Indian Journal of Engineering & Materials Sciences
Vol. 27, August 2020, pp. 819-825

Optimization of process variables in electric discharge machining (EDM) using Taguchi methodology

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Received: 26 May 2020

The present study engrossed with the functional relationship between the input and output parameters of the electric discharge machining (EDM). Four controllable machining parameters, viz. gap voltage (A), current (I_p), duty cycle (C) and pulse on time (T_{on}) have been chosen to ascertain the electrode wear rate (EWR) and surface roughness (SR) of AISI 420 material with copper electrode. Through Taguchi method, a design of experiment developed and it has been used to perform the experiment based on L16 orthogonal array (OA). During machining of AISI420, the highest influencing factor in EWR is I_P and least is C. Similarly, for SR T_{on} is most and C is least significant factor. From analysis of variance (ANOVA), for EWR, I_P is having most significant 79.43% contribution and C is having least significant 2.36 % contribution. Similarly, for SR, T_{on} is having most significant 39.95% contribution and A is having least significant 11.79 % contribution.

Keywords: EDM, AISI420 steel, Taguchi Method, ANOVA

1 Introduction

Non – traditional methods (NTM) have been widely used due to growing need of precision machining of high strength materials[1]. NTM offers superior machining capabilities in comparison to conventional machining processes and offers economical and practical viable suitability for solutions in case of complex and intricate shapes[2]. Since the inception, newer methods are being developed by researchers to offer machining solution to newer developed materials. These processes take part a distinguished character in the tool making, die making, aircraft and automobile industries. Now, It is recognized as a normal machining process for manufacturing different tools to produce dies, machining of tool steels (heat treated), metal matrix composites (MMC), super alloys and ceramics requiring high exactness, complicated shapes with high surface finish *etc.*, because of its excellent machining characteristics and high correctness which can't be done by other conventional machines[3]. Though working principle of EDM (Fig. 1) has already been discussed in past by researchers, authors attempt hereby to briefly outline the working principle of EDM for better understanding of readers[4]. EDM includes material removal employing controlled discharge through a gap (approx.10 – 50 μm) with fluid between workspiece and an electrode. Discussion about EDM principle and working has been made by the researchers earlier[5].

Table 1 presents briefly important research produced by several researchers[6-23] in the preceding few years along with remarkable result (s) to give way for the research work shown in this article. This helps the authors in identifying the different process variables and output parameters in order to optimize the process under question.

Authors have worked for extensive literature review of the problem concerned and found that very limited work has been performed by the researchers

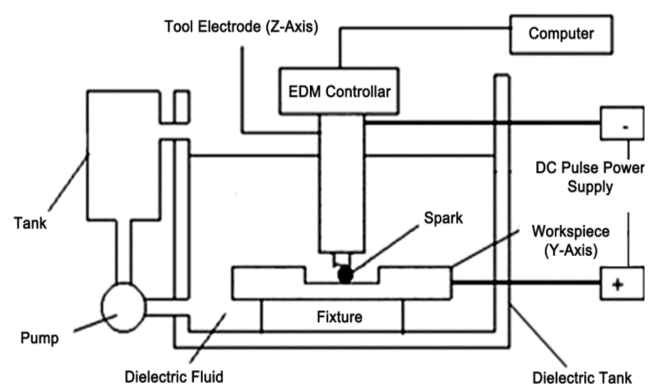

Fig. 1 — Schematic diagram of EDM.

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Table 1 — Brief recent related research work summary.

Sl. No.	Author (s) (Year)	Work piece material	Electrode material	Performance parameters	Salient Outcome (s)
1	Mohd Amri Lajis *et al.* (2009)[6]	Tungsten Carbide	Graphite	MRR EWR SR	Studied the effect of I_p and T_p on EWR, SR and MRR.
2	Sanjeev Kumar & Rupinder Singh (2010)[7]	OHNS type die steel	Cu	SR	Described the effect of I_p, T_{on}, T_{off} and P' of the tool electrode on SR.
3	S Prabhu & B.K. Vinayagam (2011)[8]	Inconel-825 (Nickel alloy)	Cylindrical copper rod	SR	Better surface finish and reduced micro cracks obtained.
4	Razak M.A. *et al*. (2016)[9]	AZ31 magnesium alloy	Cu	SR	T_{on} & T_{off} most and least significant factor to affect SR respectively.
5	S Marichamy *et al.* (2016)[10]	α–β Brass (Duplex Brass)	Cu	MRR EWR SR	I_p most significant factor to affect MRR, EWR & SR.
6	Jeykrishnan. J *et al.* (2016)[11]	EN24 tool steel	Nickel platted copper	MRR TWR	I_d affect both MRR and SR significantly.
7	Banh Tien Long *et al.* (2016)[12]	SKT4, SKD61, SKD11 die steels	Cu Gr Ti Powder	MRR	Maximize MRR.
8	Kumar P. and Parkash R (2016)[13]	*Al–B$_4$C* composite	Cu EN-19 Graphite	MRR SR EWR	Investigated effect of I_p, T_{on} and Electrode material on MRR, EWR and SR.
9	B Koteswararao *et al.* (2017)[14]	High carbon Alloy Steel (EN31)	Cu	MRR EWR OC	I_d most influencing factor on MRR, EWR and Overcut (OC).
10	Chandramouli S (2017)[15]	17-4 PH Steel	Cu-W	MRR SR	Analyzed control of parameters on MRR & SR.
11	Pallavi Chaudhury *et al.* (2017)[16]	EN-19	Cu-W	MRR TWR OC	Used Taguchi method to optimize the parameters of EDM.
12	Abhijit Saha and Subhas Chandra Mondal (2017)[17]	Nano Structured Hardfacing Material (NanoCarb 110)	Brass (Conventional) and Zinc-coated wire	MRR SR MT	Studied effect of different wires on MRR, MT and surface[17].
13	Ugrasen G *et al.* (2018)[18]	SS304 (thickness 30 mm, 40mm)	Molybdenum wire	MRR SR Accuracy	Optimized the process parameters.
14	K Singh *et al.* (2018)[19]	AISI H-13	zinc coated diffused and Soft brass wire	MRR SR	Examined the effect of T_{on}, I_p on SR & MRR.
15	Sagar Patel *et al.* (2018)[20]	Inconel 718	Cu-W	MRR TWR SR	Optimized MRR, TWR and SR using Taguchi methodology.
16	Chandramouli S., Eswaraiah K. (2018)[21]	17-4 PH steel	Cu-W (20:80 grade)	MRR SR	Studied the effect of T_{on}, T_{off} & I_d on MRR and SR.
17	Praveena T, Prasanna J (2019)[22]	Ti–6Al–4V	Cu	MRR TWR OC	Optimized the MRR, TWR and OC using Taguchi Method.
18	Ezeddini S *et al.* (2019)[23]	Recycled Titanium based composite (an alloy Ti17)	Brass wire	MRR Kerf width	MRR and KW largely affected by Speed of advance and servo voltage.

using the AISI 420 grade steel for different issues for machining like SR, material removal rate (MRR) and EWR *etc.* The material, AISI 420 is found to have comparable mechanical properties to other grades of steel like AISI 304 and AISI 316, but offers higher hardness and thermal conductivity making it suitable for different applications like making dies, cutting tools, surgical instruments, pump shafts and steel balls *etc.*

In this paper, a EDM process is explained with four controllable process parameters, while machining of the AISI 420 with copper electrode as it has been brought up above that several researchers have been investigation worked out on the EDM process on different materials, but not above mentioned material machined with cu electrode. Hence the objective of the presented study to discuss different machining conditions for AISI 420 using EDM and presenting optimal combination of process variables (*viz.* A, I_P, C and T_{on}) over the output variables (*viz.* EWR and SR, respectively) using Taguchi methodology.

2 Experimental methodology

The workpiece used for the experiments is made of AISI 420 and is being used at temperature exceeding 427 ^{o}C due to rapid softening and loss of corrosion resistance. Nominal details of the experimental setup, workpiece and methodology adopted have been presented in Fig. 2. The properties of tool electrode material, Chemical composition and physical properties of AISI 420 are specified in Tables 2 and 3, respectively.

Experiments have been conducted by using Taguchi L16 OA where total four parameters considered as four-level were selected to analyse the influence of the parameters on the responses. Input process parameters and their levels are shown in Table 4. Every experiment has been performed three times for each experimental run to minimize any kind of error incurred and their average value is taken into account.

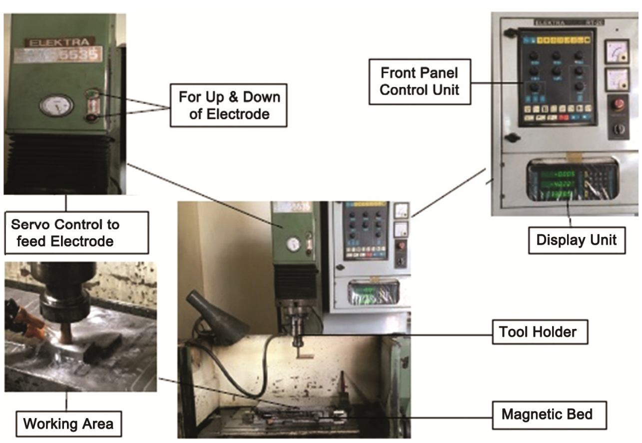

Fig. 2 — Actual experimental setup.

Table 2 — Properties of tool electrode material.

Electrode Material	Density (gm/cc)	Specific heat (J/kg.K)	Thermal conductivity (W/mK)	Electrode Resistivity (μ-ohms)	Hardness (BHN)
Copper	8.9	386	399	1.69	48

2.1 Relevance of output variables

a. The EWR is indicator of the volume of electrode removed per unit time during the machining operation and its increase with respect to time results in increased productivity.

b. SR is a indication of the irregularities in the surface and is a surface texture. It is computed in terms of vertical deviations of the real surface from its ideal surface.

c. The four controllable parameters were optimized using MINITAB 19.0 software.

3 Taguchi L16

With growing industrial need and consistent thrust over optimal utilization of machining facilities available, different optimization techniques have been employed of which, Taguchi method is prominently used[24]. It has been considered as one of simple technique with reliable, systematic and efficient tool for optimization of different process parameters including machining processes[25]. A schematics of above mentioned steps has been discussed briefly in Fig. 3.

Table 4 — Machining parameters and their levels for experimentation.

Input Parameters	Unit	Code	Range (as specified by Machine Manufacturer)	Levels and Values 1	2	3	4
Gap voltage	Volt (V)	A	15-150	15	45	75	105
Current	Ampere (A)	I_P	0-10	2	4	6	8
Duty Cycle	%	C	8-96	24	48	72	96
Pulse on time	μsec	T_{on}	0.5-2000	50	100	150	200

Table 3 — Chemical composition and physical properties of AISI420.

Chemical composition of AISI420					
Carbon	Silicon	Manganese	Chromium	Phosphorous	Sulphur
0.23	0.384	0.310	13.208	0.040	0.030
Physical Properties of AISI420					
Density (gm/cc)	Specific heat (KJ/kg.K)	Thermal conductivity (W/mK)	Hardness (HRC)	Tensile strength (MPa)	Elongation %
7750	0.46	24.9	33	1120	18.2

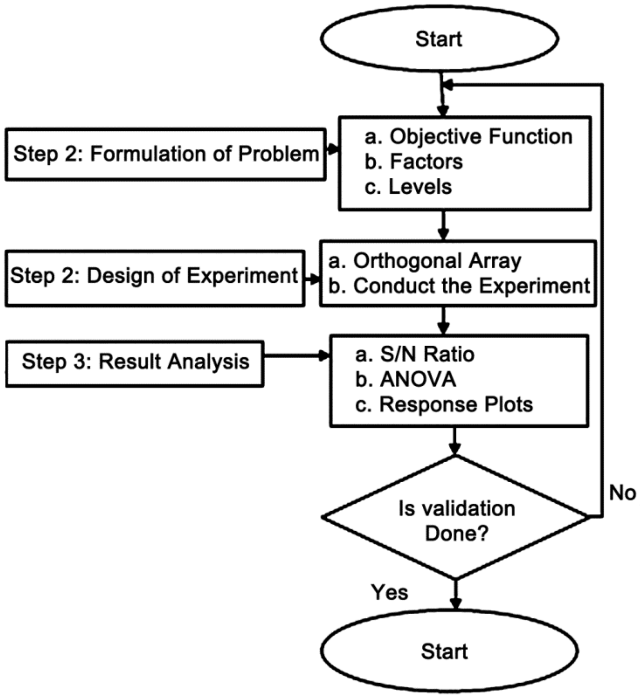

Fig. 3 — Basic steps for Taguchi methodology.

The technique involves application of OA experiments with reduced variance for the experiment designed with optimal setting. Hence, it is aimed to obtain best optimal results with design of experiments using Taguchi method. OA provides optimal number of experiments and calculation of S/N ratio (SNR), which is a log function of desired output of the objective function[26].

For larger the better (LTB) (maximize response), the model equation is as follows:

$$\eta = -10\ log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad \ldots(1)$$

For smaller the better (STB) (minimize response), the model equation is as follows:

$$\eta = -10\ log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \quad \ldots(2)$$

Taguchi method alters the values of objective function to SNR as a measure of the performance characteristics of the experiment[27]. ANOVA evaluates parameters [like Degree of freedom (DOF), sum of square (SS)], variance and percentage of individual factor. SS covers deviation between test data and mean value of data. The Fisher's ratio (F value) is calculated using F test, which indicates the quantum of effect of a parameter over the performance characteristics[28]. The L16 OA for the experiment is shown is Table 5.

Table 5 — L16OA.

	Factors			
L	A	I_p	C	T_{on}
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	2	1	2	3
6	2	2	1	4
7	2	3	4	1
8	2	4	3	2
9	3	1	3	4
10	3	2	4	3
11	3	3	1	2
12	3	4	2	1
13	4	1	4	2
14	4	2	3	1
15	4	3	2	4
16	4	4	1	3

4 Evaluation of data

In Taguchi method, the higher the levels for SNR, the stabler the overall performance it implies that the factor levels with the most leading SNR value should forever be chosen. Regardless of the STB / LTB, the higher variety characteristics, the greater SNR corresponds to the less variance of the response characteristics around the objective value. The use of SNR is to measure responses to refine products and processes indifferent to the noise factor. This indicates the degree of predictable responses of product or process in the presence of noise factors. The parameters were set with the highest SNR yield optimum value with minimum variance. The experimental results and their SNR values are shown in Table 6. LTB function is used for MRR to enhance productivity and STB is for SR and EWR. The SR characteristics to find the arithmetic mean average surface roughness (Ra). The maximum level for a factor is the level that appears in the largest SNR value in thetest field.

4.1 Analysis of S/N Ratios

In this machining process, the lowest EWR having 75 volt, 2 ampere, 72 %, 200 µsec as input variables and similarly, the lowest SR having corresponding input variables *viz.* 15 volt, 2 ampere, 24% and 50 µsec. From Table 7 shows that for EWR, IP is the most and C is the least significant factor. Similarly, Table 8 shows that for SR, Ton is most, and C is the least significant

Table 6 — The experiments results and SNR values.

Run	A	I_P	C	T_{on}	EWR (gm/min)	SNR (dB)	SR (μm)	SNR (dB)
1	15	2	24	50	0.0003	69.420942	14.18	-23.0335
2	15	4	48	100	0.0018	55.139239	33.36	-30.4645
3	15	6	72	150	0.0025	52.0412	29.46	-29.3847
4	15	8	96	200	0.0025	52.0412	34.98	-30.8764
5	45	2	48	150	0.0003	70.370279	32.37	-30.2029
6	45	4	24	200	0.0012	58.757042	35.77	-31.0704
7	45	6	96	50	0.0052	45.679933	26.25	-28.3826
8	45	8	72	100	0.0033	49.542425	20.04	-26.038
9	75	2	72	200	0.00022	73.06425	33.73	-30.5603
10	75	4	96	150	0.0004	67.234557	36.73	-31.3004
11	75	6	24	100	0.0012	58.329079	27.6	-28.8182
12	75	8	48	50	0.0024	52.395775	27.36	-28.7423
13	105	2	96	100	0.0006	64.349679	17.55	-24.8855
14	105	4	72	50	0.0006	63.806634	24.08	-27.6331
15	105	6	48	200	0.0025	52.0412	22.91	-27.2005
16	105	8	24	150	0.0020	53.9794	33.11	-30.3992

Table 7 — S/N response table for EWR.

Level	A	I_P	C	T_{on}
1	57.16	69.30	60.12	57.83
2	56.09	61.23	57.49	56.84
3	62.76	52.02	59.61	60.91
4	58.54	51.99	57.33	58.98
Delta	6.67	17.31	2.80	4.07
Rank	2	1	4	3

Table 8 — S/N response table for SR.

Level	A	I_P	C	T_{on}
1	-28.44	-27.17	-28.33	-26.95
2	-28.92	-30.12	-29.15	-27.55
3	-29.86	-28.45	-28.40	-30.32
4	-27.53	-29.01	-28.86	-29.93
Delta	2.33	2.95	0.82	3.37
Rank	3	2	4	1

factor. The observed value of EWR is 0.00022 gm/min, and the calculated value of SNR from Taguchi analysis is found to be -73.06425 dB. Similarly, for SR, the observed value is 14.18μm, and the calculated value of SNR from Taguchi analysis is found to be -23.034 dB. Hence the like input factors are most optimized controllable parameters.

The factorial effect plots are drawn by considering the mean average of the parameters of their each level of raw data. Figures (4 & 5) show factorial effect plot for SNR of EWR and SR. Fig. 4 shows that EWR is minimize when A is 75V, I_P is 2 Ampere, C is 24 % and T_{on} is 150 μsec. Similarly, Fig. 5 shows that SR is minimize when A is 105V, I_P is 2 Ampere, C is 24 % and T_{on} is 50 μsec.

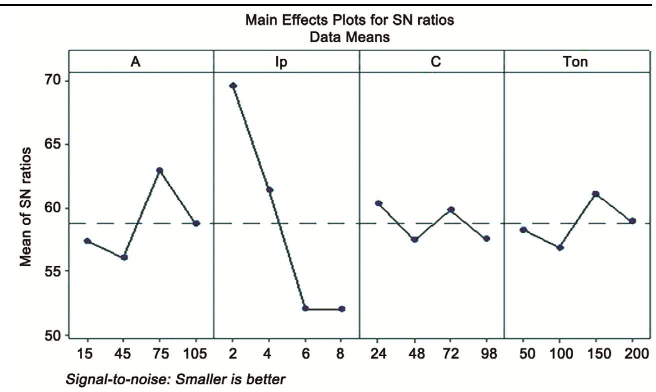

Fig. 4 — Factorial effects plot for SNRs (EWR).

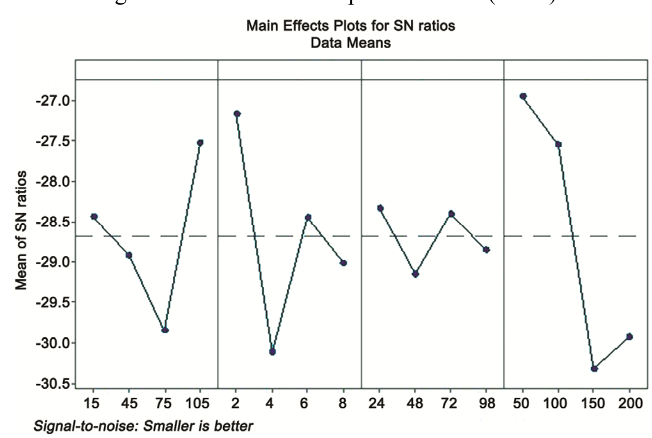

Fig. 5 — Factorial effects plot for SNRs (SR).

4.2 ANOVA

The main objective of ANOVA is to classify the impact of individual and interaction factors. Table shows the analysis ANOVA for EWR and SR. This investigation is taken out for 95 % confidence level *i.e.*, 5 % significance level. Based on the F-Statistics,

Table 9 — ANOVA for EWR.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A	3	1.3602	9.78%	1.3602	0.4534	1.98	0.295
I_P	3	11.0495	79.43%	11.0495	3.6832	16.08	0.024
C	3	0.3287	2.36%	0.3287	0.1096	0.48	0.720
T_{on}	3	0.4852	3.49%	0.4852	0.1617	0.71	0.609
Error	3	0.6871	4.94%	0.6871	0.2290		
Total	15	13.9107	100.00%				

Table 10 — Model summary for EWR.

S	R-sq	R-sq(adj)
0.478583	95.06%	75.30%

Table 11 — ANOVA for SR.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A	3	523.46	11.79%	523.46	174.49	16.41	0.023
I_P	3	1561.85	35.16%	1561.85	520.62	48.96	0.005
C	3	549.78	12.38%	549.78	183.26	17.24	0.021
T_{on}	3	1774.59	39.95%	1774.59	591.53	55.63	0.004
Error	3	31.90	0.72%	31.90	10.63		
Total	15	4441.57	100.00%				

Table 12 — Model summary for SR.

S	R-sq	R-sq(adj)
3.26074	99.28%	96.41%

Table 13 — Optimal parameter setting of process parameters.

Output parameters	Optimal combination				
	Level	A	I_P	C	T_{on}
Min. EWR	$A3I_P1C1T_{on}3$	75	2	24	150
Min. SR	A4 I_P 1C1 $T_{on}1$	105	2	24	50

define the process parameter is important or not at a selective confidence level. Larger F-Statistics showed that the modification of process parameters made a significant change on the performance. R Square describes the range to which input parameters intercept the modification of the output response and predicted variable. For a good model, R sq. should be high value. From Tables 9 and 10, it can be concluded that for EWR, I_P had the most significant 79.43 % contribution and C the least significant 2.36 % contribution. Similarly, from Tables 11 and 12, it can be concluded that for SR, T_{on} had the most significant 39.95 % contribution and A the least significant 11.79 % contribution and the remaining parameters were found insignificant. Table 13 displays, the optimal setting of process parameters.

Table 14 — Results of validation test.

	EWR(gm/min)	SR(µm)
Level	$A3I_P1C1T_{on}3$	$A4I_P1C1$ $T_{on}1$
Predicted	0.00021	14.02
Experimental	0.00022	14.18
Error (%)	4.54	1.12

4.3 Validation test

The optimum level of the process parameters is obtained in the previous section. Next move is to confirm the percentage variation of EWR and SR between the primary setting and for this optimal sequence. Table 14 parallels the results of the validation trials using the optimal process parameters. For EWR and SR, there some error exists in Table 14. The total mean of EWR decreased from 0.00022 gm/min to 0.00021 gm/min for optimal machining parameters of A3IP1C1Ton3 and also fell of SR from 14.18 µm to 15.08 µm for machining parameters of A4IP1C1Ton1 which confirms that right combination of the process parameters to the minimization of EWR and SR of the machined surface.

The predicted and experimental values for EWR and SR are shown in Table 14. It validates that the error between the confirmatory and predicted value is less than 5 %. It verifies that remarkable reproducibility of the results and also confirms that the optimized process parameters and response values are in close alliance with experimentally obtained values.

5 Conclusions

The experimental investigation of EDM on AISI 420 has been done using Taguchi technique. Four important process parameters A, I_P, C and T_{on} have been studied. The following conclusions are made:

(i) During machining of AISI420, the highest influencing factor in EWR is I_P and least is C. Similarly, for SR T_{on} is most and C is least significant factor.

(ii) The optimal levels of the four factors have been established to get optimal EWR and SR using L16 OA.

(iii) For EWR, The result showed that the A of 105 volt, I_P of 1ampere, C of 16% and T_{on} 200 µsec bears the optimal quality characteristics. Similarly, for SR, The result showed that the A of 135 volt, I_P of 1ampere, C of 16 % and T_{on} 5 µsec bears the optimal quality characteristics.

(iv) From ANOVA, for EWR, I_P is having most significant 79.43 % contribution and C is having least significant 2.36 % contribution. Similarly, for SR, T_{on} is having most significant 39.9 5% contribution and A is having least significant 11.79 % contribution.

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