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Study on Effect of Powder Mixed dielectric in EDM of Inconel 718

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***Abstract*-** Electrical discharge machining (EDM) is one of the most extensively disseminated manufacturing technologies, in particular as regards the generation of precise and difficult geometrical shapes on hard metallic components. The objective of this paper is to Study on Effect of Powder Mixed dielectric in EDM of Inconel 718. The effect of various powder mixed in dielectric is studied input parameters like Duty cycles, current, pulse on time and powder media in that Silicon carbide, Aluminium oxide, Graphite powder used. Machining characteristics measured in terms of Material removal rate, tool wear rate. To obtain the optimal process parameter combination, optimization is carried out by the Signal-to-Noise (S/N) ratio analysis of Taguchi method using L18 Orthogonal Array. An analysis of variance (ANOVA) is used to present the influence of process parameters on material removal rate, tool wear rate. Results obtained by Taguchi method and by ANOVA method, are compared and found that they match closely with each other. As the MRR is depends mostly on current [4]. Current carrying capacity of any material depends on it electric conductivity. Here Graphite is having highest electric conductivity than Aluminium oxide and Silicon carbide and therefore MRR is higher in case of Graphite powder. As well as TWR is less.

***Index Terms*-** Electro Discharge Machining (EDM), PMEDM, Electrical conductive Powder, Duty cycle, POT,ANOVA, Taguchi Method, Signal-to-Noise ratio, Inconel 718, Orthogonal array, MRR, TWR.

I. Introduction

Electro discharge machining is a non-traditional concept of machining which has been widely used to produce dies and molds. It is also used for finishing parts for aerospace and automotive industry and surgical components. This technique has been developed in the late 1940s where the process is based on removing material from a part by means of a series of repeated electrical discharges between tool called the electrode and the work piece in the presence of a dielectric fluid. The electrode is moved toward the work piece until the gap is small enough so that the impressed voltage is great enough to ionize the dielectric. Short duration discharges are generated in a liquid dielectric gap, which separates tool and work piece. The material is removed with the erosive effect of the electrical discharges from tool and work piece. EDM does not make direct contact between the electrode and the work piece where it can eliminate mechanical stresses chatter and vibration problems during machining. Materials of any hardness can be cut as long as the material can conduct electricity.

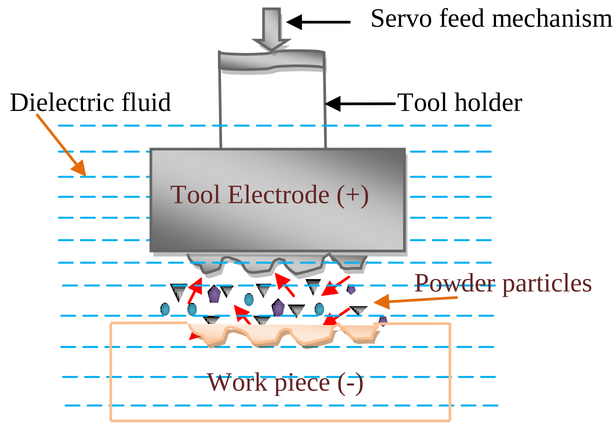

Fig. 1.1 The principle of Powder mixed EDM

When voltage is applied the powder particles become strengthened and act in a zigzag manner. These charged particles are accelerated due to the electric field and act as conductors encouraging breakdown in the gap. This rises the spark gap between tool and the work piece. Under the sparking area, these particles come adjacent to each other and arrange themselves in the form of chain like constructions. The interlocking between the powder particles arises in the direction of flow of current. The chain formation helps in linking the release gap between the electrodes. Since of bridging effect, the shielding strength of the dielectric fluid falls resulting in easy short circuit. This causes early blast in the gap and series discharge' starts under the electrode area. The quicker sparking within a discharge causes sooner erosion from the work piece surface and hence the material removal rate increases. The sparking is evenly spread between the powder particles, hence electric concentration of the spark drops. Due to constant scattering of sparking between the powder particles, narrow craters are formed on the work piece surface. This results in improvement in surface finish.

II. Literature Review

Kumar et al. [27] studied the effect of Graphite powder addition to check performance of machining it was found that addition of graphite powder enhances machining rate appreciably. Machining rate is improved by 26.85% with 12g/l of fine graphite powder at best parametric setting for machining of Inconel 718.

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Sharma et al. [2] made an attempt to study the effect of Al powder on the machining performance of conventional EDM with reverse polarity. They have found that with increase in the grain size of the Aluminium powder particles in the dielectric, the material removal rate increases continuously.

Ghewade et al. [28] studied The material removal rate (MRR) mainly affected by peak current (Ip) and gap voltage (Vg). The effect of pulse-on time (Ton) is less on MRR. Duty cycle (t) has least effect on it. The electrode wear rate (EWR) is mainly influenced by pulse-on time (Ton) and duty cycle (t). The effect of peak current (Ip) & gap voltage (Vg) is less on EWR and has least effect on it.

Kansal et al. [4] studied the effect of Silicon powder mixing into the dielectric fluid of EDM on machining characteristics of AISI D2 (a variant of high Carbon high Chrome) die steel. Peak current, concentration of the Silicon powder, pulse-on time, pulse-off time, and gain significantly affect the material removal in PMEDM. Peak current and concentration of Silicon powder are the most influential parameters for causing material removal. The suspension of Silicon powder into the dielectric fluid of EDM appreciably enhances material removal rate.

Kung et al. [11] studied the effect PMEDM on Cobalt-bonded tungsten carbide (WC-Co). They have showed that the MRR generally increases with an increase of aluminum powder concentration. This trend is valid up to a maximum value, after a certain limit, the increase of aluminum powder concentration leads to the decrease of MRR. MRR also increases with grain size and pulse on time.

Singh et al. [10] made an attempt to study the effect of Aluminium powder mixed in the dielectric fluid of electric discharge machining on the machining characteristics of Hastelloy. They have found that the addition of Aluminium powder in EDM oil results in appreciable reduction in TWR of Hastelloy when machined with Copper electrode.TWR of Copper electrode can be lowers down by reducing the size of suspended Aluminium powder particles in EDM oil.

Ojha et al. [18] studied on PMEDM of EN-8 steel. Response surface methodology (RSM) has been used to plan and analyze the experiments. They have found TWR increases with lower range of powder concentration shown in Figure 2.8 but then decreases. Increase in tool diameter results in decreasing tool wear.

III. EXPERIMENTAL SET UP

Powder_mixed Electric discharge machining has a various machining mechanism from the conventional EDM [3]. In this process, a suitable material in the powder form is mixed into the dielectric fluid either in the same tank or in a separate tank. For better circulation of the powder mixed dielectric, a stirring system is employed. For constant reuse of powder in the dielectric fluid, a modified circulation system (Fig. 3.2) is used.

Work piece material is Inconel 718. Inconel alloy 718 is a high-strength, corrosion-resistant nickel chromium material used at -423° to 1300°F.

Table 3.1 Physical Properties of Inconel 718

Density	8.2 g/cm³
Melting point	1260-1340 °C

Fig 3.1 Setup of Powder Mixed Electric Discharge Machining

Typical physical properties are shown in Table 1.1. The age-hardenable alloy can be readily fabricated, even into complex parts. Its welding characteristics, especially its resistance to post weld cracking, are outstanding. The ease and economy with which Inconel alloy 718 can be fabricated, combined with good tensile, fatigue, creep, and rupture strength, have resulted in its use in a wide range of applications. Examples of these are components for liquid fueled rockets, rings, casings and various formed sheet metal parts for aircraft and land-based gas turbine engines, and cryogenic tank. It is also used for fasteners and instrumentation parts.

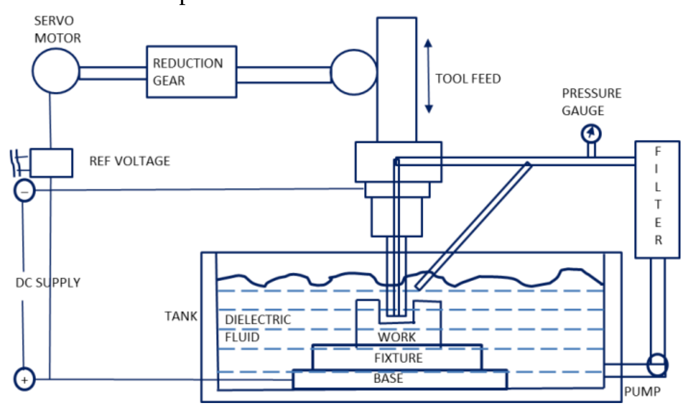

Fig 3.2 Setup of Electric Discharge Machining

Inconel 718 alloy is Austenitic structure, precipitation hardening generate "γ" made it excellent mechanical performance. Grain boundary generate "δ" made it the best plasticity in the heat treatment.

Table 3.2 Inconel 718 Alloy Minimum Mechanical Properties at the Room Temperature

Alloy	Tensile strength N/mm²	Yield Strength N/mm²	Elongation 5%	Brinell Hardness HB
Solution treatment	965	550	30	≤ 363

Copper is used as a tool electrode and dielectric fluid used is power mixed (Graphite, Al2O3 and SiC) Kerosene. Properties of abrasive which are used as dielectric medium are as shown in Table 3.5.

Table 3.3 Properties of Abrasive

Powder	Density (gm/cm^3)	Thermal conductivity (w/cm-k)	Electrical resistivity (Ohm-cm)	Melting point (k)	Sp. Heat (J/gm-k)
Graphite	2.15	119-165	1.350	3800	1.190
Silicon Carbide	3.21	120	$1*10^6$	3170	0.790
Aluminium Oxide	3.95	31-40	$1*10^{11}$	2350	0.77

Following input parameters are taken into consideration:

i. Powder media (Graphite, Al2O3 ,SiC)
ii. Current (A)
iii. Pulse on time(μsec)
iv. Duty cycle (%).

Current: Current is measured in Amp, which is allowed to flow per cycle. Discharge current is directly proportional to the Material removal rate.

Spark On-time (pulse time or Ton): The duration of time (μs) the current is allowed to flow per cycle. Material removal is directly proportional to the amount of energy applied during this on-time. This energy is really controlled by the peak current and the length of the on-time.

Duty cycle (τ): It is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time (on-time pulse off time) as shown by Equation 3.1.

$$\text{Duty cycle } (\tau): \frac{Ton}{Ton+Toff} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.1$$

Straight polarity (electrode negative) is used because it is desirable setting for material transfer to occur and also has better surface finish [6].

Response Variable :

There are many response variables such as MRR, TWR, and hardness of machined surface, surface roughness, dimensional accuracy and surface integrity

Following parameters are selected:

i. MRR (Material removal rate)
ii. TWR (tool wear rate)

MRR: MRR generally increases with an increase of powder concentration. This trend is valid up to a maximum value, after a certain limit, the increase of powder concentration leads to the decrease of MRR. MRR also increases with grain size and pulse on time [2, 4].

TWR: The TWR value tends to decrease with the powder concentration down to a minimum value after which it tends to increase.TWR also increases with grain size, with the increase of the discharge current and pulse on time [10, 18].

Table 3.4 Response Variables used

Response variable	Response type	Unit
Material Removal Rate	Higher the Better	gm/min
Tool wear Rate	Lower the Better	gm/min

IV. RESULTS AND DISCUSSION

The experiments are performed according to design of experiments (DoE). Among the available methods, Taguchi method is one of the most powerful DoE methods for design of experiment. It is widely recognized in many fields particularly in development of new products and processes in quality control. Here material removal rate, tool wear rate values are response variables. They are analyzed using Minitab software. Initially some trials are taken so we have some direction to experiments.

MRR (eq. 1) and TWR (eq. 2) are calculated by the following formula:

$$MRR = \frac{\text{Wt. of the WP before machining– Wt. of WP after M/cg}}{\text{Time}}$$

$$TWR = \frac{\text{Wt. of the WP before machining– Wt. of WP after M/cg}}{\text{Time}}$$

Copper electrode with a diameter of 6 mm is used as tool electrode. The machining is performed in standard Kerosene. SiC, Graphite and Al2O3 powder is mixed in Kerosene as per the requirements of the experiments. The powder particle size of 15 microns and powder concentration of 50gm/l is used. The parameters selected are peak current, pulse on time, duty cycle and different dielectric media. Material removal rate and tool wear rate are taken as the output parameter.

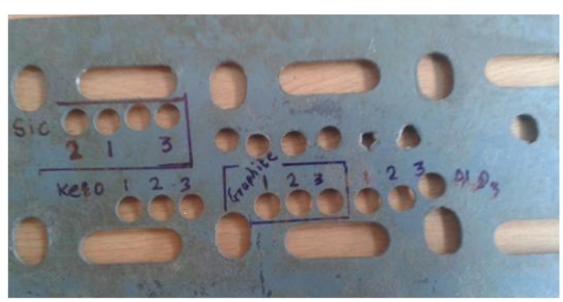

Fig 4.1 Workpiece after Machining on EDM

Orthogonal array which is used to perform final experiments and the results are as shown in Table 4.1.

Table 4.1 L18 Orthogonal Array used for Experiments with Results

Duty cycle	Powder media	Current	POT	MRR	TWR	S/N	S/N
90	Sic	12	5	0.07785	0.002193	-22.1748	53.1793
90	Sic	15	10	0.142	0.0037879	-16.9542	48.4321
90	Sic	18	20	0.1678	0.0045977	-15.5042	46.7492
90	Graphite	15	20	0.134	0.0037313	-17.4579	48.5627
90	Graphite	18	5	0.204	0.0057471	-13.8074	44.811
90	Graphite	12	10	0.0896	0.0023923	-20.9538	52.4235
90	Al2O3	12	20	0.07128	0.00292	-22.9406	50.6923
90	Al2O3	15	5	0.1236	0.0036101	-18.1596	48.8496
90	Al2O3	18	10	0.1818	0.004914	-14.8081	46.1713
85	Sic	18	5	0.2078	0.005618	-13.6471	45.0084
85	Sic	12	10	0.08799	0.0023781	-21.1113	52.4753
85	Sic	15	20	0.1132	0.0031898	-18.9231	49.9248
85	Graphite	18	10	0.2272	0.0060606	-12.8718	44.3497
85	Graphite	12	20	0.07547	0.0020964	-22.4445	53.5704
85	Graphite	15	5	0.1409	0.0039139	-17.0218	48.1478
85	Al2O3	15	10	0.1806	0.0049505	-14.8656	46.107
85	Al2O3	18	20	0.2115	0.0057971	-13.4938	44.7358
85	Al2O3	12	5	0.06882	0.00295	-23.2457	50.6036

4.1 Signal-to-noise ratio for Response Characteristics:

The parameters that influence the output can be categorized into two classes, namely controllable (or design) factors and uncontrollable (or noise) factors. Controllable factors are those factors whose values can be set and easily adjusted by the designer. Uncontrollable factors are the sources of variation often associated with operational environment. The best settings of control factors as they influence the output parameters are determined through experiments.
Depending upon the type of response, the following three types of S/N ratios are employed in practice:

Higher the Better:

(S/N) HB = -10 log (MSDHB)
Where

$$MSD_{HB} = \frac{1}{R}\sum_{i=1}^{R}\left(\frac{1}{Yi}\right)^2$$

MSDHB = Mean Square Deviation for higher-the-better response

Lower the Better:

$$(S/N)_{LB} = -10 \log (MSD_{LB})$$

Where

$$MSDLB = \frac{1}{R}\sum_{i=1}^{R}(Yi)^2$$

MSDHB =Mean Square Deviation for Lower-the-better response

Response Name : Material removal rate
Response type : Higher the better
Response Name : Tool wear rate
Response type : Lower-the-better

4.2 ANOVA (Analysis Of Variance):

In statistics, analysis of variance (ANOVA) is a collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components due to different explanatory variables. The initial techniques of the analysis of variance were developed by the statistician and geneticist R. A. Fisher in the 1920s and 1930s, and are sometimes known as Fisher's ANOVA or Fisher's analysis of variance, due to the use of Fisher's F-distribution as part of the test of statistical significance.

Analysis of MRR:

Analysis of variance (ANOVA) for material removal rate (gm/min) is given in Table 4.2. These values are obtained from Minitab 16 software. It shows that current and powder media are the significant parameters for material removal rate. The increase of peak current will increase the pulse discharge energy channel diameter and hence an increase in the crater diameter and depth which in turn can improve the metal removal rate. Similar trend is observed by S. Habib [24]. With the increase in pulse on-time the MRR decreased. This trend is exactly matching with the results of Kansal et al. [4]. This may be due to reason that with high pulse on time more material gets melted at the tool work piece interface, which require proper flushing time but as the value of pulse off time is too short, so there is not enough time for the flushing to clear the debris from the inter-electrode gap between the tool and work piece, so arcing take place which result in decreasing the MRR. As the MRR is depends mostly on current. Current carrying capacity of any material depends on it electric conductivity. Here Graphite is having highest electric conductivity than Al2O3 and SiC. Therefore MRR is higher in case of Graphite powder.

The value of F ratio is greater than 4 for current, hence this is significant. Remaining parameters are not significant. The relation between material removal rate and respective process parameters are shown in Figure 4.2. Here larger signal to noise ratio is considered as better one, hence values of plot at top positions indicate better results.

Table 4.2 ANOVA for Material Removal Rate (gm/min)

Source	DF	Seq SS	Adj MS	F	P
Powder Media	1	0.000821	0.000821	3.29	0.100
Current (A)	2	0.000464	0.000232	0.93	0.426
POT (µsec)	2	0.044298	0.022149	88.79	0.000
Duty Cycle (%)	2	0.001577	0.000788	3.16	0.086
Error	10	0.002494	0.000249		
Total	17	0.049655			
S = 0.01579		R-Sq = 95.0%	R-Sq(adj) = 91.5%		

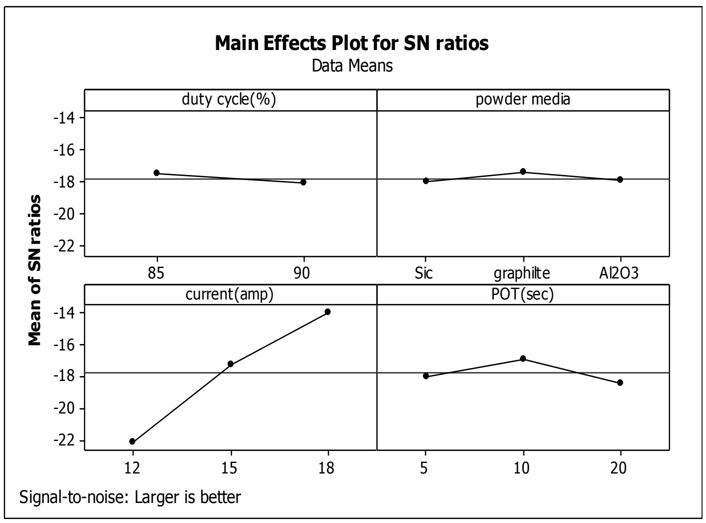

Fig 4.2: Main Effects Plot of SN Ratios for Material Removal Rate (gm/min)

The interaction between process parameters, i.e. the combined effect of parameters on response variables are shown in the Figure 4.3. Considering powder media and current, the lowest value for material removal rate is obtained at 12 A current and SiC as powder media while the highest value is obtained at 18 A current and Graphite.

Considering powder media and POT, the lowest value is obtained at 5 µsec POT and SiC as a powder media while highest value is obtained at 5 µsec POT and Graphite as powder m media.

Whereas for powder media and duty cycle, lower value is obtained at 90% duty cycle and SiC as powder media while highest value is obtained at 90% duty cycle and Graphite as powder media.

Now, considering current and POT, lower value of material removal rate is obtained at 12 A current and 20 µsec POT while

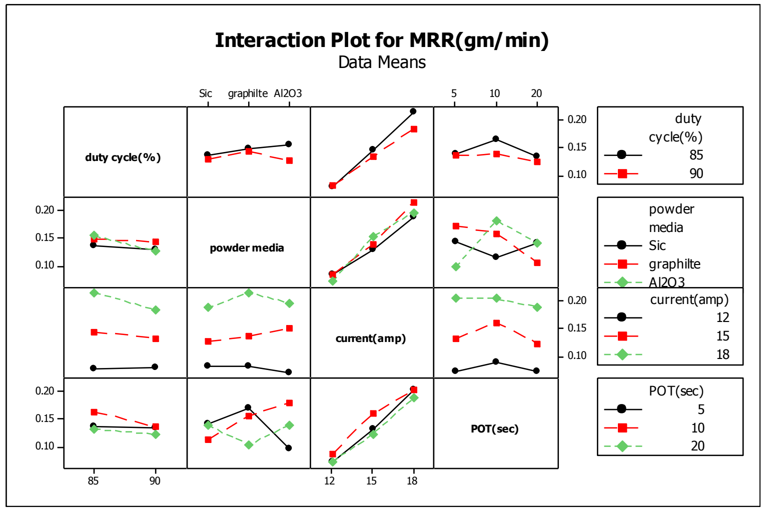

Fig 4.3 Interaction Plot for Material Removal Rate (gm/min)

higher value is obtained at 18 A current and 5 µsec POT. For current and duty cycle, lowest value of material removal rate is obtained at 12 A current and 90% duty cycle while highest value is at 18 A current and 85% duty cycle. Whereas for POT and duty cycle , lowest value is obtained at 20 µsec POT and 90% duty cycle while highest value is obtained at 10 µsec POT and 85% duty cycle.

Analysis of TWR :

Analysis of variance (ANOVA) for tool wear rate (gm/min) is given in Table 4.3. These values are obtained from Minitab 16 software. It shows that current and powder media are the significant parameters for Tool Wear rate. Increasing discharge current results in the melting and evaporation of a larger amount of material from the craters formed on both tool and work surfaces. As the TWR is depends mostly on current. Current carrying capacity of any material depends on it electric conductivity.

Table 4.3 ANOVA for Tool Wear Rate (gm/min)

Source	DF	Seq SS	Adj MS	F	P
Duty Cycle (%)	1	0.000001	0.000001	2.50	0.145
Powder Media	2	0.000001	0.000000	2.34	0.146
Current (A)	2	0.000026	0.000013	63.50	0.000
POT (µsec)	2	0.00000	0.000000	1.03	0.392
Error	10	0.000002	0.000000		
Total	17	0.000030			
S = 0.0004565		R-Sq = 93.2%	R-Sq(adj) = 88.4%		

Here Graphite is having highest electric conductivity than Al2O3 and Sic. Therefore TWR is higher in case of Graphite powder and lower in case of Al2O3 and SiC. Increasing discharge current results in the melting and evaporation of a larger amount of material from the craters formed on both tool and work surfaces thus TWR increase with current [20].

The value of F ratio is greater than 4 for current, hence this is significant. Remaining parameters are not significant. The relation between Tool wear rate and respective process parameters are shown in Figure 4.4. Here lower signal to noise ratio is considered as better one, hence values of plot at top positions indicate better results.

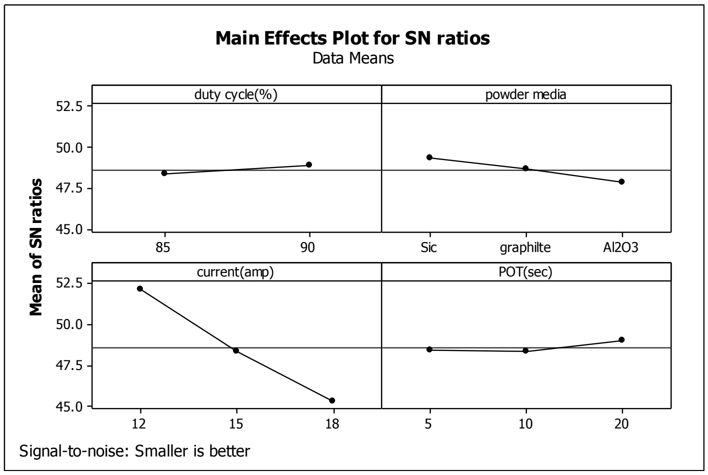

Fig 4.4: Main Effects Plot of SN Ratios for Tool Wear Rate (gm/min)

The interaction between process parameters, i.e. the combined effect of parameters on response variables are shown in the Figure 4.13.

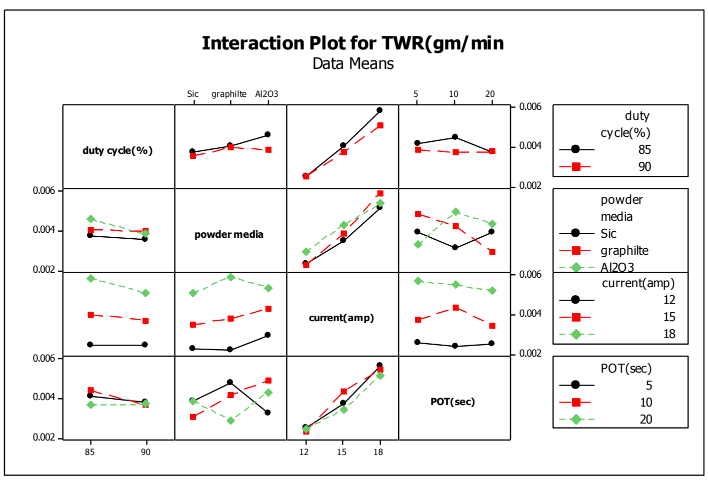

Fig 4.5 Interaction Plot for Tool Wear Rate (gm/min)

Considering powder media and current, the lowest value for tool wear rate is obtained at 12A current and SiC as powder media while the highest value is obtained at 18 A current and Graphite. Considering powder media and POT, the lowest value is obtained at 5 µsec POT and SiC as a powder media while highest value is obtained at 5 µsec POT and as powder media. Whereas for powder media and duty cycle, lower value is obtained at 90% duty cycle and SiC as powder media while highest value is obtained at 90% duty cycle and Graphite as powder media.
Now, considering current and POT, lower value of material removal rate is obtained at 12 A current and 30 µsec POT while higher value is obtained at 18 A current and 5 µsec POT. For current and duty cycle, lowest value of Tool wear rate is obtained at 12 A current and 90% duty cycle while highest value is at 18 A current and 85% duty cycle. Whereas for POT and duty cycle, lowest value is obtained at 30 µsec POT and 90% duty cycle while highest value is obtained at 10 µsec POT and 85% duty cycle.

V. Conclusion

Powder mixing into the dielectric fluid of EDM is one of the innovative developments that ensure better machining rates at desired surface quality and at reduced tool wear rate. The present work on addition of powder in Kerosene based on trial and main experiments resulted in high MRR and minimum TWR. The results are obtained from the present investigation for selecting the optimum machining conditions for Inconel-718 work material, which is extensively used in steam turbine, rocket engine, and exhaust system of formula one car. Within the range of parameters selected the following specific conclusions are drawn from the experimental results.

- Maximum MRR is obtained at a high peak current of 18 A, a moderate Ton of 5µs, duty cycle 85% and Graphite as powder media.
- Low TWR is achieved at a current of 12 A, a moderate Ton of 20 µs, duty cycle 90% and SiC as powder media.

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