MIJEEC

Maejo International Journal of
Energy and Environmental
Communication

Journal homepage: https://ph02.tci-thaijo.org/index.php/MIJEEC

ARTICLE

Optimization of process parameters in machining of nimonic super-alloy on EDM using genetic algorithm

Madderla Sandhya [1,2,*], D. Ramasamy [2,3], Irshad ahamad Khilji [4], Anil Kumar [1], S. Chandramouli [1], G. Vinod Kumar [1]

[1]Department of Mechanical Engineering, KITS College, Warangal, Telangana State, 506015, India
[2]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[3]Automotive Engineering Centre, Universiti Malaysia Pahang, 26600, Pekan, Malaysia
[4]Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

ARTICLEINFO

Article history:
Received 07 February 2020
Received in revised form
11 March 2020
Accepted 14 March 2020

Keywords:
EDM
Taguchi method
Genetic algorithm
Nimonic material

ABSTRACT

This project aims to investigate and predict the optimal choice for each EDM parameter using Taguchi Method by conducting a limited number of experiments on "Nimonic" Material. These parameters have a significant influence on the machining characteristics like MRR and TWR. Taguchi design of experiments (DOE) are implemented, particularly L9 orthogonal array is chosen and the effect of dominating process parameters is evaluated using analysis of variance. Nimonic refers to a family of Nickel-based high-temperature low creep superalloys. Due to its ability to withstand very high temperatures, Nimonic is ideal for typical applications such as aircraft parts, gas turbine components and blades, exhaust nozzles etc., for instance, where the pressure and heat are extreme. However, the conventional methods are not suitable to machine the hardest material such as Nimonic superalloy. The EDM, one of the popular unconventional machining methods, is used to the machine with a copper electrode, which in turn uses Taguchi methodology to analyze the effect of each parameter on the machining characteristics. The optimal choice for each EDM parameter such as peak current, gap voltage, duty cycle and pulse on time using the Taguchi method and Genetic Algorithm are identified. These parameters have a significant influence on machining characteristics such as MRR, EWR and surface roughness.

1. Introduction

Two Russian scientists, Lazarenko and Lazarenko, were tasked in 1943 to investigate ways of preventing the erosion of tungsten electrical contacts due to sparking. They failed in this task but found that the erosion was more precisely controlled if the electrodes were immersed in a die electric fluid (Wang, 2003). This led them to invent the EDM machine used for working difficult to machine materials such as tungsten. The Lazarenkos' machine is known as an R-C type machine after the RC circuit is used to charge the electrodes. Simultaneously, but independently, an American, Harold Stark, Victor Harding and JackBeaver, developed an EDM machine for removing broken drills and taps from aluminum castings. Initially, constructing machines from electric-etching tools, they were not very successful (Ho and Newman, 2003). But more powerful sparking units, combined with automatic spark repetition and fluid replacement with an electromagnetic interrupter arrangement, produced practical

* Corresponding author.
E-mail address: madderla.sandhya@gmail.com (Madderla Sandhya)

machines. Stark, Harding, and beaver's machines were able to produce 60 sparks per second. Later, machines based on the Stark-Harding-Beaver design used vacuum tube circuits that were able to produce thousands of sparks per second. Significantly increasing the speed of cutting (Lee et al., 2001).

Nomenclature and abbreviation	
OA	Orthogonal Arrays
MRR	Material Removal Rate
TWR	Tool Wear Rate
EWR	Electrode Wear Rate
UTS	Ultimate tensile strength

"Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Dr. Taguchi's Signal-to-Noise ratios (S/N), which are log functions of the desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results. Taguchi method involves reducing the variation in a process through the robust design of experiments (Yahya and Manning, 2003). The overall objective of the method is to produce high-quality products at a low cost to the manufacturer. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning (Lee and Tai, 2003). The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied; it allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources.

As the objective is to obtain the high material removal rate, low tool wear rate, and best surface finish, it is concerned with obtaining a larger value for MRR, smaller value of tool wear rate and a smaller value of surface roughness (Goyal, 2017). Hence, the required quality characteristic for high MRR is larger the better, which states that the output must be as large as possible, and for tool wear rate and surface roughness is smaller the better, which states that the output must be as low as possible (Kalpajian, 2003). This work aims to investigate and predict the optimal choice for each EDM parameter using Taguchi Method by conducting a limited number of experiments on "Nimonic" Material. These parameters have a significant influence on the machining characteristics like MRR (Material Removal Rate) and TWR (Tool Wear Rate) (Ozgedik and Cogun, 2006). Taguchi design of experiments (DOE) are implemented, particularly L9 orthogonal array is chosen and the effect of dominating process parameters is evaluated using analysis of variance (ANOVA).

2. Materials and methods

This work is limited to machining by using EDM with Nimonic super alloy and copper as the electrode; also EDM parameters that will be considered in the present work are the pulse-on-time, pulse-off-time, and discharge current (Kalpajian, 2003). MRR, material removal rate can be calculated by measuring the amount of material being removed after a certain period of machining and the EWR, electrode wear rate is calculated after measuring the weight of the electrode and even work-piece before and after machining. The experimental results are carried out by using the Taguchi Method.

2.1. Tool Material - Copper

The desirable properties of the copper are good electrical conductivity, good thermal conductivity, and corrosion resistance and easy to machine (Ho and Newman, 2003). Because of its good electrical and thermal conductivity, it allows the electrons to flow freely from the tool to the workpiece. Tool specifications involve a Diameter: 20mm and Length: 45mm. Tool properties are as follows Density-15.10 gm/cc, Rockwell Hardness-94 HRC, Ultimate Tensile Strength-662 MPa, Electrical Resistivity-0.00000380 ohm-cm.

Fig. 1. Tool electrode.

2.2. Work Material - Nimonic

Nimonic alloy is composed of nickel and chromium, with the nickel content more than 50%. These alloys exhibit high-temperature low creep and are high-performance alloys. The addition of metals like titanium aluminum increases the strength of the alloy. It is a precipitation-hardenable nickel-chromium alloy with additives for strengthens. This alloy exhibits excellent corrosion resistance at high temperatures. Apart from being corrosion resistant, the alloy also shows good creep resistance and tensile strength at elevated temperatures. The machining methods used on iron alloys may be used for this alloy. The alloy work-hardens during machining and exhibits higher strength. The specifications are as follows Size: 60mm×55mm×5mm and Weight: 178gm. The composition of Nimonic work material as follows Ni-51.6, Cr-19.46, Co-19.68, Ti-2.13, Fe-0.462, Al-0.0896, C-0.0696, Cu-0.0116, Mn-0.374. Properties are as follows Density-8.06 gm^3, Electrical resistivity-1.09μΩ-m at 20°C, Thermal conductivity-1.7 W/m at 20°C, UTS (Ultimate tensile strength)-1050 MPa, Specific heat-461 J/kg at 20°C.

2.3. Dielectric

The EDM setup consists of a power supply whose one lead is connected to the work piece immersed in a tank having dielectric coil. The tank is connected to a pump, oil reservoir, and a filter system. The pump provides pressure for flushing the work area and moving the oil while the filter system removes and traps the debris in the oil. The oil reservoir restores the surplus oil and provides a container for draining the oil between the operations (Wang, 2003).

In EDM, material removal mainly occurs due to thermal evaporation and melting as thermal processing is required to be carried out in the absence of oxygen so that the process can be controlled and oxidation avoided. Oxidation often leads to poor surface conductivity (electrical) of the work-piece hindering further machining (Goyal, 2017). Hence, the dielectric fluid should provide an oxygen free machining environment. Further, it should have enough strong dielectric resistance so that it does not breakdown electrically too easily but, at the same time, ionize when electrons collide with its molecule. Moreover, during sparking, it should be thermally resistant as well. EDM oil Grade 30 was used as a dielectric. The properties of dielectric are as follows Colour-Clear, Allowable Burn Rate-150 amps, Filter Compatibility-Paper cartridge, Specific Gravity-0.83, Density-6.9 lbs/gal (826 kg/m3), Viscosity at 40°C-3.5 cSt, Flash Point-215°F (102°C), Boiling Point-300°F (149°C).

2.4. Machining parameters

For optimizing a machining processor to perform efficient machining, one should have to identify the process and performance measuring parameters. The machining parameter of EDM process can be categorized into:

(i) Input/Process parameters: The input parameters of the EDM process are voltage, discharge current, spark-on time, duty factor, flushing pressure, workpiece material, tool material, inter-electrode gap, quill-up time, working time, and polarity, which affects the performance of machining process. So, suitable selections of process parameters are required for optimal machining conditions.

(ii) Response/Performance parameters: Response or performance parameters are used to evaluate the machining process in both qualitative and quantitative terms, namely Material Removal Rate (MRR), Surface Roughness (Ra or SR), Over Cut (G or OC), Tool Wear Rate(TWR), White Layer Thickness (WLT) and Surface Crack Density (SCD).

2.5. Power supply system

The power supply unit is an aluminum ensemble. It has a control panel in the front, side louvered panels, a back door, a top panel with an exhaust fan & a connector panel that provides interconnection of cables from & to the power supply. An isolator cut-out is also provided on this panel. A six-unit card cage houses a control PCB, two amplifiers PCBs & three drive PCBs depending upon sparking current. The bottom panel houses heavier items like the transformer, rectifier & its associated circuits. The amplifier PCBs are identical & hence interchangeable. A Power supply PCB is also provided in the card cage. Current limiting wire wound resistors are provided below the roof of the console.

2.6. Optimization by Taguchi Method

While there are many standard orthogonal arrays available, each of the arrays is meant for a specific number of independent design variables and levels (Yahya and Manning, 2003). For example, if one wants to conduct an experiment to understand the influence of 4 different independent variables with each variable having 3 set values (level values), then an L9 orthogonal array might be the right choice (Kumar et al., 2010). The L9 orthogonal array is meant for understanding the effect of 4 independent factors, each having 3 factor level values. This array assumes that there is no interaction between any two factors. While in many cases, no interaction model assumption is valid, there are some cases where there is clear evidence of an interaction. A typical case of interaction would be the interaction between the material properties and temperature.

Table 1
The layout of L9 orthogonal array.

L_9 (3^4) Orthogonal array					
	Independent Variables				Parameter
Experiment #	Variable 1	Variable 2	Variable 3	Variable 4	
1	1	1	1	1	p1
2	1	2	2	2	p2
3	1	3	3	3	p3
4	2	1	2	3	p4
5	2	2	3	1	p5
6	2	3	1	2	p6
7	3	1	3	2	p7
8	3	2	1	3	p8
9	3	3	2	1	p9

Table.1 shows an L9 orthogonal array. There are a totally 9 experiments to be conducted and each experiment is based on the combination of level values as shown in the table. For example, the third experiment is conducted by keeping the independent design variable 1 at level 1, variable 2 at level 3, variable 3 at level 3, and variable 4 at level 3. Once the orthogonal array is selected, the experiments are conducted as per the level combinations. It is necessary that all the experiments be conducted. The interaction columns and dummy variable columns shall not be considered for conducting the experiment but are needed while analyzing the data to understand the interaction effect. The performance parameter understudy is noted down for each experiment to conduct the sensitivity analysis.

2.7. Data analysis

Since each experiment is the combination of different factor levels, it is essential to segregate the individual effect of independent variables. This can be done by summing up the performance parameter values for the corresponding level settings. For example, in order to find out the main effect of level 1 setting of the independent variable 2 (refer Table 1), sum the performance parameter values of the experiments 1, 4 and 7. Similarly, for level 2, sum the experimental results of 2, 5 and 7 and so on.

Once the mean value of each level of a particular independent variable is calculated, the sum of the square of deviation of each of the mean values from the grand mean value is calculated. This sum of square deviation of a particular variable indicates whether the performance parameter is sensitive to the change in level setting. If the sum of square deviation is close to zero or insignificant, one may conclude that the design variables are not influencing the performance of the process (Kumar et al., 2018). In other words, by conducting the sensitivity analysis and performing analysis of variance (ANOVA), one can decide which independent factor dominates over other and the percentage contribution of that particular independent variable. The input parameters are selected based on the literature survey and the manual operation limitation of the EDM machine (Wang, 2003). The three main input parameters are current, pulse on time, pulse off time, are varied to study MRR, TWR and SR.

2.8. Calculation of MRR and TWR

To calculate the value of MRR and EWR the workpiece and tool are to be weighted, for this purpose SHIMADZU PHILLIPPINES Manufacturing Inc; Japan sensitive weighing balance, which is of 1mg accuracy, was used. The workpiece sample is weighted before machining and the value is noted. After performing the machining operation, the workpiece is weighted again, and the value is noted. The difference between these two values gives the metal removal rate value.

$$MRR = \frac{W1 - W2}{T} \text{ mg/min} \quad \ldots\ldots\ldots\ldots (1)$$

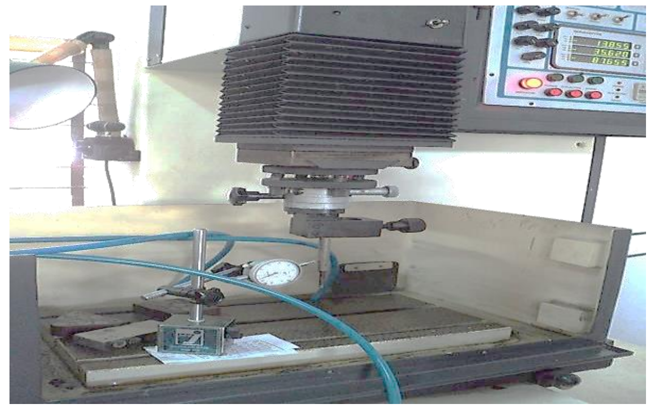
Where W1 = Weight of the sample before machining, W2 = Weight of the sample after machining, T = Machining time (mins). Similarly, EWR is calculated, taking the weight of the tool before performing the machining operation and after the machining and electrode wear is calculated. The experiments are conducted according to L9 orthogonal array and the results for metal removal rate, and electrode wear rate are calculated using the above equation 1.

3. Experimental procedure

The experiments were conducted on the V3525 precision die to sink electric discharge machine, as shown in Fig.2, which consists a worktable, a Servo control system and a dielectric supply system. The machine has 8 current settings from 3A to 24A, 9 settings of pulse on time, 9 settings of pulse off time and spark gap of 50-75 microns. The experiments are conducted on Nimonic and the workpiece dimensions are 60 mm x 55 mm x 5 mm. and the machining is done with straight polarity. EDM oil Grade 30 is used as the dielectric fluid and the experiments were performed for a particular set of input parameters. The MRR and TWR are calculated using a digital balance of accuracy 1mg and the machining time is using a digital watch of accuracy 1 microsecond. Machining Time for each experiment is 3 minutes. The workpieces before and after machining on EDM for various input process parameters are shown in Fig.3 a and b.

The basic steps followed during the machining are:

- Setting of EDM.
- Setting of machining parameters.
- Weighing work-piece and electrode before machining.
- Adjusting the work-piece and electrode on EDM.
- Switch ON the Dielectric and Spark.
- Removing of metal particles with Flushing Nozzles.
- Switch OFF the Spark, Dielectric and Power.
- Clean the work-piece and electrode properly and weigh.



- Calculate the Metal Removal Rate and Tool Wear Rate.

Fig. 2. Experimental Set up of EDM.

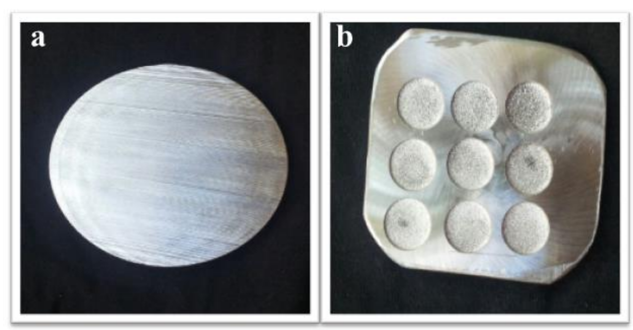


Fig. 3. The workpieces before and after machining on EDM for various input process parameters.

Machining Conditions:

- Open circuit voltage –230 V
- Gap Voltage – 3 V
- Electrode –Copper
- Work piece – Nimonic Super alloy
- Dielectric Fluid – EDM oil Grade 30
- Polarity – Positive
- Electrode gap – 0.25 to 0.9 mm
- Servo Uptime – 20 micro sec.
- Servo Downtime – 20 microsec.
- Current frequency – 50 Hz

The experiments are conducted by varying the inputs based on the available machine settings and tool and work material properties to study the effect of input parameters on the performance measures like Metal Removal Rate (MRR), Tool Wear Rate (TWR).

4. Results and discussion

4.1. Effect of current on output parameters

The pulse current is normally selected on the basis of the maximum removal rate possible within the allowable mean current, electrode wear and surface integrity. The experiments were carried out for a machining time of 3 minutes for different pulse current settings 15A, 18A and 21A. Since there are exist many ways of measuring MRR and TWR. Values have been calculated by weight difference of work and tool material before and after machining.

4.2. Effect of pulse on time on output parameters

In the present study for pulse current 9A and pulse off time 50µs kept constant and studied the effect of pulse on time from the ranges 50µs to 200µs on performance measures like MRR and TWR.

4.3. Effect of pulse current on MRR

The effect of pulse current on metal removal rate shows that as the pulse current increases. The increase in MRR, increase in pulse current is due to enhancement of spark energy that facilitates the action of melting and vaporization. This action results in advancing the impulsive force in the spark gap and thereby increasing the MRR.

4.4. Effect of pulse on time on MRR

The effect of pulse on time on MRR. The pulse on-time increases the MRR increases at pulse on time 200µs then after decreasing gradually and the burning of work material observed due to high pulse density. At high values of pulse on current, instead of sparking in the inter-electrode gap arcing observed.

4.5. Influences on MRR

The leading statistical analysis software MINITAB 15 was used for the design and analysis of experiments to perform the Taguchi and ANOVA analysis and to establish regression models. The optimization of process parameters using Taguchi method provides the evaluation of the effect of individual independent parameters on the identified quality characteristics. The statistical analysis of variance (ANOVA) was carried out. Based on the ANOVA, the contribution of each parameter in influencing the variation in quality characteristics was evaluated. The ANOVA also provides an indication of which process parameters are statistically significant. The response table with input factors is shown below.

Table 2
Input parameters.

Input Parameters	Symbol	Level1	Level2	Level 3
Current (I) Amps	A	15	18	21
Pulse on Time (Ton)	B	20	50	100
Pulse off Time (Toff)	C	10	20	50

4.6. Taguchi analysis: MRR vs Current, Ton, Toff

The below tabular and graphical analysis of Material Removal Rate varying Current, pulse on time and pulse off time provides experimental Linear Model analysis values of SN ratios and means.

4.6.1 Linear model analysis: SN ratios vs Current, Ton, Toff

The analysis of variances of the factors is shown in Table 7.6.1b which clearly indicates that the Current is the most important for influencing RT followed by Ton and Toff. The data values are Current, Ton and Toff are 2.68, 2.07 and 0.17, respectively, depicted in Table 7.2.1 e. The case of RT, it is Larger is better for MRR, so from this table it is clearly defined that Current is the most important factor.

Table 3
Calculations of MRR and TRR.

CURRENT	TON	TOFF	MRR	SN RATIO (MRR)	MEAN (MRR)	TWR	SN RATIO (TWR)	MEAN (TWR)
15	20	10	229.66	47.2217	229.66	6.333	-16.0322	6.333
15	50	20	263	48.3991	263	15.333	-23.7125	15.333
15	100	50	296.5	49.4405	296.5	0.666	3.5305	0.666
18	20	20	289	49.218	289	28.666	-29.1475	28.6665
18	50	50	307.5	49.7569	307.5	8.6665	-18.7569	8.6665
18	100	10	359.83	51.1219	359.83	9.3315	-19.399	9.3315
21	20	50	316.66	50.0119	316.66	45.333	-33.1283	45.333
21	50	10	354.33	50.9882	354.33	13.999	-22.9223	13.9995
21	100	20	403	52.1061	403	2.333	-7.3583	2.333

Table 4
Estimated model coefficients for SN ratios.

Term	Coef	SE Coef	T	P
Constant	49.8071	0.05717	871.154	0
Current 15	-1.4534	0.08086	-17.975	0.003
Current 18	0.2251	0.08086	2.784	0.108
Ton 20	-0.99	0.08086	-12.244	0.007
Ton 50	-0.0924	0.08086	-1.143	0.371
Toff 10	-0.0299	0.08086	-0.369	0.747
Toff 20	0.1006	0.08086	1.244	0.34

S = 0.1715   R-Sq = 99.7%   R-Sq(adj) = 98.7%

Table 5
Analysis of variance for SN ratios (ANOVA).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Current	2	11.0146	11.0146	5.50728	187.2	0.005
Ton	2	6.4803	6.4803	3.24015	110.14	0.009
Toff	2	0.048	0.048	0.02402	0.82	0.551
Residual Error	2	0.0588	0.0588	0.02942		
Total	8	17.6017				

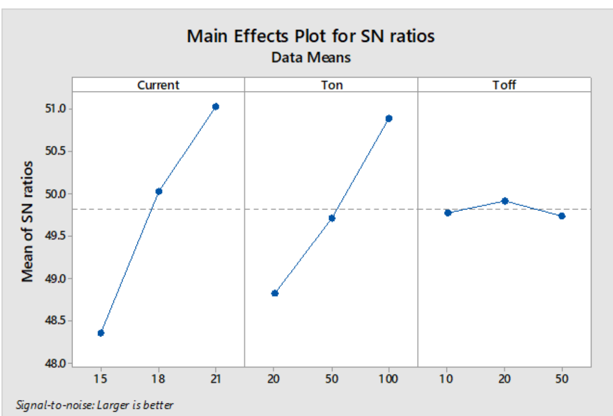


Fig. 4. Main Effects Plot for SN ratios.

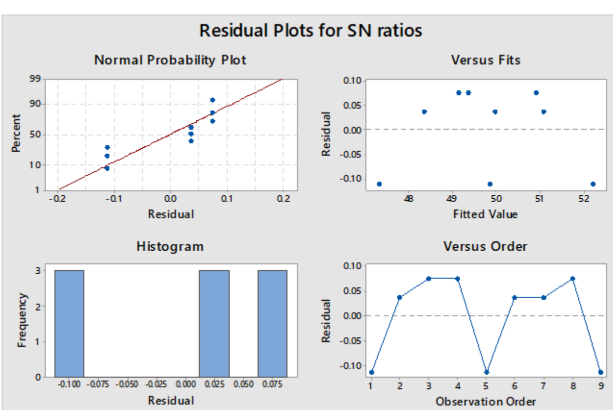


Fig. 5. Main Effects Plot for SN ratios.

Table 6
Response Table for SN Ratios- Larger is better.

Level	Current	Ton	Toff
1	48.35	48.82	49.78
2	50.03	49.71	49.91
3	51.04	50.89	49.74
Delta	2.68	2.07	0.17
Rank	1	2	3

4.7.2 Linear Model Analysis of Means vs Current, Ton, Toff.

The analysis of variances of the factors is shown in Table 6.2.2b, which clearly indicates that the Current is the most important for influencing RT followed by Ton and Toff. The data values are Current, Ton and Toff are 94.9, 74.7 and 11.4, respectively, depicted in Table7.2.2 e. The case of RT, it is Larger is better for MRR, so from this table, it is clearly defined that Current is the most important factor.

Table 7
Estimated model coefficients for means.

Term	Coef	SE Coef	T	P
Constant	313.276	0.06447	4859.006	0
Current 15	-50.222	0.09118	-550.81	0
Current 18	5.501	0.09118	60.333	0
Ton 20	-34.836	0.09118	-382.057	0
Ton 50	-4.999	0.09118	-54.825	0
Toff 10	1.331	0.09118	14.599	0.005
Toff 20	5.058	0.09118	55.471	0

S = 0.1934 R-Sq = 100.0% R-Sq(adj) = 100.0%

Table 8
Analysis of variance for means.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Current	2	13657.5	13657.5	6828.77	182533.14	0
Ton	2	8475.9	8475.9	4237.93	113280.03	0
Toff	2	204.5	204.5	102.26	2733.31	0
Residual Error	2	0.1	0.1	0.04		
Total	8	22338				

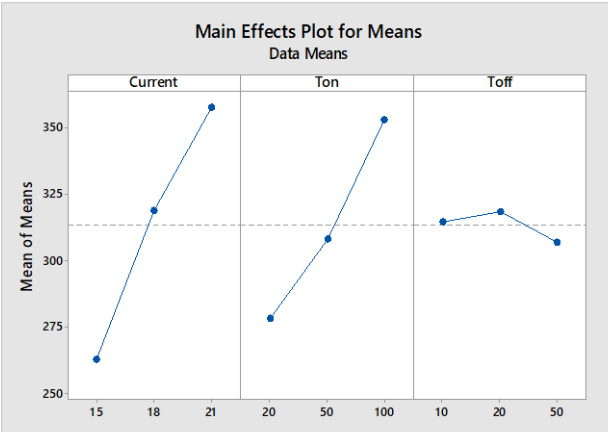


Fig. 6. Main Effects Plot for means.

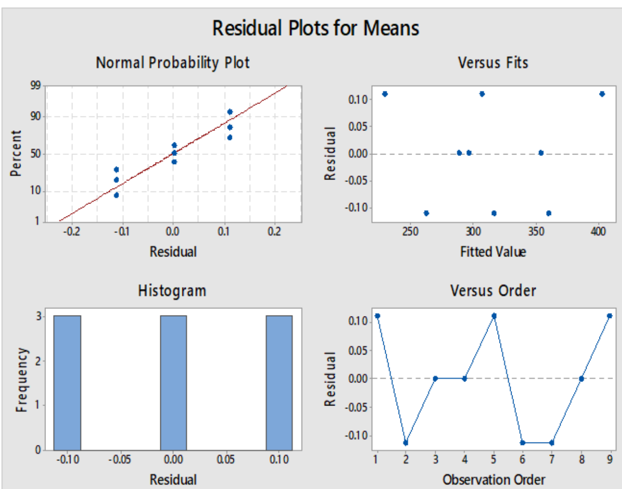


Fig. 7. Residual plots for means.

Table 9.
Response table for means – larger is better.

Level	Current	Ton	Toff
1	263.1	278.4	314.6
2	318.8	308.3	318.3
3	358	353.1	306.9
Delta	94.9	74.7	11.4
Rank	1	2	3

4.8. Taguchi Analysis: TWR versus Current, Ton, Toff

The below tabular and graphical analysis of Tool Wear Rate varying Current, pulse on time(TON) and pulse off time (TOFF) provides experimental Linear Model analysis values of SN ratios and means (Soni and Chakraverti, 1996).

4.8.1 Linear model analysis: SN ratios vs Current, Ton, Toff

Table 10
Estimated model coefficients for SN ratios.

Term	Coef	SECoef	T	P
Constant	-18.5474	3.488	-5.318	0.034
Current 15	6.476	4.932	1.313	0.32
Current 18	-3.8871	4.932	-0.788	0.513
Ton 20	-7.5553	4.932	-1.532	0.265
Ton 50	-3.2498	4.932	-0.659	0.578
Toff 10	-0.9038	4.932	-0.183	0.872
Toff 20	-1.5254	4.932	-0.309	0.786

S = 10.46 R-Sq = 77.9% R-Sq(adj) = 11.6%

Table 11
Analysis of variance for SN ratios.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Current	2	191.25	191.25	95.63	0.87	0.534
Ton	2	553.18	553.18	276.59	2.53	0.284
Toff	2	27.13	27.13	13.57	0.12	0.89
Residual Error	2	218.94	218.94	109.47		
Total	8	990.51				

The analysis is of variances of the factors is shown in Table 7, which clearly indicates that the Ton is the most important for influencing RT followed by Current and Toff. The data values are Current, Ton and Toff are 10.363, 18.60 and 3.955, respectively, depicted in Table7.7.1e. The case of RT, it is Smaller is better for TWR. So from this table, it is clearly defined that Ton is the most important factor (Puertas and Luis, 2004).

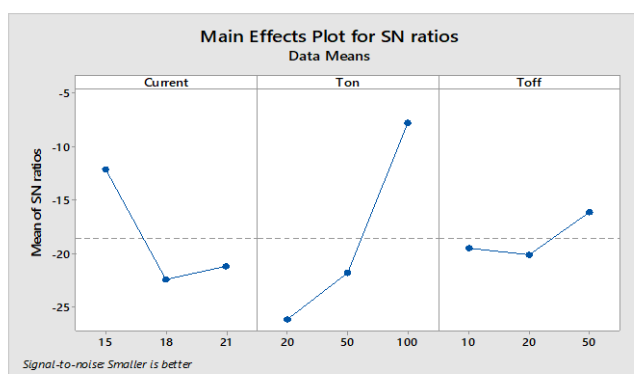


Fig. 8. Main effects plot for SN ratios.

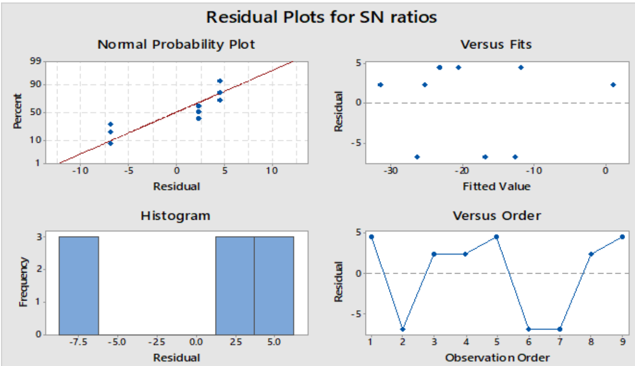


Fig. 9. Residual plot for SN ratios.

Table 12
Response table for SN Ratios - smaller is better.

Level	Current	Ton	Toff
1	-12.071	-26.103	-19.451
2	-22.434	-21.797	-20.073
3	-21.136	-7.742	-16.118
Delta	10.363	18.36	3.955
Rank	2	1	3

4.8.2 Linear model analysis: Means vs Current, Ton, Toff

Table 13
Estimated model coefficients for means.

Term	Coef	SECoef	T	P
Constant	14.518	5.068	2.865	0.103
Current 15	-7.074	7.167	-0.987	0.428
Current 18	1.0368	7.167	0.145	0.898
Ton 20	12.2595	7.167	1.711	0.229
Ton 50	-1.8517	7.167	-0.258	0.82
Toff 10	-4.63	7.167	-0.646	0.584
Toff 20	0.9262	7.167	0.129	0.909

S = 15.20 R-Sq = 71.4% R-Sq(adj) = 0.0%

The analysis of variances of the factors is shown in Table 7, which indicates that the Ton is the most important for influencing RT followed by Current and Toff. The data values are Current, Ton and Toff are 13.111, 22.667 and 8.334, respectively, depicted in Table7.7.2e. The case of RT, it is Smaller is better for TWR. So from this table, it is clearly defined that Ton is the most critical factor (Ayers and Moore, 1984; McGeough and Rasmussen, 1982; Nipanikar, 2012).

Table 14
Analysis of variance for means.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Current	2	262.7	262.7	131.35	0.57	0.638
Ton	2	786.1	786.1	393.07	1.7	0.37
Toff	2	108	108	54.02	0.23	0.811
Residual Error	2	462.3	462.3	231.15		
Total	8	1619.2				

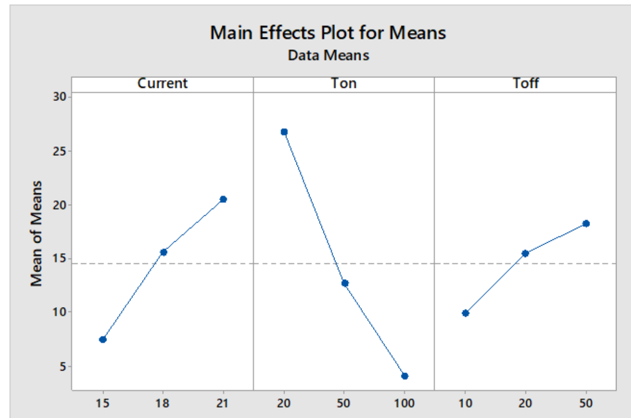


Fig. 10. Main effects plot for means.

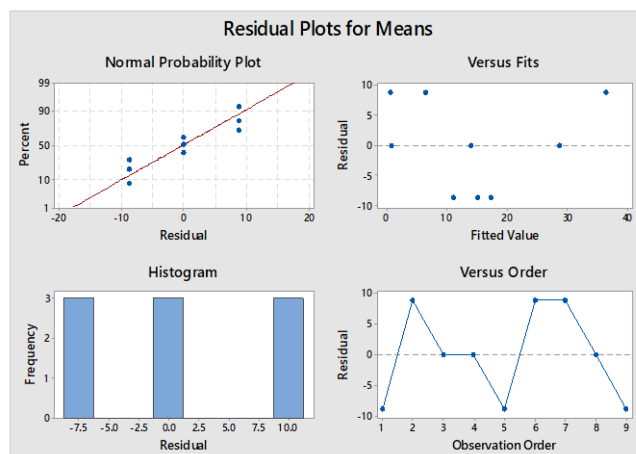


Fig. 11. Residual plots for means.

Table 15
Response table for means – smaller is better.

Level	Current	Ton	Toff
1	7.444	26.778	9.888
2	15.555	12.666	15.444
3	20.555	4.11	18.222
Delta	13.111	22.667	8.334
Rank	2	1	3

A residual plot is a graph that shows the residuals on the vertical axis and the independent variable on the horizontal axis. If the points in a residual plot are randomly dispersed around the horizontal axis, a linear regression model is appropriate for the data; otherwise, a non-linear model is more appropriate. The residual plot shows a fairly random pattern; this random pattern indicates that a linear model provides a decent fit to the data. The data look fairly linear, although there might be a slight curve in the middle. Overall, linear regression is appropriate for these data at this level (Gopalakrishnan and Al-Khayyal, 1991; Baraskar et al., 2011).

The residual plot of S/N ratios is shown in the above figure 7.6.1 d and 7.6.2 d. This layout is useful to determine whether the model meets the assumptions of the analysis. The residual plots in the graph and the interpretation of each residual plot are:

a. A normal probability plot helps in detecting non-normality. An approximately straight line indicates that the residuals are normally distributed. The above Normal probability plot indicates that the data are normally distributed, and the variables are influencing the response. Outliers do not exist in the data, as the standardized residues are between -0.1 and 0.1.

b. The plot of residuals versus the fitted values helps in detecting non-constant variance, missing higher-order terms and the outliers. The residuals should be scattered randomly around zero. The above residuals versus fitted values plot indicate a constant variance as well as the absence of the outliers in the data.

c. The plot of the histogram of the residuals helps in detecting multiple peaks, outliers, and non-normality. The histogram should be approximately symmetric and bell-shaped. The above plot of the histogram of the residuals points towards the presence of multiple peaks and also shows that the histogram is approximately symmetric and bell-shaped.

d. The plot of residuals versus order helps in detecting the time-dependence of residuals. The residuals should exhibit no clear pattern. The above Residuals versus order plot indicate the random pattern of the residuals.

4. Conclusion

The aim of this work is experimental investigations and optimization of the process parameters during electro-discharge machining of NIMONIC superalloy. For this, a number of experiments were carried out for the different range of input parameters. Taguchi's design of experiments has been employed for experiment design. Analysis of variance has been employed to see the level of significance of each input parameter on performance measures. Taguchi's method has been employed as a single-objective optimization technique to find to optimal combinations of input parameters for each performance measure. On the basis of experimental results and their analysis, the general conclusions of the work are given in the subsequent section:

- Nimonic alloy can be machined on EDM with reasonable speed. It is difficult to machine Nimonic superalloy on conventional machining because of shorter tool life and severe surface abuse due to its outstanding high-temperature strength and extreme toughness.
- The most important factor affecting the EDM of Nimonic material has been identified as discharge current for response MRR.
- The most important factor affecting the EDM of Nimonic material has been identified as pulse-on-time for response TWR.
- Discharge current and pulse-on-time are identified as common influencing factors for MRR and TWR.
- Pulse off time is found the least influential parameter during EDM of Nimonic superalloy.
- Optimal factor/level combinations of process parameters for MRR and TWR are obtained by employing Taguchi's method as single-objective optimization technique. A3B3C2, i.e.,21 amps current 100 microsecs pulse on time and 20 micro secs pulse off time are recommended as optimum factor/level combination for MRR as larger the better quality characteristic and A2B1C2 18 amps current 20 microsecs pulse on time and 20 micro secs pulse off time are recommended as optimum factor/level combination for TWR as smaller the better quality characteristic respectively.
- The influence of the input parameters on the response (output parameters) is found.
- Mathematical model is developed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank University Malaysia Pahang (UMP) for Grant RDU 190194, FRGS/1/2018/TK03/UMP/02/26 and UMP Flagship RDU192204 for financial assistance and facilities provided. The author MS also thankful for KITS, Warangal, for providing facilities.

References

Ayers, J. D., & Moore, K. 1984. Formation of metal carbide powder by spark machining of reactive metals. Metallurgical and Materials Transactions A 15(6), 1117-1127.

Baraskar, S. S., Banwait, S. S., & Laroiya, S. C. 2011. Mathematical Modeling of Electrical Discharge Machining Process through Response Surface Methodology.

Gopalakrishnan, B., & Al-Khayyal, F. 1991. Machine parameter selection for turning with constraints: an analytical approach based on geometric programming. The International Journal OF Production Research 29(9), 1897-1908.

Goyal, A. 201). Investigation of material removal rate and surface roughness during wire electrical discharge machining (WEDM) of Inconel 625 super alloy by cryogenic treated tool electrode. Journal of King Saud University-Science 29(4), 528-535.

Ho, K. H., & Newman, S. T. 2003. State of the art electrical discharge machining (EDM). International Journal of Machine Tools and Manufacture 43(13) 1287-1300.

Kalpajian S., & Schmidt, S. R. 2003: Material removal processes: abrasive, chemical, electrical and high-energy beam in manufacturing Processes for Engineering Materials, Prentice Hall, New Jersey, pp. 541.

Kumar, A., Maheshwari, S., Sharma, C., & Beri, N. 2010. Research developments in additives mixed electrical discharge machining (AEDM): a state of art review. Materials and Manufacturing processes 25(10), 1166-1180.

Kumar, V., Jangra, K. K., Kumar, V., & Sharma, N. 2018. GA-based optimisation using RSM in WEDM of Nimonic-90: a nickel-based super alloy. International Journal of Industrial and Systems Engineering 28(1), 53-69.

Lazarenko, B. R., & Lazarenko, N. 1943. About the inversion of metal erosion and methods to fight ravage of electric contacts. WEI-Institute, Moscow in Russian.

Lee S. H., & Li X. P. 2001. Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. Journal of Material Processing Technology 344-353.

Lee, H. T., & Tai, T. Y. (2003). Relationship between EDM parameters and surface crack formation. Journal of Materials Processing Technology, 142(3), 676-683.

McGeough, J. A., & Rasmussen, H. 1982. A macroscopic model of electro-discharge machining. International Journal of Machine Tool Design and Research 22(4), 333-339.

Nipanikar, S. R. 2012. Parameter optimization of electro discharge machining of AISI D3 steel material by using Taguchi method. journal of Engineering research and studies 3(3), 7-10.

Ozgedik, A., & Cogun, C. 2006. An experimental investigation of tool wear in electric discharge machining. The International Journal of Advanced Manufacturing Technology 27(5-6), 488-500.

Puertas, I., & Luis, C. J. 2004. A study of optimization of machining parameters for electrical discharge machining of boron carbide. Materials and Manufacturing Processes 19(6), 1041-1070.

Soni, J. S., & Chakraverti, G. (1996). Experimental investigation on migration of material during EDM of die steel (T215 Cr12). Journal of Materials Processing Technology, 56(1-4), 439-451.

Wang, K. 2003. A Hybrid: Intelligent Method for Modelling the EDM Process. International journal of Machine Tools and Manufacture 2003, 995-999.

Yahya A., & Manning C. D. 2003. Modelling, simulation and controller design for electro discharge machine system. Electronic systems and control division research 2(1), 1.