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Effect of process parameters on machining behaviour using S/N ratio and ANOVA analysis

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ABSTRACT

Inconel 725 super alloy is a significant and often used material for many technical applications such as oil and gas industries, aerospace, nuclear and marine areas owing to its exceptional physical and mechanical properties. The major drawback of utilizing this alloy is challenging it is to machine using traditional machining techniques. Production sectors often aim to produce goods with excellent surface finishes and high production rates at reasonable prices. Hence, in the current study deals with the effect of electric discharge machining (EDM) parameters viz. pulse-on time (T_{on}), pulse-off time (T_{off}) and discharge current (I_p) on metal removal rate (MRR) and surface roughness (Ra) of Inconel 725 alloy. According to the Taguchi's L9 orthogonal design the EDM studies were performed. The optimal condition of EDM parameters was obtained by signal to noise (S/N) ratio analysis with an aim was to minimize the Ra and maximize the MRR. S/N ratio results obtained that the higher MRR produced at T_{on} of 45 µs, T_{off} of 60 µs and I_p of 10 A. Similarly, the lower Ra produced at T_{on} of 15 µs, T_{off} of 40 µs and I_p of 5 A. ANOVA results reveals that discharge current (I_p) has the most noteworthy factor for MRR and Ra followed by pulse-on time (T_{on}).

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1. Introduction

Inconel 725 super alloys have exceptional strength, good ductility and resistance to corrosion even at very high temperatures. These super alloys are frequently utilized in the aerospace, automotive, nuclear power plant, marine, and other sectors due to their enhanced mechanical characteristics [1–4]. Because of its quick work hardening propensity, high hardness and toughness, poor thermal conductivity and propensity to produce built-up edges (BUE), Inconel is challenging to machine by conventional methods. The BUE formation in the tool is the cause of their poor machinability. There is a significant tooling expenditure since the cutting tool wears out fast during machining [5–7]. For the machining of Inconel alloys, EDM technique becomes the obvious choice. Due to its low setup costs and great precision final product quality, EDM is the widely employed method for Inconel alloys [8–10]. Dhanabalan et al. presented the influence of input factors namely, I_p, T_{on} and T_{off} on the tolerances in EDM process of Inconel 625 and 718 alloys. They observed that T_{on} and I_p have more dominant factors for MRR. It has also reported that the MRR slightly improved with an increase in T_{on} [11]. Basha Shaik Khadar et al. have examined the performance features like MRR, Ra and recast layer thickness for Inconel X-750 alloy while EDM process. They concluded that I_p and T_{on} have most noteworthy factor for MRR, while T_{on} and I_p were more important for Ra [12]. Dileep Kumar Mishra et al. performed the EDM process of Inconel 625 using Cu electrode. They have analyzed the effect of parameters on responses like MRR, Ra, circularity and overcut and hole taper. The results shows that increase in T_{on} increasing the Ra [13]. Muthukumar et al. have developed the empirical model for radial overcut on EDM process of Inconel 800 alloy using response surface method and they stated that voltage and current have highly notable factor for the response [14]. Chinmaya P Mohanty et al.

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optimized the EDM variables on surface quality and MRR for Inconel 718 alloy. They revealed that tool materials, I_p and T_{on} were the more imperative factor for achieving the better response [15]. Uhlmann et al. studied the influence of variables on Ra for MAR-M247 alloy while EDM. They noticed that Ra value improved with an increased in discharge current and also reported that I_p and pulse duration were more significant variables for Ra [16]. Manohar et al. described the machining behaviour of Inconel 718 in EDM and they understood that better surface finish exhibits in convex bottom profile electrode, while flat profile electrode provides higher MRR [17]. Gangadharudu Talla et al. have reported the surface integrity of Inconel 625 during addition of Graphite (Gr) powder in EDM process. They found that Ra value increased due to inclusion of large quantity of Gr content in dielectric fluid. They also noted that increase in I_p increased the heat energy which creates more craters resulting in more Ra formed [18]. Alexia Torres Salcedo et al. have presented the EDM of Inconel 600 using Cu-Gr electrode. They have noticed that negative polarity provides greater MRR with better surface finish [19]. Mithilesh K Dikshit et al. studied the impact of machining variables in EDM of 625 Inconel and they revealed that I_p has the primary dominant variables for MRR next by T_{on}, while Ra is mainly affected by T_{on} followed by T_{off} [20]. We noted from earlier investigations that no one has discovered the optimum EDM parameter settings for Inconel 725 alloy with higher MRR and lower Ra. Hence, the aim of the present study was, S/N ratio and ANOVA has been employed to determine the optimum MRR and Ra parameter settings for the Inconel 725 alloy during EDM process.

2. Experimental details

Inconel 725 super alloy was taken as the work material for current investigation. The alloy chemical compositions are Ni (55–59 %), Cr (19–22.5 %), Fe (9 %), Mo (7–9.50 %), Nb (2.75–4 %), Ti (1–1.70 %), Al (0.35 %), Mn (0.35 %), Si (0.20 %), C (0.030 %), P (0.015 %) and S (0.010 %), respectively. Table 1 depicts the properties of aforesaid alloy. This particular high strength super alloy has a basic composition of nickel–chromium-molybdenum-niobium making it corrosion resistant and capable of withstanding high pressures and temperatures. Due to its special characteristics, Inconel 725 alloy has found employment in various applications such as marine equipment and the aerospace sector.

In this work, a die sinking EDM (Sparkonix, Pune, India) setup has been used for EDM experiments. The work piece material was the received Inconel 725 plates, which had dimensions of 50 mm × 150 mm × 5 mm. As the tool electrode, a 15 mm in length and 12 mm diameter pure (99.9 %) copper rod was used. In the experiment tests, kerosene was used as the dielectric medium. The effect of T_{on}, T_{off} and I_p (as listed in Table 2) on the responses such as MRR and Ra have been studied. The experiments were conducted as per Taguchi's L9 orthogonal layout as depicted in Table 3. The ratio of work piece weight before and after machining during a time period was used to determine the MRR. The Ra was measured by using a surface roughness tester.

3. Taguchi method

Taguchi technique is widely utilised for the reliable and complex designs that provide a simple and systematic approach while reducing the expense and duration of the experiment [21,22]. In this approach, the S/N ratio and the ANOVA are two crucial tools that may be utilised [23,24]. Finding the best setting for the intended responses is the major objective of employing S/N ratio. In this study, the larger-the-better equation (1) was used for MRR and the smaller-the-better equation (2) was used for Ra. [25]

Table 1
Properties of Inconel 725.

Density (g/cm^3)	Yield strength (MPa)	Tensile strength (MPa)	Melting point (°C)	Thermal conductivity (W/m.K)
8.3	427	855	1343	6.5

Table 2
Levels of EDM parameters.

Machining variables	Notation	Unit	Level		
			1	2	3
Pulse-on time	I_p	µs	15	30	45
Pulse-off time	T_{on}	µs	20	40	60
Discharge current	T_{off}	A	5	10	15

Table 3
L9 orthogonal layout with responses.

Ex. No	T_{on} (µs)	T_{off} (µs)	I_p (A)	MRR (g/min)	Ra (µm)
1	15	20	5	0.1104	3.11
2	15	40	10	0.1752	4.33
3	15	60	15	0.1968	5.19
4	30	20	10	0.2004	5.56
5	30	40	15	0.2136	5.22
6	30	60	5	0.1548	3.95
7	45	20	15	0.1908	6.77
8	45	40	5	0.1848	3.85
9	45	60	10	0.2568	6.43

$$S/N\,ratio = -10\log_{10}(1/n)\sum_{k=1}^{n}\frac{1}{Y_{ij}^{2}} \quad (1)$$

$$S/N\,ratio = -10\log_{10}(1/n)\sum_{k=1}^{n}Y_{ij}^{2} \quad (2)$$

where, n – no. of trials, Y_{ij} – response where i = 1, 2, 3….n; j = 1, 2, 3……k. Table 4 depicts the S/N ratio for the responses.

4. Result and discussions

4.1. Effect of EDM parameter on MRR

Figs. 1 and 2 depicts the S/N ratio and means graph for MRR. From the graph, it clearly evident that the effect of each parameter against MRR. With an increase in pulse duration, the MRR increased linearly. Moreover, the MRR marginally improved after an increase in I_p from 5A to 10A, but it started to decline at 15A. So that a significant amount of heat is generated over a longer pulse duration, thus improving the MRR. As per the results (Figs. 1 & 2), we can identified that the optimum setting of machining parameters are T_{on} of 45 µs, T_{off} of 60 µs and I_p of 10A which levels are produced higher MRR.

The response of S/N ratio and means table for MRR is listed in Table 5. From the table, it accurately noted that the order of dominant factors on MRR were identified from the delta value. Additionally, the higher delta value represented as the primary noteworthy factor followed by others. Based on the results (Table 5), it can be noted that I_p has the prominent factor for influencing the MRR followed by T_{on} and T_{off}. It was ensured by ANOVA results as shown in Table 6. The contribution of each parameters on MRR is illustrated in Fig. 3. It clearly reveals that I_p (49.12 %) has the more significant contribution factor for MRR next by T_{on} (29.25 %) and T_{off} (15.31 %), respectively. The similar observations were previously noticed by Farshid Jafarian et al. [26]. Fig. 4 depicts the residual plot for MRR and it was found that the errors are distributed normally in the designed model.

4.2. Effect of EDM parameters on Ra

Figs. 5 and 6 depicts the S/N ratio and means graph for Ra. From the graph, it clearly evident that the effect of each parameter against Ra. The Ra reduced with an initial level of T_{on} and I_p. By

Table 4
S/N ratio for the MRR and Ra.

Ex. No	MRR (g/min)	S/N ratio (dB)	Ra (µm)	S/N ratio (dB)
1	0.1104	−19.141	3.11	−9.848
2	0.1752	−15.129	4.33	−12.723
3	0.1968	−14.119	5.19	−14.298
4	0.2004	−13.962	5.56	−14.900
5	0.2136	−13.408	5.22	−14.357
6	0.1548	−16.205	3.95	−11.937
7	0.1908	−14.388	6.77	−16.611
8	0.1848	−14.666	3.85	−11.710
9	0.2568	−11.808	6.43	−16.162

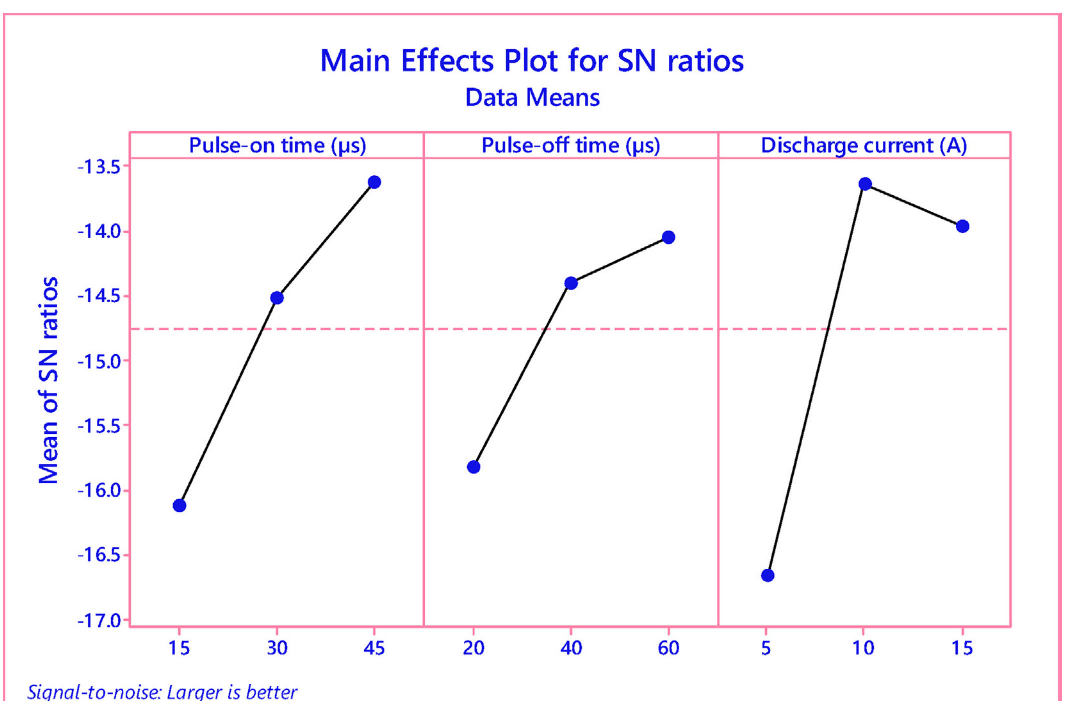

Fig. 1. S/N ratio plot for MRR.

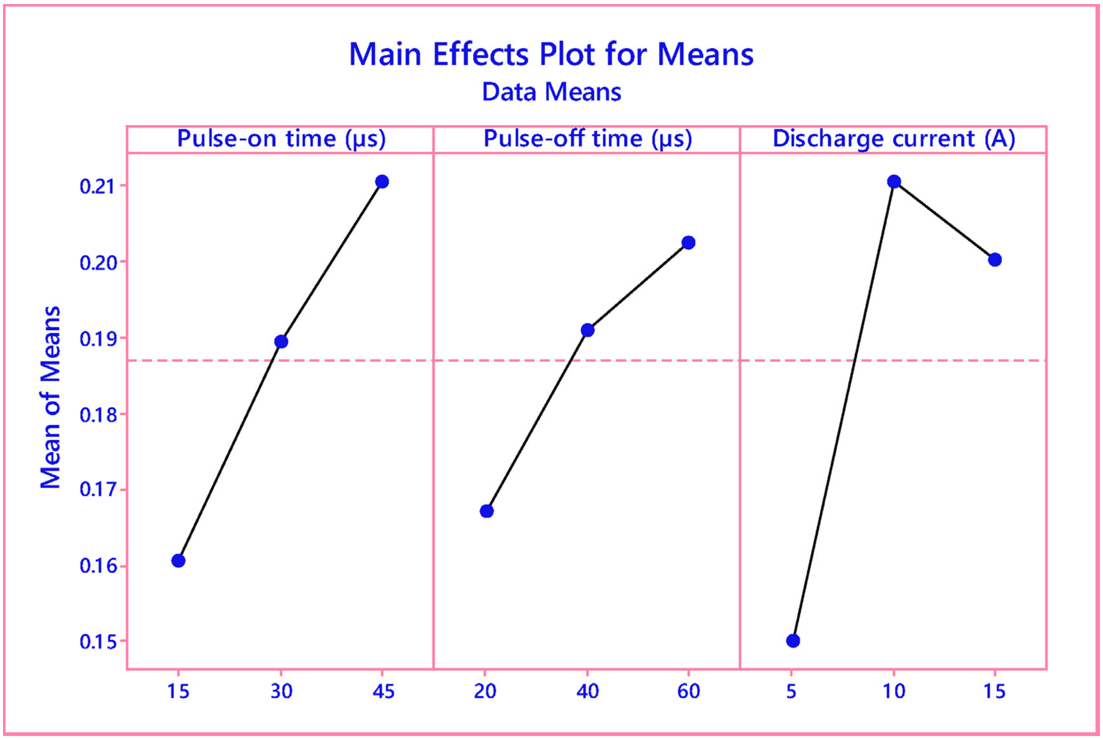

Fig. 2. Means plot for MRR.

Table 5
Response table for MRR.

S/N ratio of MRR			
Level	T_{on} (μs)	T_{off} (μs)	I_p (A)
1	−16.13	−15.83	−16.67
2	−14.52	−14.40	−13.63
3	−13.62	−14.04	−13.97
Delta	2.51	1.79	3.04
Rank	2	3	1
Means of MRR			
1	0.1608	0.1672	0.1500
2	0.1896	0.1912	0.2108
3	0.2108	0.2028	0.2004
Delta	0.0500	0.0356	0.0608
Rank	2	3	1

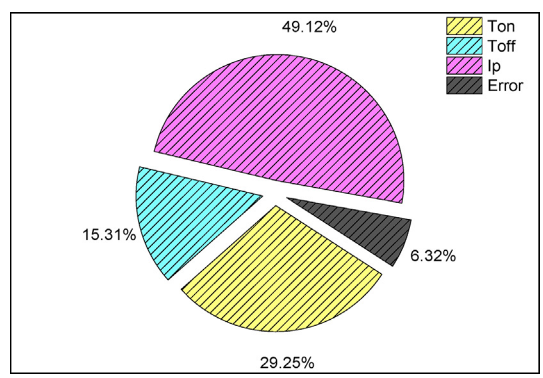

Fig. 3. Contribution of parameters on MRR.

considering T_{on}, the Ra drastically increased at higher level due to more spark produced which leads to creates more craters on machined surfae. Furthermore, the Ra steadily improved with an increase in I_p from 5A to 15A. As per the results (Figs. 5 & 6), we can revealed that the optimum setting of machining parameters are T_{on} of 15 μs, T_{off} of 40 μs and I_p of 5A which levels are produced lower Ra.

The response of S/N ratio and means table for Ra is provided in Table 7. From the table, it exactly noticed that the order of dominant factors on Ra were determined from the delta value. Based on the results (Table 7), it can be seen that I_p has the most notable factor for affecting the Ra trailed by T_{on} and T_{off}. It has been confirmed by ANOVA results as shown in Table 8. The contribution

Table 6
ANOVA result of MRR.

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P (%)
T_{on}	2	0.0037789	0.0037789	0.0018894	4.63	29.25
T_{off}	2	0.0019779	0.0019779	0.0009890	2.42	15.31
I_p	2	0.0063450	0.0063450	0.0031725	7.77	49.12
Error	2	0.0008163	0.0008163	0.0004082		6.32
Total	8	0.0129181				

S = 0.0202030 R-Sq = 93.68 % R-Sq(adj) = 74.72 %.

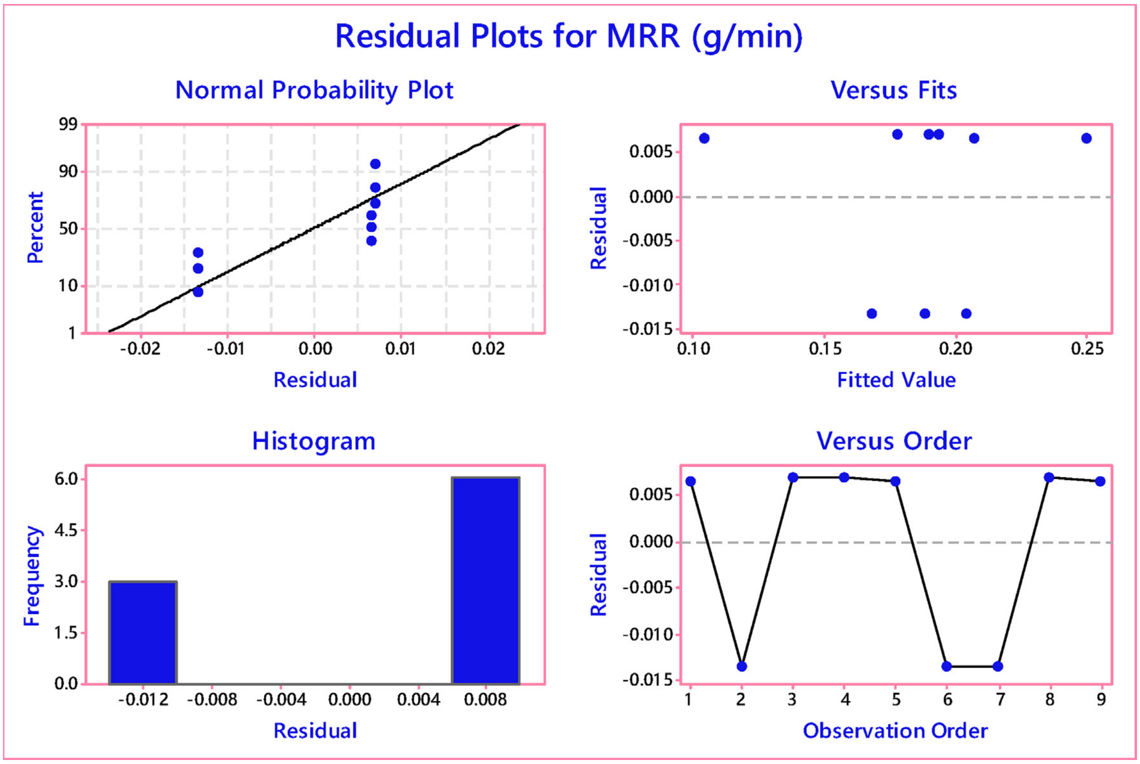

Fig. 4. Residual plot for MRR.

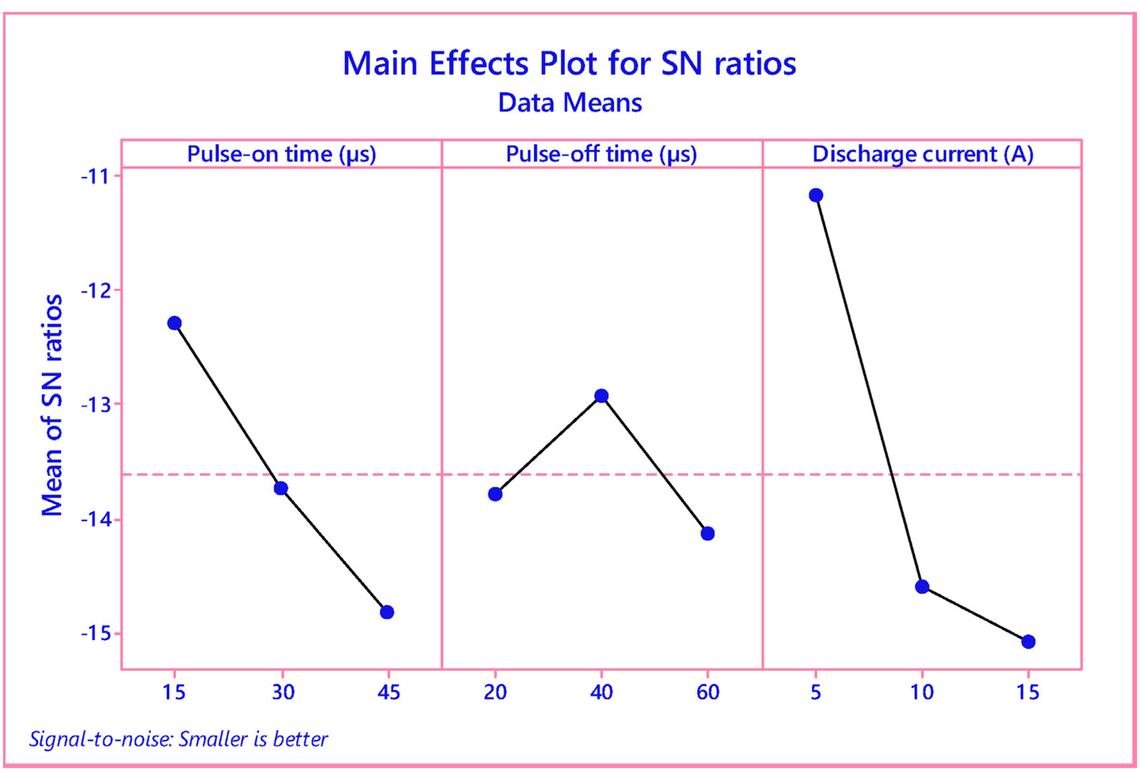

Fig. 5. S/N ratio plot for Ra.

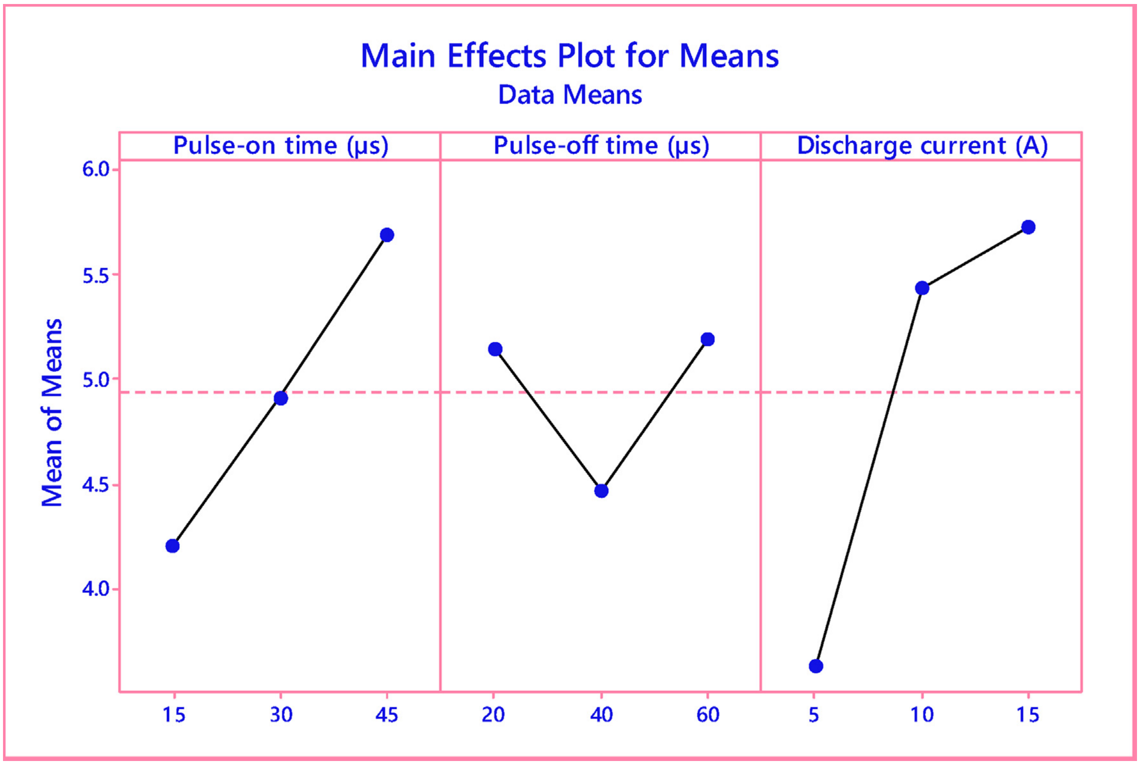

Fig. 6. Means plot for Ra.

Table 7
Response table for Ra.

S/N ratio of Ra			
Level	T_{on} (μs)	T_{off} (μs)	I_p (A)
1	−12.29	−13.79	−11.17
2	−13.73	−12.93	−14.59
3	−14.83	−14.13	−15.09
Delta	2.54	1.20	3.92
Rank	2	3	1
Means of Ra			
1	4.207	5.145	3.637
2	4.911	4.466	5.438
3	5.683	5.189	5.726
Delta	1.476	0.723	2.089
Rank	2	3	1

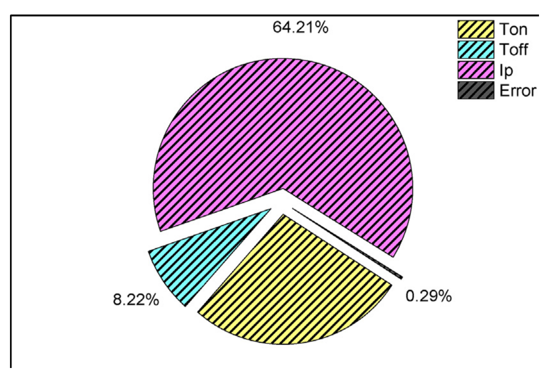

Fig. 7. Contribution of machining parameters on Ra.

of each parameters on Ra is displayed in Fig. 7. It clearly seen that I_p (64.20 %) has the primary significant factor for Ra then followed by T_{on} (27.28 %) and T_{off} (8.22 %), respectively. Sarat Kumar Sahoo et al. reported the same results while EDM process of Inconel 625 alloy [27]. Fig. 8 depicts the residual plot for Ra and it was revealed that the errors are disseminated normally in the developed model.

Table 8
ANOVA result of Ra.

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P (%)
T_{on}	2	3.2695	3.2695	1.6347	93.70	27.28
T_{off}	2	0.9854	0.9854	0.4927	28.24	8.22
I_p	2	7.6937	7.6937	3.8469	220.50	64.20
Error	2	0.0349	0.0349	0.0174		0.291
Total	8	11.9836				

S = 0.132083 R-Sq = 99.71 % R-Sq(adj) = 98.84 %.

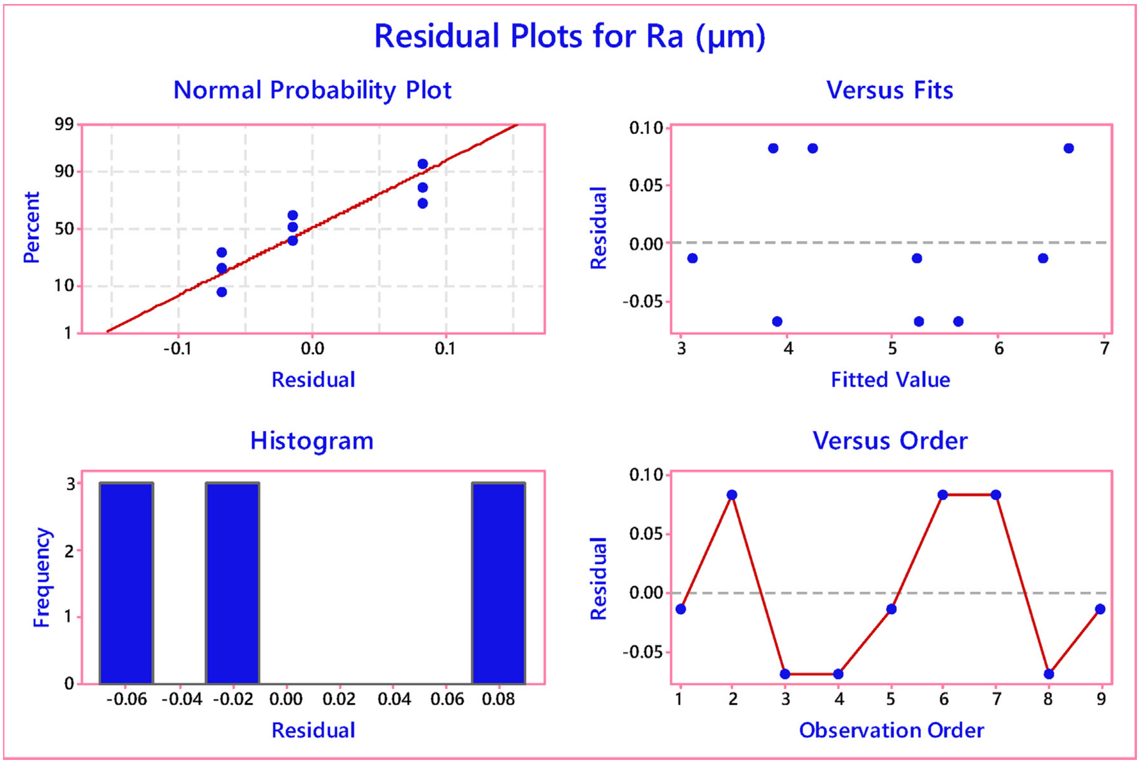

Fig. 8. Residual plot for Ra.

5. Conclusions

The conclusions were drawn from this investigation are as follows,

1. This work was carried out to investigate the effect of process parameters on MRR and Ra while EDM of Inconel 725 alloy.
2. The machining was executed as per Taguchi's L9 orthogonal layout by chosen three input parameters such as T_{on}, T_{off} and I_p. The S/N ratio and ANOVA were employed to predict the optimal parameter setting for obtain higher MRR with lower Ra.
3. The S/N ratio results reveal that the higher MRR achieved at T_{on} of 45 μs, T_{off} of 60 μs and I_p of 10 A. Similarly, the lower Ra produced at T_{on} of 15 μs, T_{off} of 40 μs and I_p of 5 A.
4. ANOVA results found that I_p (MRR- 49.12 % & Ra- 64.20 %) was the more significant factor for MRR and Ra next by T_{on} (29.25 % & 27.28 %) and T_{off} (15.31 % & 8.22 %), respectively.

CRediT authorship contribution statement

S. Balaji: Conceptualization, Validation. **C. Sivakandhan:** Formal analysis. **P. Maniarasan:** Methodology. **D. Deepak:** Validation. **K. Senthamarai:** Writing – review & editing. **S.V. Alagarsamy:** Writing – original draft, Supervision.

Data availability

Data will be made available on request.

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.

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