Analyzing the Machining Effectiveness of EDM on Inconel 718 Using Copper and Graphite Electrode

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Abstract
Inconel 718 is a nickel-based super alloy that is well suited for applications requiring high strength and better wear resistance in a varying temperature environment. Owing to its higher strength, most of the conventional machining techniques fail to machine Inconel 718 material. Electric discharge machining was found to be a good alternative to the conventional techniques to machine such superalloys. In this paper, the machining characteristics of Inconel 718 were investigated using copper and graphite electrode. A mixed-level Taguchi L18 orthogonal array is chosen to conduct the experiments with varying process parameters like tool material, pulse on time (Ton), voltage (v), and current (I). Material Removal Rate (MRR), Tool Wear Rate (TWR), and Surface roughness (Ra) are the performance characteristics selected for evaluation. The developed model was found to be in good agreement and the Cu tool gives the best result.

Keywords: *Electrical Discharge Machining, Inconel 718, Taguchi L18 array; Optimization, MRR, TWR, Ra*

1. Introduction

EDM process often referred to as spark machining, spark eroding, die sinking, wire burning, or wire erosion (sparks) helps in creating a desired shape on the surface of the workpiece. Material removal takes place by a series of rapidly recurring current discharges between the two terminals of the DC power source, separated by a spark gap filled with a suitable dielectric fluid [2, 9]. The tool-electrode, also known as the tool or electrode, is one of the electrodes, and the workpiece-electrode, also known as the work piece, is the other. The procedure relies on there being no physical touch between the tool and work component [10]. The electric field's intensity in the space between the two electrodes increases as the voltage between them rises, which causes the liquid's dielectric properties to break down and results in an electric arc. As a result, material is removed from the electrodes [11]. In order to remove the solid particles (debris) and restore the dielectric's insulating characteristics, fresh dielectric fluid is introduced into the inter-electrode region after the supply of current stops. Flushing is the term used to describe the addition of fresh liquid dielectric to the inter-electrode volume [12]. The voltage between the electrodes is returned to its initial value following a current flow, allowing another liquid dielectric breakdown to take place and complete the cycle [13, 14]. The majority of the time, hard metals or ones that would be extremely challenging to cut using conventional methods are the focus of electrical discharge machining [15]. EDM normally works with materials that are electrically conducting, Although strategies for using EDM to machine insulating ceramics have also been explored [16]. Without the need of heat treatment to soften and re-harden the steel, EDM can cut intricate curves or cavities in pre-hardened steel [17]. Any other metal or metal alloy, including titanium, Hastelloy, Kovar, and inconel, can be machined using this technique. Additionally, it has been stated that this method has been used to shape polycrystalline diamond tools [18]. EDM is frequently categorised as part of the "non-traditional" or "non-conventional" group of machining techniques, in contrast to the "conventional" group [19].

Figure 1: Electronica PS- Series Nc-EDM

Inconel super alloys has various categories according to its chemical composition. Those are inconel 601, inconel 625, inconel 718, inconel 825. nconel 718 is made to withstand a variety of extremely corrosive conditions, including pitting and crevice corrosion [14]. At high temperatures, it also exhibits unusually high yield, tensile, and creep rupture properties. From cryogenic temperatures through long-term use at 1200°F, this nickel alloy is used [15]. Niobium has been added to Inconel 718's composition to enable age hardening, which enables welding and annealing without the risk of spontaneous hardening during the cycle of heating and cooling. Niobium and Molybdenum work together to stiffen the matrix of the alloy and offer high strength without the use of a strengthening heat treatment [20]. The precipitation (age) hardened or annealed conditions of this alloy can both be used for welding.

Numerous researchers have worked to improve the input parameters of the EDM process as well as machining responses including material removal rate (MRR), surface roughness (Ra), dimensional accuracy, etc. Even with the most advanced EDM machine, the problem of choosing the cutting settings to increase machining efficiency or accuracy remains unresolved. The nature of the intricate stochastic process mechanisms in EDM is mostly to blame for this. The following aspects impacting the EDM process have been the subject of extensive research on the effects of various process parameters:

- Effects of the machining parameters on the Material Removal Rate
- Effects of the process parameters on the surface finish
- Effects of the process parameters on dimensional deviations

Mohanty et al. [1] applied a multi objective particle swarm optimization (MOPSO) algorithm to study the various machining parameters for the electrical discharge machining (EDM) procedures on Inconel 718 super alloy.The suggested model demonstrates the complex and interactive impacts of numerous significant process factors, including open circuit voltage (V), discharge current (Ip), pulse-on-time

(Ton), and tool material on responses, which are confirmed by analysis and experiments. **Manikandan and Venkatesan [2]** used the Taguchi method to determine the best combination of EDM parameters, such as discharge current, pulse-on time, and pulse-off time, in order to analyse the impact of EDM parameters on the machining parameters (such as metal removal rate, overcut, and tool wear ratio, etc.) for Inconel 718 work material.It was observed that these variables significantly affected the machining properties. **Yadav and Yadava [3]** analyzed the effect of tool rotation during nickel alloy, electro-discharge drilling (EDD). The results of the experiments proved that tool rotation had a significant impact on the hole's average circularity and surface roughness. **Newton et al. [4]** conducted an experimental analysis to identify the key Electro-Discharge Machining (EDM) factors that affected the production of recast layers for the Inconel 718 work material.It was determined that the energy per spark, peak discharge current, and duration of the current pulse were the main factors increasing average recast layer thickness.It was observed that the recast layer had less elastic modulus, less hardness, and in-plane tensile residual stress than the bulk material. **Ay et al. [5]**employed grey relational analysis to enhance the multi-performance characteristics of the Inconel 718 super alloy through micro-electrical discharge machining (drilling) process (viz. hole taper ratio, and hole dilation). On performance parameters, it was observed that the pulse current outperformed the pulse duration. **Kumar et al. [6]** demonstrates that a longer pulse length of up to 750µs has improved MRR during Inconel 718 EDM. In order to increase productivity, the main goal in EDM of materials is to always have a higher material removal rate (MRR).In order to boost the performance and productivity of EDM Inconel 718, larger peak current and pulse length were used in this experimental work. **Imran et al. [7]** explored the viability of nickel-based super alloys for deep-hole micro drilling.The impact of processing variables such drill feed rate, spindle speed, and peck depth were assessed in this experiment.Investigations were also done into the mechanism of tool wear.The authors emphasised that the micro-drilling method offered a satisfactory hole dimension and potentially affordable lead times. **Kumar S. et al. [8]** The effects of the Powder-Mixed Electro-Discharge Machining (PMEDM) method on the improvement of the machined work surface properties of cryogenically treated Titanium alloy were investigated. Peak current turns out to be a highly significant parameter in this study that affected both the micro-hardness and surface quality of the machined surface. **Ramakrishnan and Karunamoorthy [9]** anticipated the ideal WEDM cutting parameters for working with Inconel 718 work material.In addition to Taguchi's parametric design method, the responses (material removal rate and surface roughness) were simultaneously adjusted utilising multi-response Signal-to-Noise (S/N) ratio.The level of significance of the machining factors on the various performance metrics was determined using Analysis of Variance (ANOVA).

2. Material Methods

High-strength and high-thermal resistance materials that perform better in challenging circumstances are in greater demand. Inconel 718 is a well-known superalloy utilised in a variety of applications owing to its high-strength, temperature-resistant material. Therefore, a commercially viable Inconel 718 is chosen as the work material for the experiments in the current investigation. In all the experimental trials, a 100mm × 100mm × 5mm size of inconel 718 has been taken.

In this present work an ELECTRONICA PS- Series Electrical Discharge Machine is used. The experiment is designed using Taguchi mixed level L18 orthogonal array. Inconel 718 (100mmX100mmX5mm) is used as a work piece material and copper electrode of 10 mm diameter and a graphite electrode of 10mm diameter has taken as electrode material. Process parameters such as pulse on time (Ton), voltage (v), peak current (I) are varying continuously to get the Metal removal Rate (MRR), Tool Ware Rate (TWR) and surface roughness (Ra). EDM 30 oil is used as the di-electric fluid which is a combination of paraffin and kerosene. The machining time has been taken as four minutes for each experiment. Nine numbers of experiments were conducted by using copper tool and rest nine numbers of experiment were conducted by using graphite tool. The EDM used in this experiment is a NC- EDM (Numerical Control – Electrical Discharge Machine). The design of experiments (DOE) analysis has been done by Minitab 17 software by using a Taguchi mixed level analysis by continuously varying the 3 controllable factors i.e., peak current (I), pulse on time (Ton) and voltage (v) at 3 levels.

Table 1: Controllable factors and their levels

Current		Ton		Voltage	
1	15A	1	50mA	1	8V
2	20A	2	100mA	2	9V
3	25A	3	200mA	3	10V

2.1 Calculation of Material Removal Rate

MRR can be defined as the rate at which loss of material takes place from the work piece. MRR can be calculated by the given formula

$$\textbf{MRR} = \frac{(Wi - Wf)}{t \times \rho} \text{ in mm3/min} \quad \ldots\ldots\ldots\ (1)$$

Where Wi and Wf denotes initial and final weights (in gram) of the workpiece, respectively. The term t denotes machining time (in minutes) and ρ represents density of the workpiece (in g/mm3) (density of Inconel 718 = 0.008192 g/mm3).

2.2 Calculation of Tool Wear Rate

TWR can be defined as the rate at which loss of material takes place from the electrode. TWR can be calculated by the given formula

$$\textbf{TWR} = \frac{(Ti - Tf)}{t \times \rho} \textbf{ in mm3/min.} \quad \ldots\ldots\ldots\ (2)$$

Where Ti and Tf denotes initial and final weights of the tool electrode (in gram), respectively. The term t denotes machining time (in minutes) and ρ represents density of the tool material (in mm3/min). (Density of copper is 0.00896 in g/mm3 and density of graphite is 0.00227 g/mm3).

2.3 Surface Roughness

Arithmetic average roughness, or Ra, is the arithmetic average of the heights of surface irregularities (peak heights and valleys) with respect to the mean line, measured within the sampling length. It is measured in surface roughness tester.

2.4 Result for Machining of Inconel 718

Table 2: machining result of inconel 718

SL No	Tool	Peak Current	Pulse on Time	Voltage	MRR	SN RATIO for MRR	TWR	SN RATIO for TWR	Ra	SN RATIO for Ra
1	Cu	15	50	8	2.61	8.333	0.055	25.193	0.519	5.697
2	Cu	15	100	9	5.35	14.567	0.080	21.938	1.775	-4.984
3	Cu	15	200	10	6.57	16.351	0.139	17.140	2.434	-7.726
4	Cu	20	50	9	6.46	16.205	0.050	26.021	1.279	-2.137
5	Cu	20	100	10	7.84	17.886	0.083	21.618	2.134	-6.584
6	Cu	20	200	8	9.75	19.780	0.167	15.546	3.113	-9.864
7	Cu	25	50	10	11.57	21.267	0.061	24.293	1.813	-5.168
8	Cu	25	100	8	13.31	22.484	0.112	19.016	2.134	-6.584
9	Cu	25	200	9	19.83	25.947	0.279	11.088	3.262	-10.270
10	Graphite	15	50	8	1.42	3.046	1.341	-2.549	3.162	-9.999
11	Graphite	15	100	9	2.75	8.787	1.950	-5.801	3.489	-10.854
12	Graphite	15	200	10	2.80	8.943	3.013	-9.580	3.956	-11.945
13	Graphite	20	50	9	3.30	10.370	1.760	-4.910	3.306	-10.386
14	Graphite	20	100	10	3.05	9.686	2.564	-8.178	3.636	-11.213
15	Graphite	20	200	8	5.42	14.680	3.120	-9.883	4.147	-12.355
16	Graphite	25	50	10	3.75	11.481	2.202	-6.856	3.579	-11.075
17	Graphite	25	100	8	6.50	16.258	2.783	-8.890	3.760	-11.504
18	Graphite	25	200	9	12.07	21.634	3.303	-10.378	4.795	-13.616

3. Result Analysis

3.1 Taguchi Analysis: MRR versus Tool, Peak Current, Ton, Voltage

Table 3: Analysis of Variance for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	1	186.46	186.46	186.464	136.18	0.000
Peak current	2	290.60	290.60	145.302	106.12	0.000
T_{on}	2	111.89	111.89	55.943	40.86	0.000
Voltage	2	17.21	17.21	8.603	6.28	0.017
Residual error	10	13.69	13.69	1.369		
Total	**17**	**619.85**				

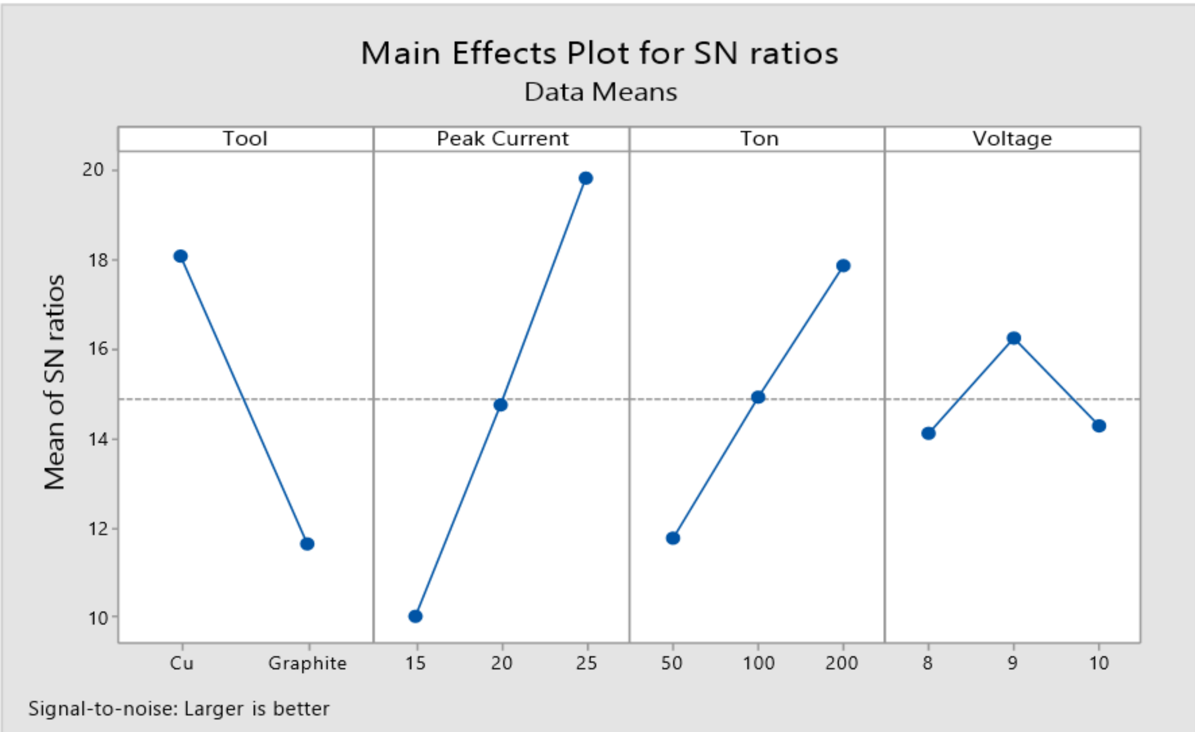

Figure 2: Main Effects Plot for SN ratios for MRR

The Figure 2 reveals that, higher MRR is obtained during machining with copper electrode at current 25A, pulse on time of 200mA and voltage of 9V. In the Table 2 we can see at experiment 9 the parameters are 25A, 200mA and 9v we are getting the MRR as 19.83 and SN ratio for MRR as 25.947 which is larger among all 18 number of experiments conducted by both copper and graphite tool.

3.2 Taguchi Analysis: TWR versus Tool, Peak Current, Ton, Voltage

Table 4: Analysis of variance for TWR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool	1	3441.13	3441.13	3441.13	944.42	0.000
Peak current	2	28.15	28.15	14.07	3.86	0.057
T_{on}	2	186.63	186.63	93.32	25.61	0.000
Voltage	2	0.03	0.03	0.01	0.00	0.997
Residual error	10	36.44	36.44	3.64		
Total	17	3692.37				

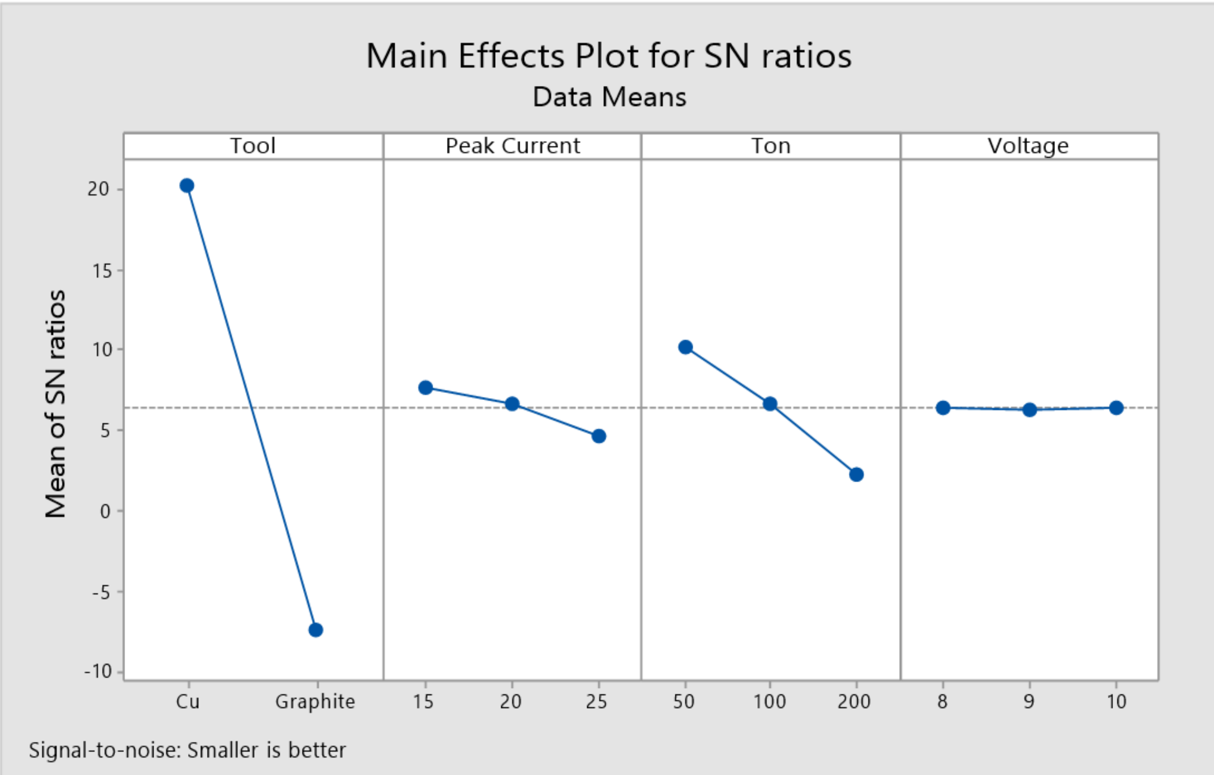

Figure 3: Main effects plot for TWR

The figure 3 reveals that, lower TWR is obtained during machining with graphite electrode at current 25A, pulse on time of 200mA and voltage of 9V. In the Table 2 we can see at experiment 18 the parameters are 25A, 200mA and 9V we are getting the TWR as 3.303 and SN ratio for TWR as -10.378 which is lowest among all 18 number of experiments conducted by both copper and graphite tool.

3.3 Taguchi Analysis: Ra versus Tool, Peak Current, Ton, Voltage

Table 5: Analysis of Variance for Surface Roughness (Ra)

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Tool	1	170.055	170.055	170.055	25.01	0.001
Peak current	2	29.606	29.606	14.803	2.18	0.164
T_{on}	2	89.728	89.728	44.864	6.60	0.015
Voltage	2	7.964	7.964	3.982	0.59	0.575
Residual error	10	68.000	68.000	6.800		
Total	**17**	**365.353**				

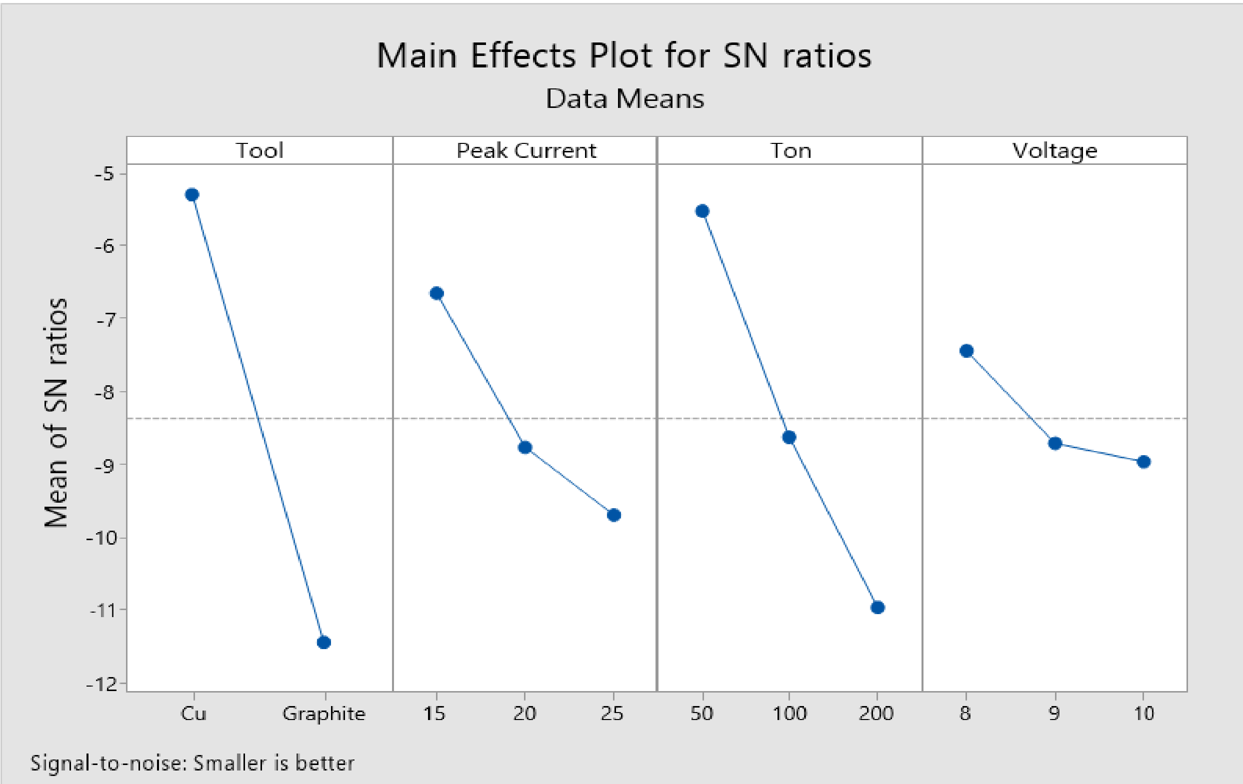

Figure 4: Main Effects Plot for Ra

The fig 4.3 reveals that, lower Ra is obtained during machining with copper electrode at current 15A, pulse on time of 50mA and voltage of 8V. In the Table 2 we can see at experiment 1 the parameters are 15A, 50mA and 8V we are getting the Ra as 0.519 and SN ratio for Ra as 5.697 which is lowest among all 18 number of experiments conducted by both copper and graphite tool.

4. Conclusion

The foregoing research highlights an experimental investigation on machining (EDM) of Inconel 718. The work has focused application feasibility of Taguchi optimization approach for correlated multi-response Optimisation during EDM of Inconel 718. The main conclusions drawn from the current work have been summarized below.

- Out of the controllable process parameters selected in the present work (Voltage, peak current, pulse-on-time and electrode material) peak current and electrode material has been found as the most significant factor on influencing process responses.
- Usage of Cu electrode has been recommended for EDM on Inconel 718 in combination with optimal values of process parameters to achieve satisfactory machining yield (in terms of increased MRR, reduced TWR, lesser extent of Ra on the machined work piece).
- The most favorable process environment appeared as: current of 25A, pulse on time of 200mA and voltage of 9V for getting a good MRR, lesser TWR and better surface finish.

5. References

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