REVIEW AND OPTIMIZATION OF GRAPHITE POWDER MIXED ELECTRIC DISCHARGE MACHINING OF INCONEL 718 ALLOY

Vipin Yadav - M Tech scholar, Department of Mechanical Engineering,C V Raman University, Bilaspur, C.G., India
Email id: vipinyadav1503@gmail.com

Nitin Shukla - Assistant Professor, Department of Mechanical Engineering,C V Raman University, Bilaspur, C.G., India
Email id: nitin184shukla@gmail.com

Abstract: Inconel-718 is a high performance super-alloys has excellent mechanical strength at elevated temperature, as cryogenic temperature. While these materials are harder, tougher, less heat sensitive and more resistant to corrosion and fatigue, they are more difficult to machine. Because of work hardening property, Inconel-718 is difficult to machine by using conventional machining techniques

Electric discharge machining is a non-conventional machining process used to machine very hard materials such as Inconel alloy which is most widely used in aerospace industry, Die and Mould making industries to produce complex cavity and intricate shapes. In the present work, studies have been conducted to investigate the effect of process discharge current, pulse on time, pulse off time and concentration of powder on material removal rate, tool wear and surface roughness in Graphite powder mixed electrical discharge machining (PMEDM).

The investigations have been conducted on Inconel 718 alloy, which is having wide industrial applications. Inconel 718 has high strength at elevated temperature, good corrosive and wear resistance at different environmental conditions. In the present work, experiments have been conducted using Design of Experiments and single parameter optimization has been carried out using Taguchi technique to establishing the graphite powder range. Response surface methodology is used to developed mathematical models and Single Objective optimization of process parameters for maximum MRR and minimum tool wear and surface roughness with graphite powder mixed EDM of Inconel 718 alloy. The ANOVA analysis revealed that the discharge current, pulse on time and graphite powder concentration are most significant parameters which affecting the performance characteristics.

This paper summarizes some of the major aspects of machining parameter of Inconel 718 alloy machining operation through PMEDM and an attempt has also been made to optimize the process parameters of PMEDM in order to maximize the material removal rate, minimize the tool wear rate and surface roughness.

Key Words: PMEDM, EDM, Inconel 718 alloy, unconventional machining.

1.Intriduction:

In recent years, materials with unique metallurgical properties such as, nickel based alloys, titanium based alloys, tungsten carbide and its composites, tool steels, hardened steels, stainless steels, and other super alloys have been developed to meet the demands of different industrial applications. Difficult-to-cut materials have been widely used these days not only in the aerospace industry but also in the other industries. Therefore, the machining of difficult-to-cut materials is an important issue in the field of manufacturing.

1.1 Inconel-718 alloy:

Inconel-718 is a type of austenite nickel chromium based super alloys. The name is a trademark of Special metals Corporation. Inconel alloys are resistant to oxidation and corrosion materials well suited for use in extreme environmental condition, subjected to pressure and kinetic energy. Inconel-718 alloys sustain a very high temperature at elevated environmental condition. Inconel 718 alloy is age hardened with additions of aluminum and titanium combine with nickel to form Ni3 (Ti, Al) or gamma prime (γ') compound.

The composition of Inconel 718 alloys are given in the following table:

Table **Fehler! Kein Text mit angegebener Formatvorlage im Dokument.**.1 Physical properties of Inconel 718 alloy

Element	Percentage	Element	Percentage
Nickel & Cobalt	50-55	Carbon	0.08 max
Chromium	17-21	Manganese	0.35 max
Iron	Balance	Silicon	0.35 max
Niobium & Tantalum	4.75-5.5	Phosphorous	0.015 max
Molybdenum	2.8-3.3	Sulfur	0.015 max
Titanium	0.65-1.15	Boron	0.006 max
Aluminium	0.2-0.8	Copper	0.30 max
Cobalt	1.00 max		

Inconel is a difficult to machine and shape metal using traditional machining technique due to its rapid work hardening so after the first machining pass either tool or work piece plastically deform due to work hardening nature of the material. Inconel 718 alloys have a wide application in the aerospace and other manufacturing industries due its high temperature resistant capacity.

1.2 Applications of Inconel-718 alloys:

Inconel-718 alloys have so many applications in the aerospace and modern manufacturing industries. It is commonly using in gas turbine, blades, seals, and combustors, as well as turbocharger rotors and seals, electric submersible well pump motor shafts, high temperature fasteners, chemical processing and pressure vessels, heat exchanger, tubing, steam generators in nuclear pressurized water reactors, natural gas processing with contaminants such as H2S and CO2 , firearm sound processor sound baffles and Formula One racing car and rotary engine exhaust systems where exhaust temperatures reach more than 1000 C0.

1.3 Machining issues of Inconel-718 alloy:

Inconel-718 is a high performance super-alloys has excellent mechanical strength at elevated temperature, as cryogenic temperature. While these materials are harder, tougher, less heat sensitive and more resistant to corrosion and fatigue, they are more difficult to machine. Because of work hardening property, Inconel-718 is difficult to machine by using conventional machining techniques. During the machining material plastically deform due to work hardening. The properties that make Inconel-718 important engineering materials are also responsible for its generally poor machinability. When turning Inconel 718, nonuniform flank wear and depth of cut notching has been reported to be the main cause of tool failure. The cutting forces generated are also very high, around double that found when cutting medium carbon alloy steels. Nickel based superalloys also have a high chemical affinity for many tool materials and form an adhering layer leading to diffusion wear of tool.

The non-conventional machining processes are more capable than conventional machining process adopted to ease of machining of hard materials such as inconel-718 alloys and other super alloys with complex shapes and cavity in the shortest duration of time. Now-a-days, electrical discharge machining (EDM) is extensively used for machining of high strength to weight ratio conductive and toughened materials which are very difficult to be machined by traditional machining processes. The process has many applications in manufacturing of dies and moulds in manufacturing industries and components in aerospace and automotive industries.

EDM is widely used in industries to machine 'difficult to machine materials' like HCHC steel (tool and die material). INCONEL 718 is one of the alloys that have relatively poor machinability in the conventional machining processes, due to its work-hardening nature, retention of high strength at high temperature (700 k) and low thermal conductivity.

For Inconel alloy, EDM is a preferred material removal process due to its advantages like higher material removal rate, reduced machining stresses, lesser work-hardening effects and lesser metallurgical damage.

1.4 **Powder mixed EDM:**

Electrical discharge machining (EDM) in a non conventional non-contact type thermo-electrical machining in which material is removed by melting and evaporation of material between the tool and work piece. In this machine spark is generated between the tool and the work piece, this small gap is known as "Spark gap". In EDM machine electrical energy is used to generate a electrical spark, and due to this spark a high temperature approx 8000 C0 to 12000 C0 is generated between gap and material will removed by melting and evaporation. EDM is mainly used to machine difficult to machine material and very high strength at elevated temperature alloy such as Ni alloy, Titanium alloy and Metal matrix composites (MMC). EDM should be used in very big scale industry or for any job shop production unites. Generally EDM is able to machine only conductive materials.

However its poor machining efficiency and poor surface quality restricted this machine for further machining applications. To overcome one new technique used to improve the machining efficiency and surface quality of machined surface. In this technique conductive metal powder is mixed with the dielectric fluid of EDM. This new technique is known as "Powder mixed EDM" (PMEDM) and it is also known as "Additive EDM" machining process. Due to mixing of this fine metal powder with dielectric fluid significantly affects the performance of EDM process.

1.5 Principle of PMEDM:

PMEDM has different machining mechanism compare to the conventional EDM process. In PMEDM a conductive fine powder particle is mixed with the dielectric fluid in the fluid tank. For better circulation of powder with the dielectric fluid a stirrer mechanism is used to continuous mixing and to avoid the settlement of powder particle at bottom of the tank.

In this process fine powder is mixed with the dielectric fluid and because of this suspended powder particle improves the breakdown characteristics of the dielectric fluid and insulating strength of the dielectric fluid decreases and at that same time the spark gap between the tool and the work piece increases. Due to opposite polarity of the tool and work piece and voltage is produced between tool and work piece. Because of this voltage a current is flow from negative to positive side and spark is generated between the gap, and material get eroded from machined surface due to melting and evaporation. Due to this flushing nozzle arrangement at the gap it will improves the debris cleaning between the tool and work piece and produce better surface finished machined surface.

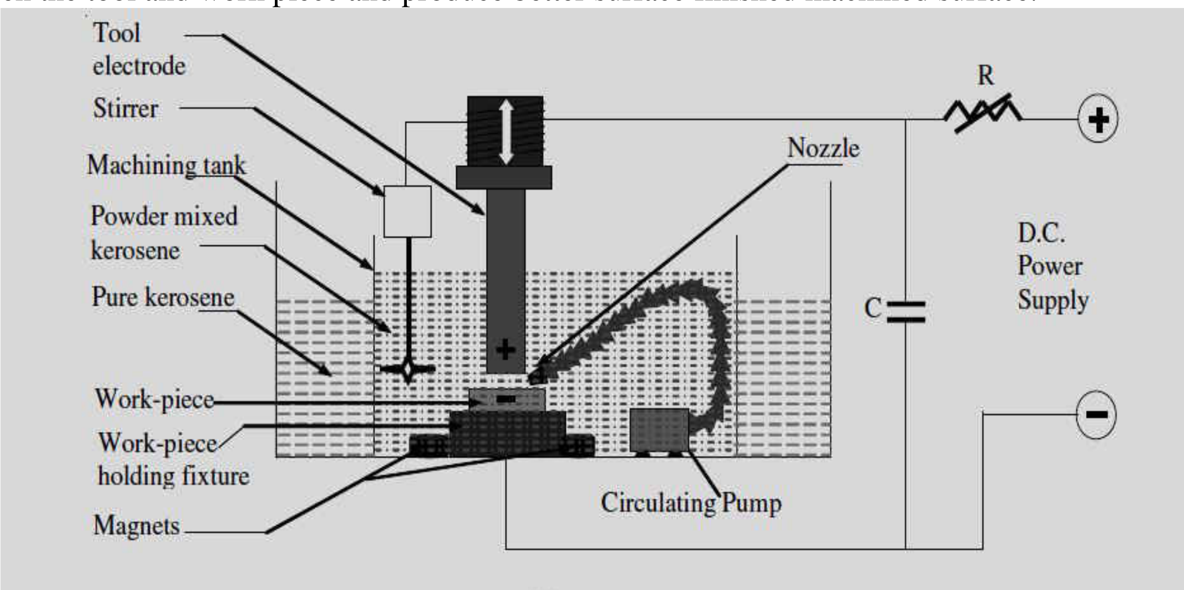

Figure 1.1 Schematic diagram of PMEDM process

2. Experimental work:

2.1 Work Material:

The work piece material selected for present study is Inconel 718 super alloy. Inconel 718 alloys use in various industries for different applications. Inconel 718 has high strength at elevated temperature, good corrosive and wears resistance at different environmental condition.

Inconel 718 alloys are used in various industries for different applications such as die and mould making, Aerospace, Automobile etc. It is very difficult to machine by using conventional machining because of its work hardening property so this material is easy to machine by using unconventional machine. Inconel 718 has high strength at elevated temperature, good corrosive and wear resistance at different environmental condition. It has become the most usable material over the others.

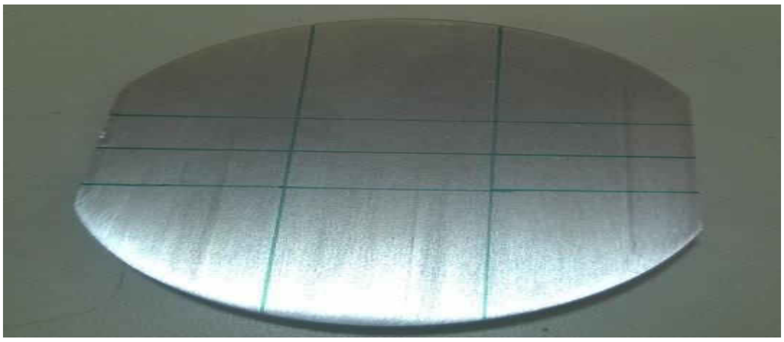

Figure 2.1 Inconel 718 alloy Work piece

Table 2.1 Chemical composition of Inconel 718 alloy (wt %)

Element	Cu	Mn	Si	Ti	Al	Co	Mo	Cb	Fe	Cr	Ni
Percentage	0.08	0.35	0.35	0.6	0.8	1.0	3.0	5.0	17.0	19.0	52.82

Table 2.2 Mechanical properties of Inconel 718 alloy

Ultimate Strength (MPa)	Yield Point (MPa)	Elongation (%)	Elongation (%)
1260 – 1390	1041 – 1160	14 – 19	40 - 45

2.1.1 Electrode material:

Tool material is selected such as it won't be easily wear out. Generally tool is give as a negative charge to reduce the wear rate causes improves the surface finish. Tool will be easily changed in the intricate shape because tool is the replicate of the cavity to be produced at the work piece.

In this present work Copper selected as a tool electrode with cylindrical shape 14 mm diameter.

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Figure 2.2 Copper Tool

The following table shows the Physical property of the Cu electrode

Table 2.3 Physical property of Cu electrode

Yield strength (MPa)	140
Tensile Strength (MPa)	270

Density (g/cm^3)	8.96
Melting point (^{0}C)	1083
Elastic Modulus (Gpa)	110-140
Bulk thermal conductivity (W/mK)	391
Specific thermal conductivity (W/mK)	45

2.2 Experimental Setup:

The experiments have been conducted on a Formatic EDM model 50 die sinking machine manufactured by Electronica Machine Tools Ltd. India, with modified dielectric fluid circulation system as shown in fig 3.1. Machine is equipped with PSR-20 power controller unit to operate the machine. Machine also have DC servo controller to provide feed to the tool electrode towards work piece. The machine has maximum current capacity 20 A. This machine can be run on straight or reverse polarity. But straight polarity is default for this machine i.e. work piece is connected with positive side and tool electrode is connected with positive side. This machine has (1 to 99) pulse on time which shows different pulse on time value at different digits up to maximum limits 1050 µs similarly for (1 to 9) pulse off time maximum limit is up to 363 µs. Spark erosion die 450 EDM oil is used as a dielectric fluid contain in a reservoir tank having 20 liters capacity and working tank where machining was done have 15 liters capacity. Three submersible pumps (0.5MP pressure) is use for circulation of the dielectric fluid.

The EDM machine is consist of different parts which are discus here:

1) Power generator system and Control unit
2) Servo tool feed system
3) Tool electrode holder
4) Working tank and Work piece fixture device
5) Dielectric fluid circulation system

2.4 Experimental Condition:

Table 2.4 Experimental Condition

Working condition	**Description**
Work Piece	Inconel 718 Alloy
Work piece Size	65 mm Diameter
Electrode	Electrolyte Copper Ø 14 mm and length 70 mm
Dielectric	Commercial EDM Oil grade SAE 450+Gr Powder
Flushing	Side flushing with pressure 0.5 MPa
Gr powder particle size	35-37 µm
Polarity	Straight
Supply Voltage	110V
Gap Voltage	70 V
Machining Time	30 Min

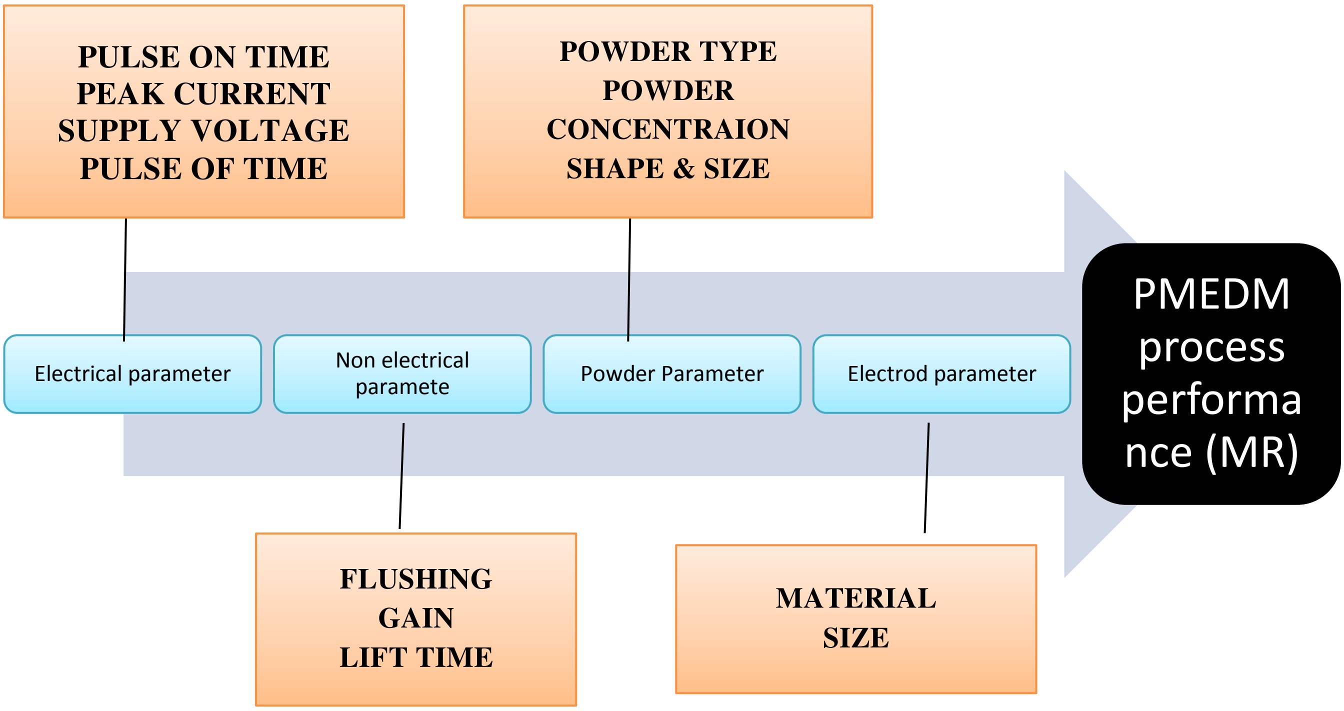
2.5 Important process parameter :

The important process parameter which affects the response parameter of PMEDM is classified according to the Ishikawa cause–effect diagram was constructed as shown in Fig 2.3

The parameters are classified

1) Electrical parameters: Discharge current (I), Pulse on time (Ton), Pulse off time (Toff) and Voltage Gap (V)
2) Non-Electrical parameters: Nozzle flushing pressure, gain, electrode lifting time, working time
3) Powder based parameters: Type of conductive powder, Powder concentration and other properties such as shape, size, conductivity, etc.
4) Electrode based parameters: Material type, Shape and Size of electrode.

The process parameters of PMEDM are shown in the Ishikawa cause-effect diagram fig 3.4. Four parameters, namely Discharge current, pulse-on time, pulse-off time, Concentration of graphite powder have been selected for the present study. Other parameters such as Nozzle flushing pressure, Gap voltage are kept as a constant. The ranges of these parameters were selected on the basis of preliminary or Trial experiments.



3. Experimental procedure:

In this investigation the experiments are perform in three stages. In the first stage experiments are performed by using Taguchi method in order to maximize the desirable performance parameter and minimize the undesirable performance parameter. In the second stage, experiments it carried out by using one factor- at-a time approach. In this approach first set the optimum process parameter as a constant and adding the Graphite powder concentration from 1 to 21 gm/lit in the dielectric fluid. And identify the effective powder range for Inconel 718 alloy material. In third stage, experiments are performed by response surface methodology by addition of different graphite powder concentration in the dielectric fluid.

- Optimization of process parameter using Taguchi method
- Trial experiment for establishing range of powder concentration
- Optimization of process parameter using Response surface methodology

3.1 Design of Experiments (DOE):

A Design of Experiment (DOE) is a structured, organized method for determining the relationship between factors affecting a process and the output of that process Conducting and analyzing controlled tests to evaluate the factors that control the value of a parameter or group of parameters. "Design of Experiments" (DOE) refers to experimental methods used to quantify indeterminate measurements of factors and interactions between factors statistically through observance of forced changes made methodically as directed by mathematically systematic tables.

The Design of Experiment Methods is:

- Taguchi Design
- Response Surface methodology

In this study Taguchi and Response surface methodology method was used for optimizing process parameter.

3.1.1 Taguchi method:

Taguchi is very simple systematic and effective approach to optimize the process parameters. It deals with the response parameter which affects by many machining parameters. This is the simple method to reduce the number of experiments, which is use to analyze and optimize the response parameter. A large number of experiments have to be carried out when the number of the process parameter increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Here Taguchi method was specially used for optimize the response parameter, optimum levels of machine parameters and its individual affects on the response [10]. Taguchi uses the signal-to-noise ratio (S/N) ratio to analyze the variation in the response data [5]. The significant of S/N ratio is determining the deviation of response parameter from the mean value. “Higher the better” represent the response parameter that is to be maximize and “Lower the better” represent the response parameter that is to be minimize [10]. In this study the response such as MRR need to be maximized and TWR, SR need to be minimize.

In the present study the number of process parameter consider are three and level of each parameter are three. The degree of freedom for all the three parameters is 2 (i.e. number of levels-1) and total degree of freedom for all the factors is 6 (i.e. 3×2=6). The selected orthogonal arrays (OA) degrees of freedom (DOF) (i.e., number of experiments - 1 = 9–1 = 8) must be greater than the total DOF of all the factors (6). Hence, L9 (34) OA is considered for the present study. Based on the preliminary experimentation, there is no interaction between the selected process parameters. Hence interaction is not considered for the present study. Three trails of each experiment were conducted to average of these values so that minimize the pure experimental error. The selected OA is presented in Table 3.1.

Table 3.1 Selected OA L9 (34)

Exp. No.	Current (A)	Pulse on time (μs)	Pulse off time (μs)
1	8	40	23
2	8	60	35
3	8	80	46
4	12	40	35
5	12	60	46
6	12	80	23
7	16	40	46
8	16	60	23
9	16	80	35

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Regardless of the category of the quality characteristics, a greater S/N ratio corresponds to the better quality characteristics. Therefore, optimal level of process parameters is the level with the greater S/N ratio. Furthermore, a statical analysis of variance (ANOVA) is performed to see which process parameters are statically significant with S/N ratio and ANOVA analyses, optimal combination of the process parameters can be predicted.

Equation no. (1), Define the S/N ratio:

$$\eta = -10 \log (MSD) \quad (1)$$

Where η is the S/N ratio and MSD is the mean square deviation for response

The MSD for “Higher the better” for MRR can be represented as:

$$\sum_{i=1}^{n} \frac{1}{MRR_i^2} \quad \textbf{(2)}$$

Where n is the total number of experiments and MRRi is the value of MRR at ith experiment.

The MSD for “Lower the better” for TWR and SR can be represented as:

$$MSD = \frac{1}{n} \sum_{i=1}^{n} TWR_i^2 \quad (3)$$

$$MSD = \frac{1}{n} \sum_{i=1}^{n} SR_i^2 \quad (4)$$

Where TWRi and SRi is the value of TWR and SR at ith experiment
By using above equations the S/N ratio can be calculated for each experiment L9 OA for MRR, TWR and SR. Higher S/N ratio provides the better performance characteristics and optimum level parameter. The mean S/N ratio for each machining parameter at each level can be calculated by averaging the S/N ratio of corresponding levels. Mean of mean graphs and mean of mean response value of each levels for MRR, TWR and SR are get by using MINITAB 17 software.
The three average value of MRR, TWR and SR using Eqs. (1) to (4) is shown in the Table 5.1.
The optimization of the process parameter using Taguchi method shows the effects of parameter on the response. Analysis of variance (ANOVA) is use to determine process parameter are significant and have mostly affect the response parameter.
ANOVA was used to find out which parameter is most significant and it's the percentage of contribution to affects the response parameter. The F-value reveals the most influenced parameter which is significantly effects the MRR, TWR and SR. When F ratio is larger it means, that corresponding process parameter has most significant and contribute more effect on the response [16].
From ANOVA, the total sum of square deviation SST by using total mean S/N ratio ηm can be calculated by:

$$SS_T = \sum_{i=1}^{n}(\eta_i - \eta_m)^2 \quad (5)$$

ANOVA also provide the indication of which process parameter combination has significant effects and its optimal results.
Mean square is calculated as:

$$MS = \frac{\text{Adj SS}}{\text{DF}} \quad (6)$$

F ratio is used to determine whether a given interaction or main effect is significant. F test is calculated as:

$$F = \frac{\text{MS Term}}{\text{MS (Error)}} \quad (7)$$

Maximum value of F ratio shows the factor and interaction are significant.

Evaluation of MRR:

The material MRR is expressed as the ratio of the difference of weight of the work piece before and after machining to the machining time and density of the material. It measure in mm^3/ min.

$$MRR = \frac{W_{wb} - W_{wa}}{\rho_i t} \quad (8)$$

Where
Wwb = Weight of work piece before machining in grams
Wwa = Weight of work piece after machining in grams
t = Machining time in minutes
ρ_i = Density of Inconel 718 (8.12 g/cm^3).

Evaluation of TWR:

TWR is expressed as the ratio of the difference of weight of the tool before and after machining to the machining time. It measure in mm^3/ min. That can be explained by this equation.

$$TWR = \frac{W_{tb} - W_{ta}}{\rho_c t} \quad (9)$$

Where
Wtb = Weight of the tool before machining in grams
Wta = Weight of the tool after machining in grams
t = Machining time in minutes
ρc = Density of copper (8.91 g/mm3).

4 Results and Discussion:

In this chapter discuss about the optimization of process parameter without PMEDM and Identify the effective graphite powder range and after that Optimization of process parameter by addition of graphite powder into the dielectric fluid of Inconel 718 alloy with PMEDM to achieve the objective of the experiments. In this experimental study the design of experiments used was Taguchi method, one factor-at-a-time approach and RSM method. The experiment has been performed to study the single and combine effect of process parameter on the response parameter such as MRR, TWR and SR.

The experimental results are discussed in the following sequence in which machining to be performed.

4.1 Results for optimization of process parameter by using Taguchi method

Table 5.1 shows the experimental data for MRR, TWR and SR. This data was used for analyzed the optimum process parameter and study the individually and combine effect of process parameter on the performance measure.

Table 4.1 Experimental layout for L9 (34) and result of MRR, TWR and SR

Exp No.	Current (A)	Pulse on time (µs)	Pulse off time (µs)	MRR (mm^3/min)	S/N Ratio (db)	TWR (mm^3/min)	S/N Ratio (db)	SR (µm)	S/N Ratio (db)
1	8	40	23	6.5453	18.59	0.8571	-0.219	5.67	-16.23
2	8	60	35	8.8520	25.48	0.9935	-6.726	6.53	-16.14
3	8	80	46	10.6200	25.87	1.2670	-8.577	7.35	-16.69
4	12	40	35	28.8390	29.06	2.9890	-11.46	6.66	-16.90
5	12	60	46	26.7740	26.46	3.6260	-8.173	6.72	-16.73
6	12	80	23	29.5690	26.84	4.8330	-8.76	7.65	-17.02
7	16	40	46	35.1350	31.73	3.9850	-14.07	6.97	-17.50
8	16	60	23	39.2930	27.44	4.6710	-10.85	7.36	-17.77
9	16	80	35	41.6340	26.66	6.9400	-8.41	8.22	-16.91

Material removal rate Table 4.1 shows the results for MRR and its corresponding S/N ratio value based on the experiments perform on the basis of Experimental layout L9 (34). Table 4.2 shows the ANOVA results for MRR. From the ANOVA analysis we can conclude that current is the most significant factor for MRR with higher F ratio value and contribution (97.93 %) compare to other parameter Pulse on time (3.66 %) and Pulse off time (0.54 %).

Table 4.2 ANOVA analysis for MRR

Symbol	EDM parameter	DOF	Sum of squares	Mean of squares	F ratio	P value
A	Current	2	1395.79	697.894	289.58	0.003
B	Pulse on time	2	21.64	10.822	4.49	0.182
C	Pulse off time	2	7.76	3.879	1.61	0.383
Error		2	4.82	2.410		
Total		8	1430.01			

Fig 4.1 shows the Main effect plot for S/N ratio and Means of MRR. This graph indicates the value of S/N ratio for parameter at different levels. It can be observed from the Fig 5.1 (A) that with increase in current, the MRR value is also increases. It is because of increase in current, the input energy of the spark is also increased. So at the same time carriers (ions and electrons) accelerated towards their respective electrodes more effectively. While moving, they accumulate more energy and collide with the dielectric particle, produce high energy ions and electrons causes increase the energy of plasma channel [11]. So this causes more discharge per unit time between the tool and work piece. Faster sparking causes more erosion of the material, hence MRR increases. In this work the Discharge current is the key factor for increasing the MRR from the Inconel 718 alloy. So from the graph current is the most significant factor among the others.

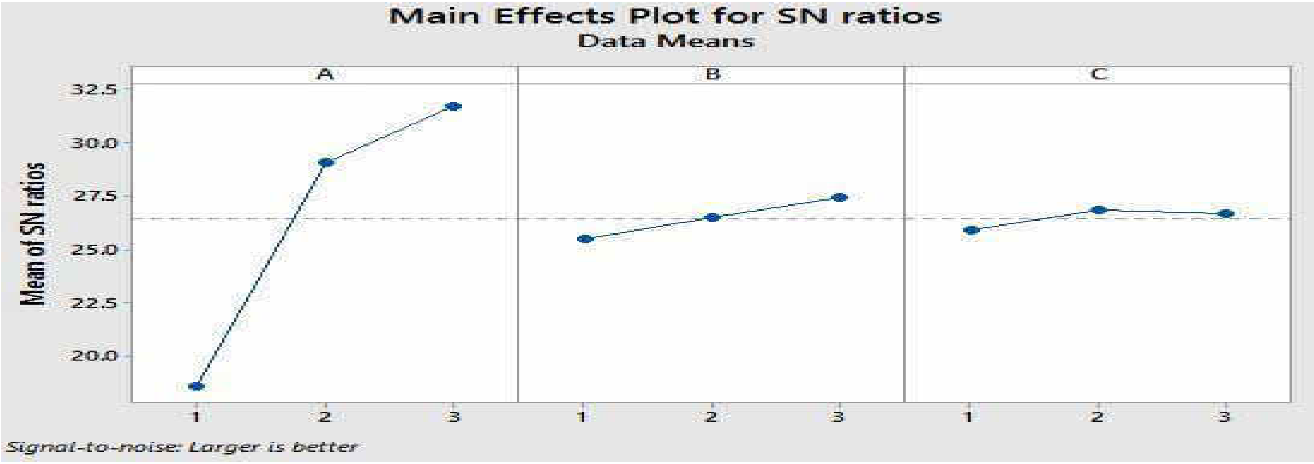

Figure 4.1 Main Effects plot for S/N ratio of MRR

Here Fig 4.1 shows the A3B3C2 parameter i.e. current at 16 A, pulse on time at 80 µs and Pulse off time at 35 µs respectively gives the optimal parameter condition for higher MRR. By using regression analysis an empirical model is developed to predict the MRR.

4.2 Tool wear rate

Table 4.1 shows the results for TWR and its corresponding S/N ratio value based on the experiments perform on the basis of Experimental layout L_9 (3^4). Table 4.3 shows the ANOVA results for TWR. From the ANOVA analysis we can conclude that current is the most significant factor for TWR rate with higher F ratio value and contribution (82.87 %) compare to other parameter Pulse on time (14.83 %) and Pulse off time (2.30 %).

Table 4.3 ANOVA analysis for TWR

Symbol	EDM parameter	DOF	Sum of squares	Mean of squares	F ratio	P value
A	Current	2	26.9235	13.4618	25.21	0.038
B	Pulse on time	2	4.8135	2.4067	4.51	0.182
C	Pulse off time	2	0.7439	0.3719	0.70	0.589
Error		2	1.0678	0.5339		
Total		8	33.5487			

Fig 4.2 (A) that with increase in current, the TWR value is also increases. It is because of increase in current, the input energy of the spark is also increased. The higher discharge current leads to high input energy causes more material remove from work material and tool electrode, hence TWR is also increase. Here current is the most significant parameter with higher contribution for TWR.Fig 4.2 (B) show the effect of pulse on time on the TWR. Here the tool wear rate increases with increase in Pulse on time. This is because of the pulse on time controls the duration of time to supply current per cycle. Increase in pulse on time causes duration for supply discharge current per cycle also increases. So higher material remove from the tool surface causes increase in TWR. Pulse on time is the second significant factor which effect the TWR Fig 4.2 (C) we can observe that initially the tool wear rate is increasing with increases in pulse off time and further increase in pulse off time tool wear rate decreases. During pulse off time no current is supplied so no material is removed from the tool surface. This result shows that the pulse off time is less significant and lowest contribution for TWR.

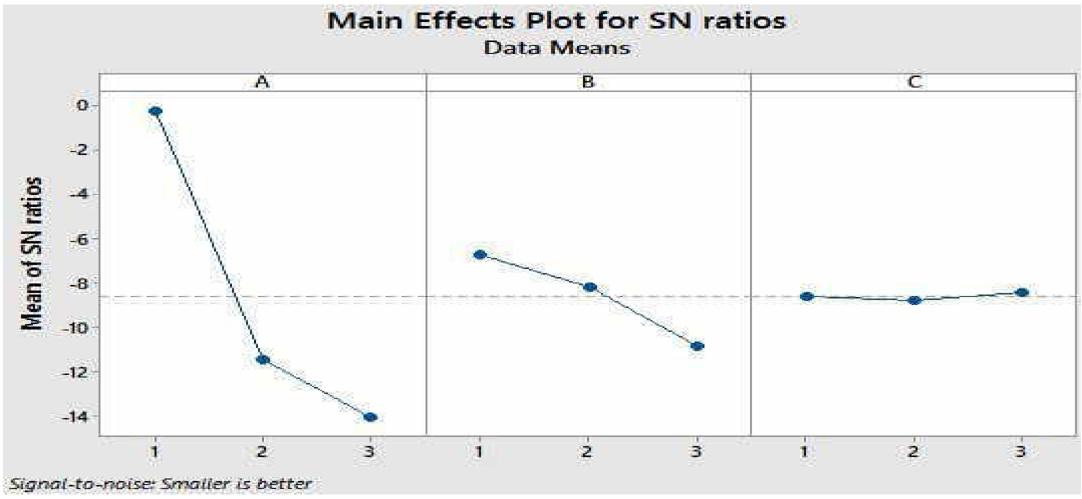

Figure 4.2 Main Effects plot for S/N ratio and Means of TWR

Here from Fig 5.1.2 we conclude that the A1B1C3 parameter i.e. current at 8 A, pulse on time at 60 µs and Pulse off time at 46 µs respectively gives the optimal parameter condition for lower TWR. By using regression analysis an empirical model is developed to predict the TWR.

4.3 Surface roughness

Table 5.1 shows the results for SR and its corresponding S/N ratio value based on the experiments perform on the basis of Experimental layout L_9 (3^4). Table 5.4 shows the ANOVA results for SR. From the ANOVA analysis we can conclude that pulse on time is the most significant factor for SR with higher F ratio value and contribution (62.56 %) compare to other parameter Current (35.34 %) and Pulse off time (2.09 %).

Table 4 .4 ANOVA analysis for SR

Symbol	EDM parameter	DOF	Sum of squares	Mean of squares	F ratio	P value
A	Current	2	1.50009	0.75004	14.71	0.064
B	Pulse on time	2	2.65496	1.32748	26.04	0.037
C	Pulse off time	2	0.08882	0.04441	0.87	0.534
Error		2	0.10196	0.05098		
Total		8	4.34582			

Fig 4.3 (A) shows that, increase in current, the SR value is also increases. It is because of increase in current, the input energy of the spark is also increased. The higher discharge current leads to high input energy causes intensity of spark is increase, so the crater produce on the machine surface is deeper and wider causes more surface roughness, Here current is the second significant parameter with contribution of 35.34 % for SR.

Fig 4.3 (B) show the effect of pulse on time on the SR. Here the surface roughness increases with increase in Pulse on time. Increase in pulse on time causes duration for supply discharge current per cycle also increases, so more material is melted away from the work piece material and broader and deeper crater produce causes rough surface. Pulse on time is the most significant factor with higher percentage contribution (62.56 %) on the SR.

Fig 4.3 (C) we can observe that initially the surface roughness is increasing with increases in pulse off time and further increase in pulse off time surface roughness decreases. During pulse off time no current is supplied so no material is removed from the material. This result shows that the pulse off time is less significant and lowest contribution (2.09 %) for SR.

Here from Fig 4.3 we conclude that the A1B1C1 parameter i.e. current at 8 A, pulse on time at 60 µs and Pulse off time at 23 µs respectively gives the optimal parameter condition for lower SR. By using regression analysis an empirical model is developed to predict the SR.

4.4 Effect of Graphite powder on MRR:

From the Fig 4.4 it is observed that MRR increases with increase in graphite powder concentration. At 13 g/l found the maximum MRR, while further increase in powder concentration MRR decreases. When graphite powder suspended into the dielectric fluid material removal rate increases, it may be due to increasing the conductivity of the dielectric fluid and reduces the dielectric strength causes increase in machining gap. As a result of this the plasma channel gets modified within the machining zone and discharge energy is maintained consistent. Because of this consistency produce deeper and wider crater causes maximum erosion of the work material [11]. The molten metal produce after the erosion easily get vaporize and debris particle between gap easily removed from the machining gap.

After 13 g/l powder concentration, the MRR reduces; it may be due to the higher density of powder particle between the machining gap causes a short circuit and instability of machining process. Higher concentration of powder causes increase density of powder particle between gap and uneven spark are occurred makes machining process unstable. This uneven spark and unstable machining causes increase in machining time.

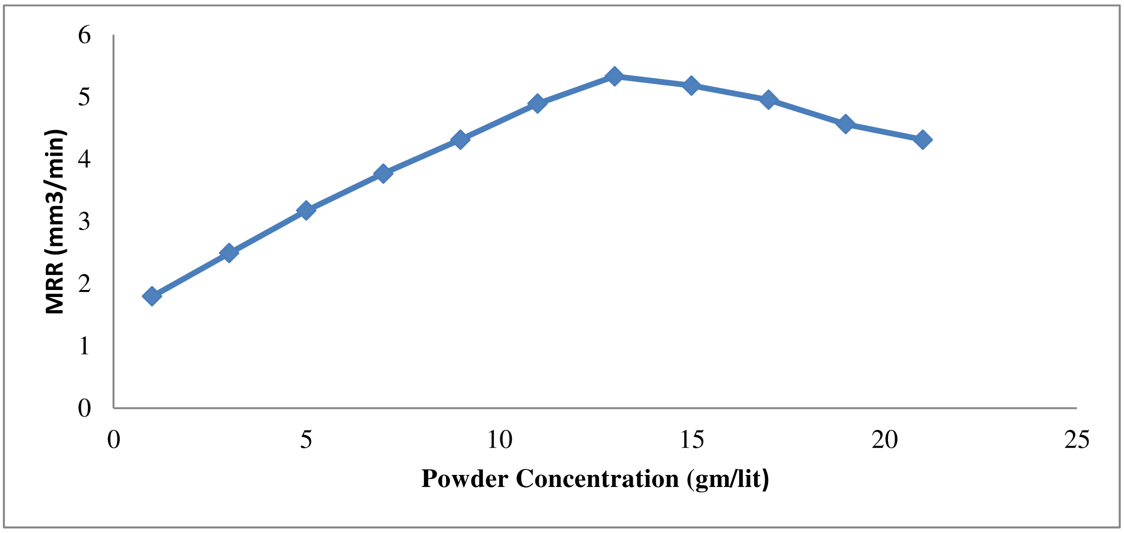

Figure 4.4 Graph for MRR vs Powder concentration

4.5 Effect of Graphite powder on TWR:

The effect of Gr powder concentration on the tool wear rate is shown in Fig 5.5. The TWR is increases with increase in powder concentration then further decrease with increase in powder concentration. Minimum TWR is obtained at 1 g/l.

It is due to the increase in thermal and electrical property of dielectric fluid, generation of mechanical polishing and removal of the carbon particle from the tool face. The electrical conductivity and sparking frequency increases with effectively removed the debris particle away from the machining gap. Increase in thermal conductivity causes effective discharge under the sparking area. Thus the electrode surface exposed to more amount of heat and the carbon particle are deposited on the too face are removed due to mechanical polishing between tool and work piece [24]. The higher concentration causes instability of the machining process and uneven spark causes decrees in TWR.

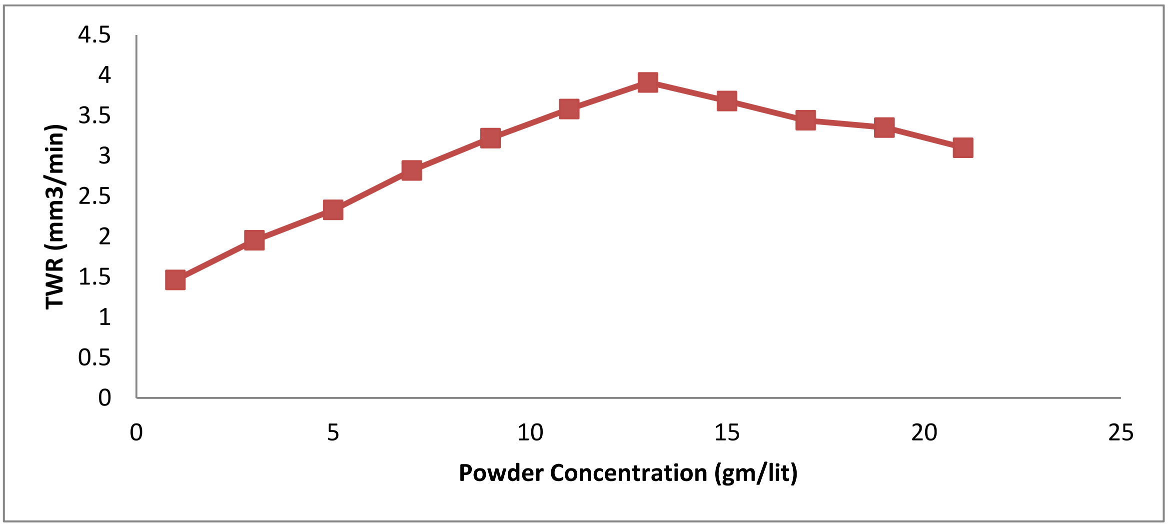

Figure 4.5 Graph for TWR vs Powder concentration

4.7 Results for optimization of process parameter by using RSM:

The 30 experiments were conducted and values of MRR, TWR and SR along with design matrix were tabulated in Table 5.5. For analysis the data, the checking of goodness of fit of the model is very much required. The model adequacy checking includes test for significance of the regression model and mathematical model, test for significance on model coefficients and test for lack of fit. For this purpose, analysis of variance (ANOVA) is performed.

4.8 Experimental Results for RSM:

Table 4.5 Results and observation table for MRR, TWR and SR

Exp. No.	Current (A)	Pulse on time (µs)	Pulse off time (µs)	Powder Concentration (g/l)	MRR (mm^3/min)	TWR (mm^3/min)	Surface Roughness (µm)
1	8	60	34.5	8	13.670	1.820	5.310
2	12	40	34.5	8	29.450	3.085	6.360
3	16	60	34.5	8	43.390	7.124	6.200
4	12	60	23.0	8	32.765	3.544	5.770
5	12	60	34.5	4	31.640	3.165	8.590
6	12	60	46.0	8	35.283	3.610	6.110
7	12	60	34.5	8	34.390	3.110	7.760
8	12	80	34.5	8	37.500	4.520	5.859
9	12	60	34.5	12	37.460	3.610	6.180
10	12	60	34.5	8	36.590	2.890	6.190
11	12	60	34.5	8	36.123	2.985	7.592
12	12	60	34.5	8	34.880	2.870	6.470
13	16	40	46.0	12	37.400	6.628	5.230
14	16	80	23.0	12	45.790	7.216	5.814
15	8	40	46.0	4	10.244	1.780	6.540
16	8	40	23.0	12	12.975	1.687	6.730
17	8	80	46.0	12	16.220	1.820	5.310
18	8	80	23.0	4	11.802	1.890	6.360
19	16	80	46.0	4	45.460	6.892	6.200
20	16	40	23.0	4	38.150	5.812	5.770
21	16	80	46.0	12	48.168	7.519	8.590
22	8	40	46.0	12	13.215	1.347	6.110
23	8	80	23.0	12	14.145	1.685	7.760
24	16	40	46.0	4	38.652	5.904	5.859

25	16	80	23.0	4	41.405	6.586	6.180
26	16	40	23.0	12	39.590	6.370	6.190
27	8	40	23.0	4	8.242	1.750	7.592
28	8	80	46.0	4	12.308	1.932	6.470
29	12	60	34.5	8	34.123	2.544	5.231
30	12	60	34.5	8	33.938	2.776	5.814

4.9 Analysis of variance for MRR:

Table 4 .6 ANOVA analysis for MRR

Source	DOF	Sum of squares	Mean square	F-Ratio	P-Value
Model	16	4482	280.17	136.75	<0.0001
A	1	3906.81	3906.81	1906.95	<0.0001
B	1	111.9	111.9	54.62	<0.0001
C	1	8.12	8.12	3.96	0.068
D	1	40.68	40.68	19.86	0.001
A2	1	93.13	93.13	45.46	<0.0001
B2	1	3.14	3.14	1.53	0.238
C2	1	0.80	0.80	0.39	0.542
D2	1	0.00	0.00	0.00	0.968
A*B	1	18.56	18.56	9.06	0.010
A*C	1	0.00	0.00	0.00	0.989
A*D	1	2.79	2.79	1.36	0.264
B*C	1	4.47	4.47	2.18	0.163
B*D	1	1.86	1.86	0.91	0.358
C*D	1	1.30	1.30	0.63	0.440
Error	13	26.63	2.05		
Lack-of-fit	10	23.42	2.34	2.19	0.282
Pure error	3	3.21	1.07		
Total	29	4509.33			
Std. Dev.	R^2	Adj R^2	Pred. R^2		
1.43134	98.41	97.68	93.75		

From the ANOVA analysis it is recommended that the quadratic model for analysis of MRR is significant. The ANOVA analysis of the quadratic model for MRR is given in Table 5.6. The value of R^2 and adjusted R^2 is 98.41% and 97.68% respectively. This means that regression model provides an excellent explanation of the relationship between the process parameter and the response (MRR). The associated *p*-value for the model is lower than 0.05 (i.e. $\lambda = 0.05$, or 95% confidence) indicates that the model is considered to be statistically significant [7]. The remaining R^2 value of 1.59% of the total variations would be due to other parameters which are not included in the model. The adjusted R^2 was a corrected value for R^2 after the elimination of unnecessary model terms. The adjusted R^2 would be smaller than the R^2 if there any non-significant terms have been included in the model [25]. The lack of fit is not significant for this model as it is desired.

Parameters A (Current), B (Pulse on time), D (Powder concentration), second order term of parameter A (Current) and interaction effect of parameter A (Current) with B (Pulse on time) have significant effect on the MRR. Parameter is significant, which have higher F ratio value. The significant parameters in decreasing order are, A (Current), B (Pulse off time), and second order term of parameter A (Current), D (Powder concentration) and interaction effect of parameter A (Current) with B (Pulse on time). The result proves that the powder suspended into the dielectric fluid increases the MRR. The other model parameters are said to be not significant.

The response regression equation for MRR (In coded terms) is given below:

$MRR = -79.36 + 12.17A + 0.183B + 0.265C + 0.68D – 0.3786A^2 -0.00278B^2 -0.00426C^2 – 0.0023D^2 + 0.01346AB – 0.00011AC – 0.0261AD +0.00230BC + 0.00426BD – 0.00620CD$

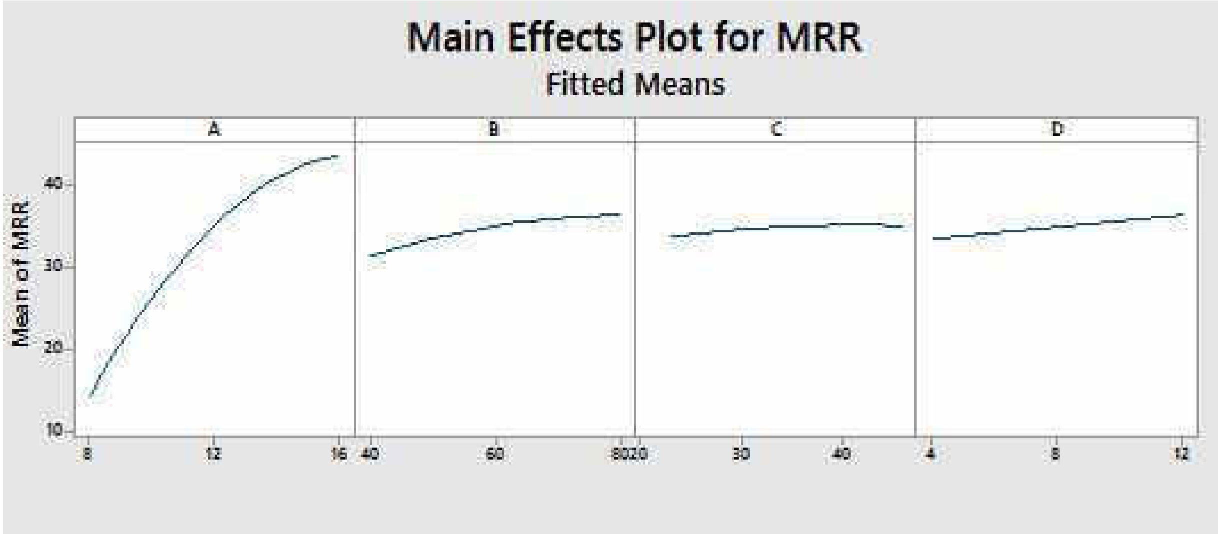

Figure 4.7 Main effect graph of individual parameter for MRR

Fig 4.7 shows that the effect of single parameter on the MRR for EDM of Inconel 718 alloy, when graphite powder are suspended into the dielectric fluid. Graphs show that the process parameters influence the material removal rate. From the ANOVA analysis suggested that the discharge current is the most significant parameter followed by pulse on time, powder concentration and pulse off- time.

From the Fig 4.7 shows that the MRR increases with increase in discharge current from 8A to 16A. Higher discharge current causes higher spark energy in the machining region which resulting in the higher melting temperature on the machine surface, higher evaporation and impulsive force resulting deeper and wider crater. Hence the MRR increased .

Fig 4.7 shows the graph of pulse on time and MRR. MRR increases with increase with pulse of time from 40µs to 80µs. The MRR is directly proportional to the amount of energy supplied during the pulse on time. When the pulse on time increases, amount of energy supplied is also increased and due to this temperature of the work surface increase, higher erosion causes higher MRR.

Fig 4.7 (c) shows that MRR is increase with increase in pulse off time from 25µs to 46µs. As the pulse off time increases the dielectric fluid gets sufficient time to flush out the debris particle between the gap and regain its dielectric strength, hence the MRR increases

From the Fig 4.7 (d) it is observed that MRR is increases with increasing the powder concentration from 4 g/l to 12 g/l. When graphite powder enters between the machining gap, the thermal mechanism is changed and Bridging effect between the gap causes dispersion of discharge energy into several number of increments and produce wider and deeper crater on the machining surface. It results MRR increased.

The interaction graph was formed based on the quadratic model to account the change of response surface. These interaction response surface graph value is secondary contribution to the model.

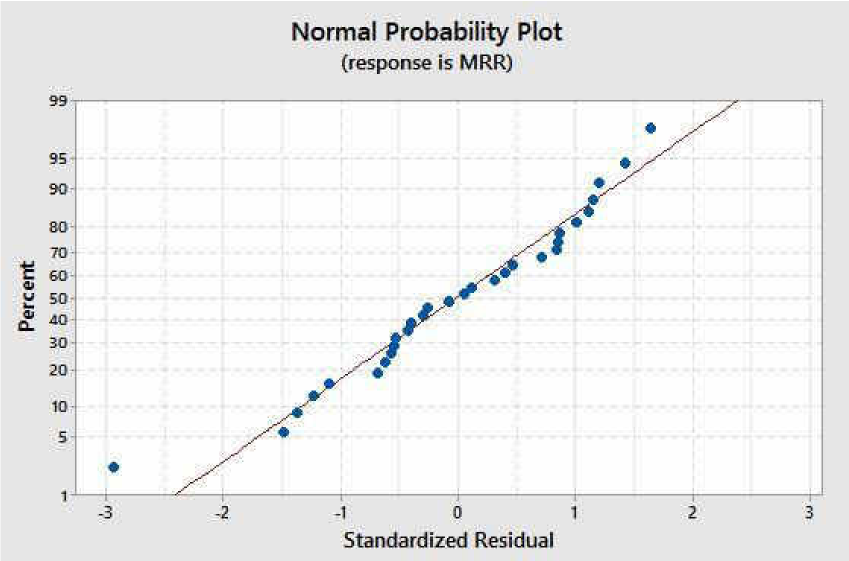

Figure 4.8 Normal probability plot residuals for MRR

Fig 4.8 displayed that the normal probability plot of the residuals for MRR. Notice that the residuals are falling on a straight line, which means that the errors are normally distributed.

4.10 Confirmation test

Table 4.9 indicated the results improvements in MRR and SR. For validation of the results a confirmatory experiments has to be performed. From the test it is found that the response function obtain through the experimental procedure are in closer with the predicted values. The results in the Table 4.9 shows the percentage errors are small. The error between experimental and predicted values of MRR, TWR and SR are 2.96%, 7.95%, 5.06%. All the confirmation test values are within the 95% of the predicted interval.

Table 4.9 Optimum condition and validation of results

Response parameter	Optimum condition	Predicted value	Experimental value	% of error
MRR (mm3/min)	I = 16A, T_{on} = 80 µs, T_{off} = 46µs, Gr con. = 12 g/l	47.55	48.96	2.96
TWR (mm3/min)	I = 8A, T_{on} = 40µs, T_{off} = 34.5µs, Gr con. = 4 g/l	1.76	1.62	7.95
SR (µs)	I = 8A, T_{on} = 40µs, T_{off} = 23µs, Gr con. = 12 g/l	6.12	6.43	5.06

5 Conclusion:

In the present study, the influence of process parameter and optimization of powder mixed electric discharge machining of Inconel 718 was studied by using Response surface methodology.

Based on the experimental results, the following conclusions are drawn:

- Taguchi method is applied to determine the optimal process parameters of EDM on Inconel 718 alloy. From the results, it was found that the process parameters contribution for MRR is discharge current (97.93%), pulse on time (3.66%) and pulse off time (0.54%), for TWR is discharge current (82.87%), pulse on time (14.83%) and pulse off time (2.30%) and for SR is discharge current (62.56%), pulse on time (35.34%) and pulse off time (2.09%).
- From the analysis it was found that the optimal levels of the process parameter for MRR is A3B3C2 (I = 16A, T_{on} = 80µs, T_{off} = 34.5µs), TWR is A1B1C3 (I = 8A, T_{on} = 40µs, T_{off} = 46µs) and SR is A1B1C1 (I = 8A, T_{on} = 40µs, T_{off} = 23µs).

- Process parameters I = 16A, T_{on} = 80µs and T_{off} = 34.5µs are used for determining effect of powder concentration into the dielectric fluid.
- Maximum MRR and Minimum SR were obtained at 13 g/l addition of graphite powder into the dielectric fluid. The working range of graphite powder mixed into the dielectric fluid is 4 g/l to 12 g/l.
- Response surface methodology was used to optimize the process parameter and developed mathematical model with graphite powder mixed EDM of Inconel 718 alloy
- Single objective optimization of process parameters using Response surface methodology for maximum MRR is (I = 16A, T_{on} = 80 µs, T_{off} = 46µs, powder con. = 12 g/l), minimum TWR (I = 8A, T_{on} = 40µs, T_{off} = 34.5µs, powder con. = 4 g/l) and minimum SR (I = 8A, T_{on} = 40µs, T_{off} = 23µs, powder con. = 12 g/l).
- Confirmation test shows that the error between experimental and predicted values of MRR, TWR and SR are 2.96%, 7.95%, 5.06%.

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