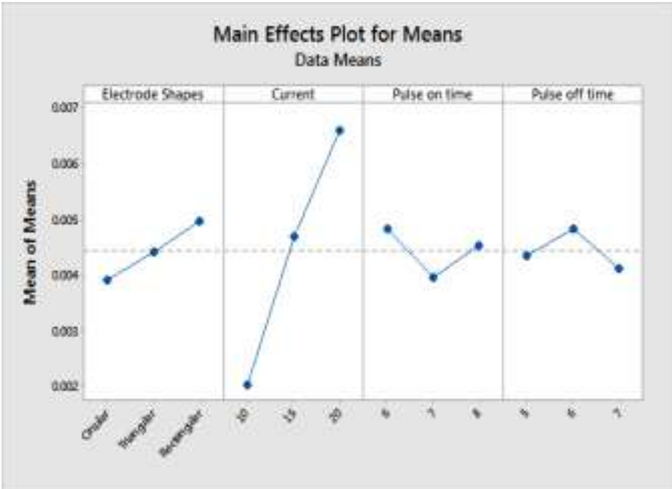


Fig.12 Main Effects Plot For Means for EWR

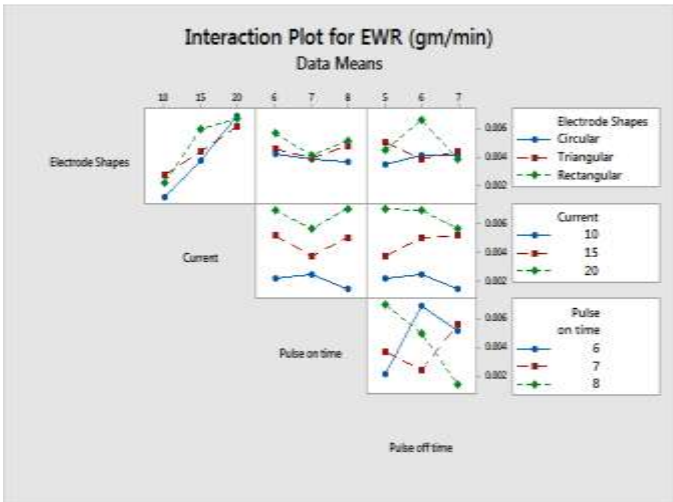


Fig.13 Interaction Plot for EWR

FOR SR

Table 7 Response Table for Signal to Noise Ratios for SR, Smaller is better

Level	Electrode shape	Current	Pulse on time	Pulse off time
1	-24.05	-22.23	-22.52	-24.66
2	-24.27	-24.81	-24.71	-23.09
3	-24.23	-25.51	-25.32	-24.80
Delta	0.22	3.29	2.79	1.71
Rank	4	1	2	3

From Response table for Signal to noise ratio Smaller is better for SR, it is seen that 1 rank is given to current so current is significant for SR, followed by pulse on time And electrode shapes, pulse off time are less significant. In 1 Rank having -25.51 is Smaller S/N ratio for level 3 so, i.e. 20 A is more significant.

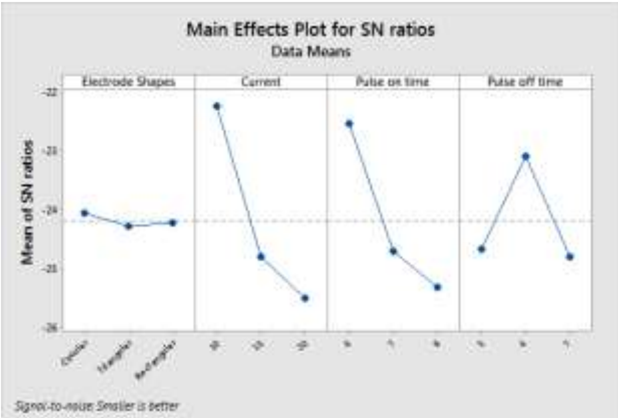
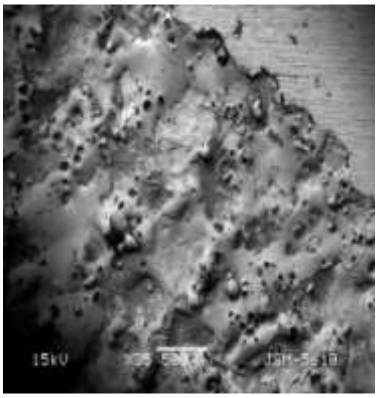


Fig.14 Main Effects Plot For SN Ratio for SR



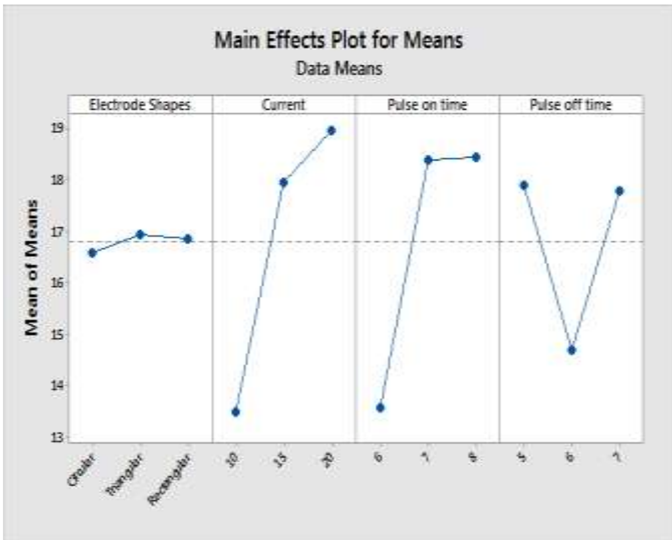


Fig.15 Main Effects Plot For Means for SR

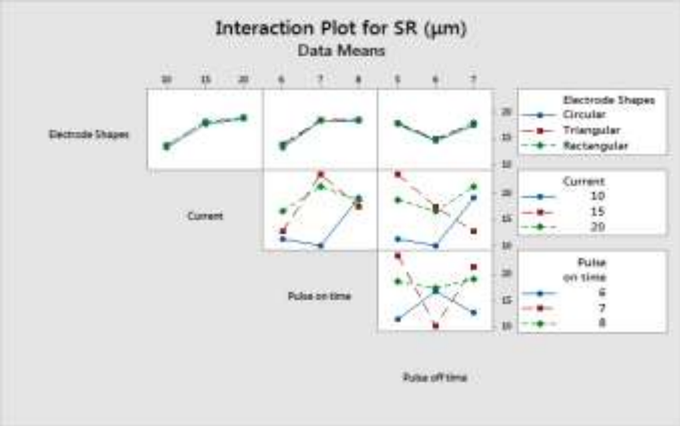
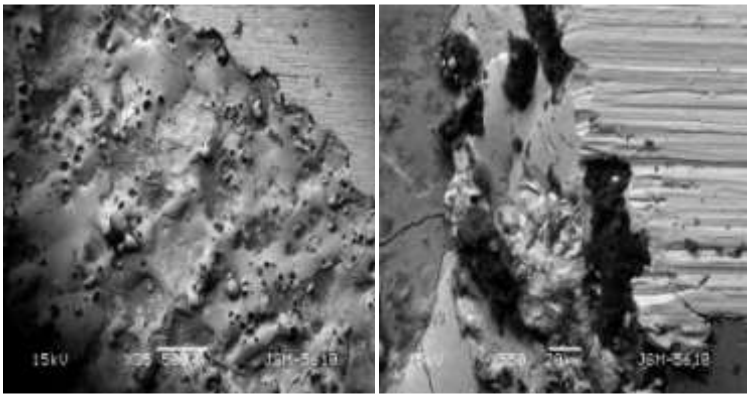


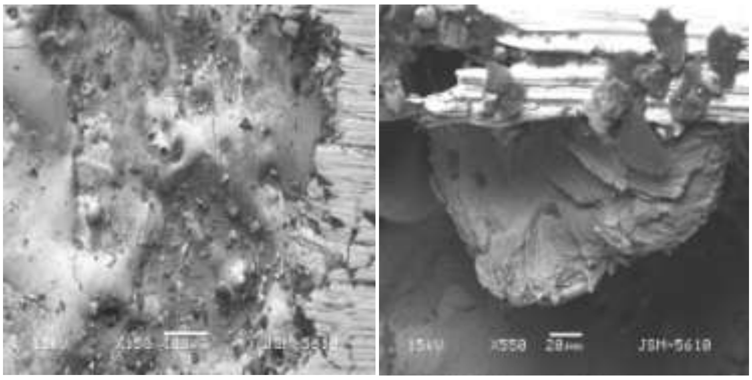
Fig.16 Interaction Plot For SR

ANALYSIS OF HAZ, RECAST LAYER THICKNESS & MICRO CRACKS

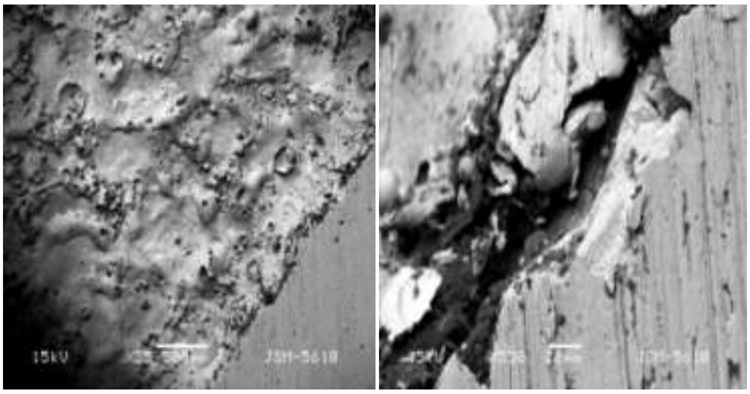
- Scanning Electron Microscope (SEM) was used to investigate the effect of machining parameters on recast layer thickness, micro cracks and heat affected zone on the machined surface.
- Among the surface defects cracking is the most significant since it leads to a reduction in the fatigue and corrosion resistance of the material especially under tensile loading condition.
- Micro cracks for workpiece were revealed at high magnification using SEM microscope.
- Formation of recast layer is as a result of molten materials that are not completely flush away by dielectric fluid from the workpiece surface. These molten materials solidify during cooling process and deposited on the workpiece.
- HAZ refers to the region of a workpiece that did not melt during electrical discharge but has experienced a phase transformation, similar to that of heat treatment processes, after being subjected to the high temperatures of electrical discharge.



(For Circular: I=20A, T_{ON}=8μs, T_{OFF}=5μs)



(For Rectangular: I=20A, T_{ON}=6μs, T_{OFF}=6μs)

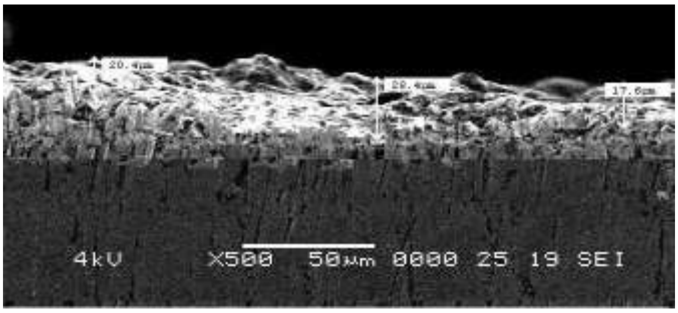


(For Triangular: I=20A, T_{ON}=8µs, T_{OFF}=5µs)

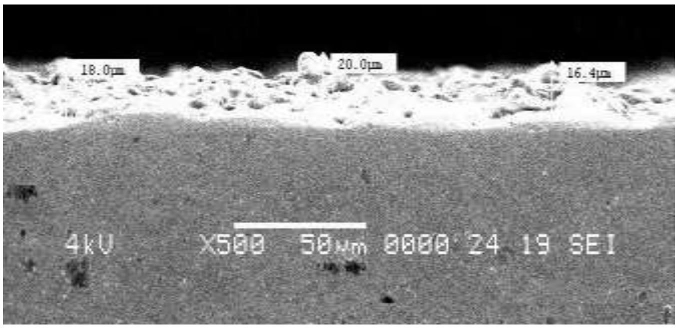
Fig 17 SEM Photographs Showing Heat Affected Zone and Recast Layer for Different Electrode Shapes (Circular, Rectangular and Triangular)

ANALYSIS OF RECAST LAYER THICKNESS AT DIFFERENT MACHINING CONDITION

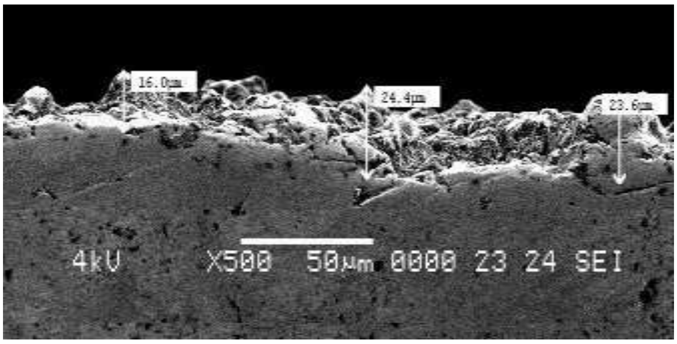
In EDM the Higher current and a higher pulse-on time produces a spark with more energy, so melt more materials from the workpiece and the tool. A higher thickness of recast layer is found at a current of 20 Amp, Fig.18 (a) compared to that at a current of 15 Amp, Fig.18 (b) Similarly, thickness of the recast layer was found to be at a higher pulse-on time, Fig 18 (c) compared to that at a shorter pulse-on time, Fig 18 (d). Hwa-Teng Lee et al., 2004 also stated that R and average white layer thickness tend to increase at higher values of pulse current and t_{on}. However, they found that for extended pulse-on duration MRR, R and crack density all decrease. Fig 18 (a, b, c, d) SEM Photographs Showing Recast Layer Thickness at Different Machining Condition.



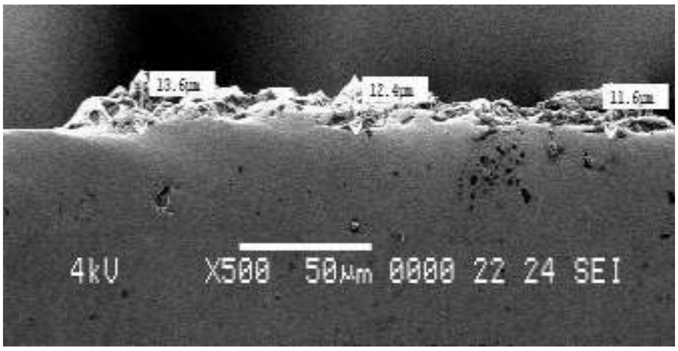
(a). $t_{average}$ 22.13 µm: Current= 20 Amp; Ton =8µs; T_{off}= 5µs



(b). $t_{average}$ 18.13 µm: Current = 15 Amp; Ton =7µs; T_{off}= 5µs



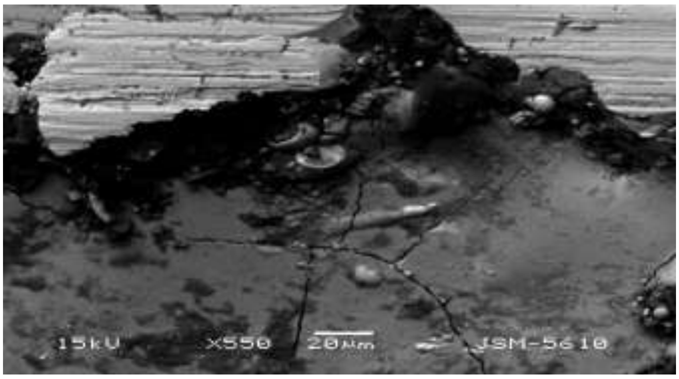
(c). $t_{average}$ 21.33 µm: Current= 15 Amp; Ton =8µs; T_{off}= 6µs



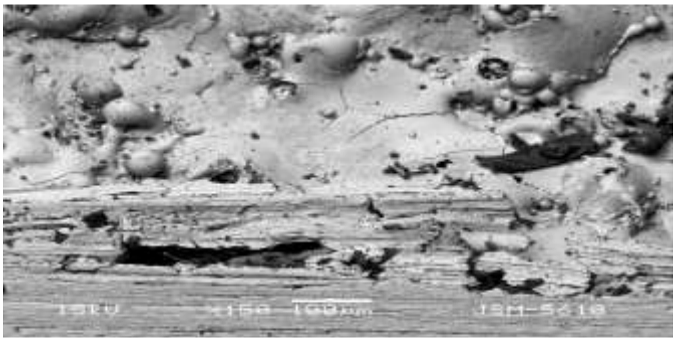
(d). $t_{average}$ 12.53 µm: current= 10 Amp; Ton =6µs; T_{off}= 5µs
Fig 18 Thickness of Recast Layer at Different Machining Condition

ANALYSIS OF MICRO CRACK

The appearances of micro cracks in the EDM process are usually recast layer sized and propagate in the vertical direction, perpendicular to the analyzed surface.



(For Circular: I=20A, T_{ON}=8µs, T_{OFF}=5µs)



(For Rectangular: I=20A, T_{ON}=6µs, T_{OFF}=6µs)
Fig-19: Shows the appearance of micro cracks,

Importance of identifying and understanding these final results made by SEM analysis and the formation mechanisms of these metallurgical alterations on workpiece and electrode is important to analyze in order to minimize their occurrence and provide a better quality for the EDM machined surfaces for better production.

CONCLUSION

In this research the influence of electrode shape, discharge current, pulse on time and pulse off time on MRR, EWR and SR are investigated. Electrodes of Three different shapes of constant cross-sectional area of 280mm2 are used for Experiment. The MRR, EWR and surface roughness are measured and analyzed. Further effect of different electrode shapes has also been studied upon Surface Roughness (SR), Heat affected zone (HAZ), Recast Layer Thickness and Micro Cracks of machined surface of the AISI 316 Stainless Steel.

The Following conclusions can be made from this experimental research.

- The main effects of current, pulse on time, pulse off time are significant in MRR, SR and EWR, also higher-order effect of pulse on time and current have significant contribution in MRR and EWR.
- The Optimum tool shape for higher material removal rate, lower electrode wear rate and lower surface roughness is circular, followed by Triangular and rectangular cross sections of tools.
- Main effects plots for MRR shows that, the MRR increases linearly with applied current, also MRR increases with pulse on-time duration and then starts decreasing with increase in pulse off time duration.
- Main effects plots for EWR shows that, the EWR increases linearly with applied current, and the EWR decreases with pulse on-time and then increase with pulse off duration.
- Main effects plots for SR shows that, the SR increases linearly with applied current, and the pulse on-time and then decrease with pulse off duration and then starts increasing with increase in pulse off time duration.
- The influence of the shape of electrodes on surface roughness is found to be insignificant. However, a round shape electrode produces a smoother surface followed by the triangular and rectangular shaped electrodes.
- When current is increased, the crack length, crack widths are also increased due to the high temperature generation at high currents. Formation of micro cracks increases during EDM with a higher current and higher pulse-on time.
- Lower discharge current and lower pulse-on duration should be used for a lower hardened surface and thinner heat affected zone HAZ but reduces the material removal rate; consequently, the machining time will increase.
- A thicker layer of white layer is formed on the machined work surface, with a higher current and pulse-on time duration.
- Cavities made by EDM die sinking may have intricate shapes and it is difficult to achieve high accuracy at the sharp corner of the cavities. The single irregular electrode contains several geometries such as flat, round, square surface, pointed tip, etc. which removes materials with different effectiveness. The present paper proposes to carefully select the EDM parameters for machining cavities with multiple and intricate shaped electrodes.

- **Optimum Values For MRR :**

SR NO	SHAPE	I (A)	T_{ON} (µs)	T_{OFF} (µs)	MRR (mm^3/min)
1	Circular	20	8	5	91.615

- **Optimum Values For EWR :**

SR NO	SHAPE	I (A)	T_{ON} (µs)	T_{OFF} (µs)	EWR (gm/min)
1	Circular	10	8	7	0.000804

- **Optimum Values For SR :**

SR NO	SHAPE	I (A)	T_{ON} (µs)	T_{OFF} (µs)	SR (µm)
1	Circular	10	7	6	9.8011

REFERENCES

1 Gurguí D, Vázquez E, Ferrer I; Influence of the process parameters to manufacture micro-cavities by Electro Discharge Machining (EDM). Procedia Engineering, 2013; 63:499-505.

2 Muthuramalingam T, Mohan B; Application of Taguchi-grey multi responses optimization on process parameters in electro erosion. Measurement, 2014; 58:495-502.

3 Manohar M, Selvaraj T, Sivakumar D, Gopinath S, George KM; Experimental Study to Assess the Effect of Electrode Bottom Profiles while Machining Inconel 718 through EDM Process. Procedia Materials Science, 2014; 6: 92-104.

4 Mhatre MS, Sapkal SU, Pawade RS; Electro discharge machining characteristics of Ti-6Al-4V alloy: A grey relational optimization. Procedia Materials Science, 2014; 5.

5 Torres A, Puertas I, Luis CJ; Modelling of surface finish, electrode wear and material removal rate in electrical discharge machining of hard-to-machine alloys. Precision Engineering, 2015;40:33-45.

6 Shabgard M, Oliaei SNB, Seyedzavvar M, Najadebrahimi A; Experimental investigation and 3D finite element prediction of the white layer thickness, heat affected zone, and surface roughness in EDM process. Journal of mechanical science and technology, 2011; 25(12):3173-3183.

7 Das MK, Kumar K, Barman TK, Sahoo P; Optimization of surface roughness and MRR in EDM using WPCA. Procedia Engineering,2013; 64:446-455.

8 Chen DC, Jhang JJ, Guo MW; Application of Taguchi design method to optimize the electrical discharge machining. Journal of Achievements in Materials and Manufacturing Engineering, 2013;57(2):76-82.

9 Rajmohan T, Prabhu R, Rao GS, Palanikumar K; Optimization of Machining Parameters in Electrical Discharge Machining (EDM) of 304 Stainless Steel. Procedia Engineering,2012; 38:1030-1036.

10 Jegan TC, Anand MD, Ravindran D; Determination of electro discharge machining parameters in AISI202 stainless steel using grey relational analysis. Procedia Engineering, 2012; 38:4005-4012.

11 Gopalakannan S, Senthilvelan T; Effect of Electrode Materials on Electric Discharge Machining of 316 L and 17-4 PH Stainless Steels. Journal of Minerals and Materials Characterization and Engineering, 2012; 11(07): 685.

12 Choudhary R, Kumar H, Garg RK; Analysis and evaluation of heat affected zones in electric discharge machining of EN-31 die steel. Indian J. Eng. Mater. Sci, 2010;17:91-98.

13 Sohani MS, Gaitonde VN, Siddeswarappa B, Deshpande AS; Investigations into the effect of tool shapes with size factor consideration in sink electrical discharge machining (EDM) process. The International Journal of Advanced Manufacturing Technology, 2009; 45(11-12):1131-1145.

14 Srivastava V, Pandey PM; Statistical Modeling and Material Removal Mechanism of Electrical Discharge Machining Process with Cryogenically Cooled Electrode. Procedia Materials Science, 2014; 5:2004-2013.

15 Singh S, Maheshwari S, Pandey PC; Some investigations into the electric discharge machining of hardened tool steel using different electrode materials. Journal of materials processing technology,2014; 149(1): 272-277.

16 Ghanem F, Fredj NB, Sidhom H, Braham C; Effects of finishing processes on the fatigue life improvements of electro-machined surfaces of tool steel. The International Journal of Advanced Manufacturing Technology, 2011; 52(5-8): 583-595.

17 Ekmekci B; White layer composition, heat treatment, and crack formation in electric discharge machining process. Metallurgical and Materials Transactions B, 2009; 40(1):70-81.

18 Ekmekci B; Residual stresses and white layer in electric discharge machining (EDM). Applied Surface Science, 2007; 253(23): 9234-9240.

19 Lee HT, Tai TY; Relationship between EDM parameters and surface crack formation. Journal of Materials Processing Technology, 2003;142(3): 676-683.

20 Casas B, Torres Y, Llanes L; Fracture and fatigue behavior of electrical-discharge machined cemented carbides. International Journal of Refractory Metals and Hard Materials, 2006; 24(1):162-167.

21 Rebelo JC, Dias AM, Kremer D, Lebrun JL; Influence of EDM pulse energy on the surface integrity of martensitic steels. Journal of Materials Processing Technology, 1998; 84(1): 90-96.

22 Kumar S, Singh R, Singh TP, Sethi BL; Surface modification by electrical discharge machining: A review. Journal of Materials Processing Technology, 2009; 209(8):3675-3687.

23 Panda DK; Study of thermal stresses induced surface damage under growing plasma channel in electro-discharge machining. Journal of materials processing Technology, 2008; 202(1): 86-95.

24 Tai TY, Lu SJ; Improving the fatigue life of electro-discharge-machined SDK11 tool steel via the suppression of surface cracks. International Journal of Fatigue, 2009; 31(3):433-438.

25 Rajesh R, Anand MD; The optimization of the electro-discharge machining process using response surface methodology and genetic algorithms. Procedia Engineering, 2012; 38: 3941-3950.

26 Assarzadeh S, Ghoreishi M; Statistical modeling and optimization of process parameters in electro-discharge machining of cobalt-bonded tungsten carbide composite (WC/6% Co). Procedia CIRP, 2013; 6: 463-468.
27 Sahu J, Mohanty CP, Mahapatra SS; A DEA approach for optimization of multiple responses in electrical discharge machining of AISI D2 steel. Procedia Engineering, 2013; 51:585-591.
28 Gopalakannan S, Senthilvelan T, Ranganathan S; Modeling and Optimization of EDM Process Parameters on Machining of Al 7075-B 4 C MMC Using RSM. Procedia Engineering, 2012; 38:685-690.
29 Muthukumar V, Rajesh N, Venkatasamy R, Sureshbabu A, Senthilkumar N; Mathematical Modeling for Radial Overcut on Electrical Discharge Machining of Incoloy 800 by Response Surface Methodology. Procedia Materials Science, 2014; 6:1674-1682.
30 Das MK, Kumar K, Barman TK, Sahoo P; Application of Artificial Bee Colony Algorithm for Optimization of MRR and Surface Roughness in EDM of EN31 tool steel. Procedia Materials Science, 2014; 6:741-751.