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OPTIMIZATION OF HYBRID ELECTRIC DISCHARGE MACHINING PARAMETERS FOR INCONEL718 USING TAGUCHI METHOD

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***Abstract*— Due to wide range of applicability of hard and difficult-to-machine materials like super alloys (Ti-alloys, Inconel, hastalloy etc), advanced ceramics and composite materials, researchers are striving to conduct the various machining operation over it. Electrical discharge diamond drilling (hybrid process) process has been carried out on Inconel 718 using Taguchi L9 orthogonal array (OA). The effects of process parameters such as peak current (I), pulse-on time (Ton), pulse-off time (Toff) and drill speed (DS) on metal removal rate (MRR) and surface roughness have been studied to optimize and improve the process capabilities. In this study MINITAB 18 software was used to find the effects of each parameter on performance measures and to predict the setting of control parameters. Analysis of variance (ANOVA) has been performed to identify the process parameters which significantly affect the performance measures such as MRR and SR. The significant parameters have been identified critically and their effects on performance measures have been studied. Optimal parametric combinations were predicted for best result on MRR and ASR. The percentage variations between predicted and experimental values of metal removal rate and surface roughness during confirmation experiment have been found within 10%.**

***Index Terms*— Electric Discharge Diamond Drilling, MRR, ASR, ANOVA, OA, Inconel718.**

I. INTRODUCTION

Machining can be defined as the process of removing extra materials from raw materials in form of chips for getting desired shape of finished products. The material removal process should be in controlled to create a finished product. A finished product is a part withdrawn from the workpiece with specification as per required blueprints or engineering drawing. Machining can be done in any materials such as ceramics, composites, plastics, wood but generally, most often use for metal products. Generally, for higher volume, machining is much more expensive. The need for machining is arises for highly accurate dimension and good surface finish.

Basic classification of machining processes is as below:

I. Conventional machining process.
II. Non-conventional machining processes
III. Hybrid machining process.

This three-machining process are discussed in below section. There is three type of principal machining operation are turning, drilling and milling. Other than this machining operation are in miscellaneous categories such as planning, boring, shaping [1].

- Turning is machining operation in which stationary tool is used against the rotary workpiece for removing the materials.
- The drilling operation is a material removal process to form a hole in solid material by using a drill bit. This drill bit generally rotates during the machining operation.
- Milling is machining operation of feeding rotary cutter against the workpiece at certain direction into it to bring undesired materials out.
- Miscellaneous operation is not considered as machining process.
- They might be a non- cheap producing process but they are performed by typical machining tool.

Electric Discharge Machining (EDM)

The thermoelectric process is involved to develop unconventional techniques for removal of material from the workpiece. There is four basic component in EDM (1) Workpiece and tool electrode submerged into dielectric fluids (2) Dielectric supply system (3) Tool electrode feeding system (4) pulsed power system as shown in Figure 1.1. The power supply is utilized for producing pulse voltage of high frequency. The dielectric supply system is consists of reservoir, pump, filter and most important dielectric fluids. The electrode feeding system helps in maintaining predetermine gap between workpiece and tool through servo control mechanism system.

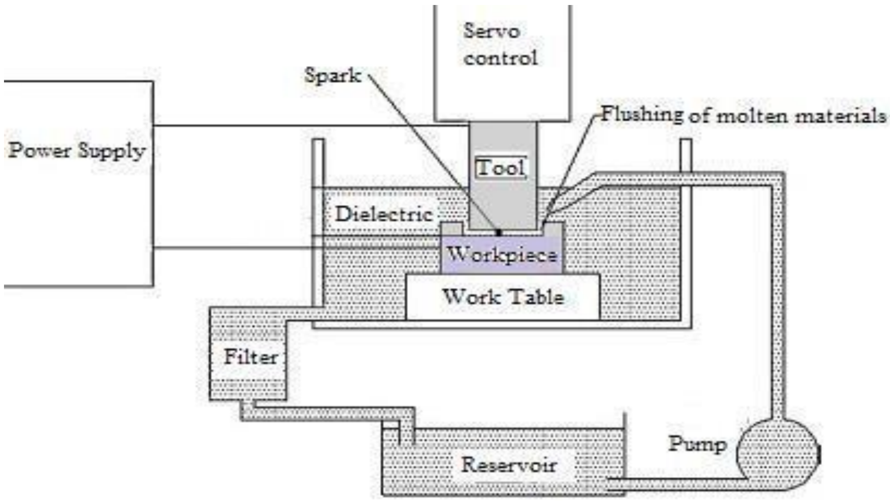

Figure1.1 Schematic Diagram of EDM

Mechanism of metal removal

During machining operation, the material removal follows the mechanism is in sequence

(1) Melting

(2) Vaporization

(3) Thermal spalling.

Especially for machining of materials having low thermal conductivity, high coefficient of thermal expansion and low ultimate strength [3]. The voltage applies between the tool electrode and the workpiece which cause the development of electrostatic force due to which electron from cathode surface accelerate toward the anode point which is at a minimum distance from the cathode. The accelerating electron will collide with molecules of dielectric fluids due to which ionization of dielectric fluids take place which results in the generation of positive ions and more electrons.

These positive ions and electron further increase more positive ions and electrons, due to the collision. As the concentration of positive ions and electron increase form a narrow column of ionized dielectric molecules known as plasma.

The accelerated electron with high kinetic energy will convert into heat energy after striking on the anode surface. The temperature will rise up to 80000C to 120000C. Similarly accelerating positive ions will strike on cathode surface and causes it’s melting and vaporization. This entire phenomenon will happen under narrow plasma zone whose pressure is so high that ejection of molten material cannot possible. As soon as pulse-off time starts the entire plasma get collapse after which molten materials flow is possible due to shock wave and flowing dielectrics. Mechanism of spark generation is shown in fig. 1.2.

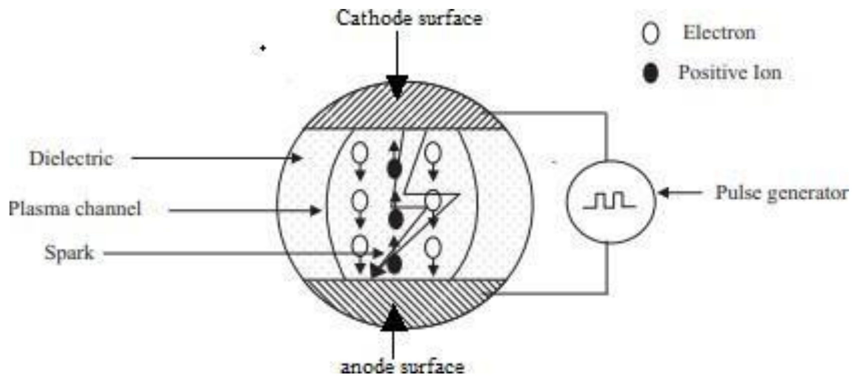

Figure 1.2: Mechanism of Spark Generation

II. LITERATURE REVIEW AND PROBLEM FORMULATION

A. Past Work

Hybrid electric-discharge machining is a combination of two or more processes involves for machining difficult-to-machine materials like composites, advanced ceramics, and super alloy in the effective way. The pure and assisted hybrid machining processes have been using in recently to fulfill the current demand. In pure hybrid machining maximum portion of material removal takes place from primary source but material removal is very low which can also be improved using assisted techniques. Machining of advanced and difficult-to-cut materials economically and more efficiently, hybrid machining process is one of the best alternative methods of machining. Advanced engineering materials are having improved chemical, thermal and mechanical properties such as heat resistance, tensile and compressive strength, wear resistance, and erosion resistance. Applications of these materials are in those areas where high specific characteristics are strictly desire. Hybrid machining techniques are being used for high precision machining of advanced engineering materials such as super alloys, cremates, carbide and metal matrix composites. Electro-discharge machining has been widely used for machining of such composites, but the major problem arising for Electro Discharge Machining (EDM) machining is recast layer or full surface micro-cracks appeared. With the implementation of new assisting techniques in EDM, recast layer, surface micro-cracks and cutting forces are further reduced. Electrical discharge diamond grinding (EDDG) process is a hybrid machining process which has been developed by combining metal bonded diamond grinding with EDM. In EDDG process, simple electrically conductive wheel commonly used in electrical discharge grinding is replaced by metal bonded diamond grit wheel. Sparking takes place between metal bonding and work piece as shown in Fig 2.1.

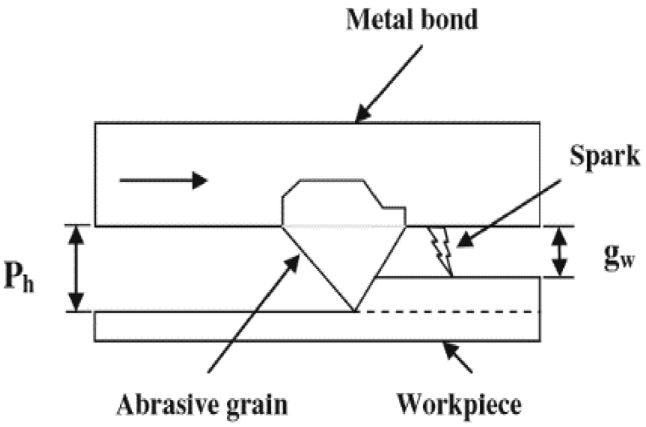

Figure 2.1: Representation of wheel-work interface in EDDG [30]

Heat is generated during sparking which softens the work material and hence diamond abrasive particles makes machining easier. Very high temperature around 8000℃ is created during sparking in EDDG process, results in continuous dressing of diamond grinding wheel and hence the wheel does not clog easily.

B. Objectives

Following objectives have been proposed to determine the effect of process parameters like current (I), drill speed(DS), pulse-on-time (Ton) and pulse-off-time (Toff) on response variables like metal removal rate (MRR) and average surface roughness (ASR) in electric discharge diamond drilling (EDDD).

1. To optimize the process parameters using Taguchi method.
2. Prediction of the optimal value of each response characteristics corresponding to their optimal parameter setting using statistical software.
3. Validation of results by conducting confirmation experiments.

III. EXPERIMENTAL METHODOLOGY

A. An introduction of Taguchi Method

A Japanese scientist Dr. Generic Taguchi having great contribution toward the field of quality engineering developed the Taguchi method. As per him rather than inspecting the product it will be better to improve the quality of product means quality not be getting through analyzing the scrutiny which is postmortem but to rectify the scrutiny before. He was in the favor of maximizing the quality by minimizing the deviation from the target value. He proposed that work of quality should be determined through the function of deviation from the standard [33].

- Taguchi Method/ Techniques are
- Off-line Quality Assurance techniques
- Ensures Quality of Design of Products and Processes
- Robust Design is the procedure used
- Makes use of Orthogonal Arrays for designing experiments

B. Experimental Design Strategy

Taguchi recommends several standards Orthogonal Array (OA). Thus there is need to be selected more suitable Orthogonal Array (OA) for the levels and factor be considered in experiments. Usually following are the fundamentals objectives to analyze the result from the Taguchi methods.

- To know the optimum or best condition for process our products.
- To know the contribution of each individual parameters or their interaction or both.
- To know the best response at optimum conditions.

Main effect plot of each parameter gives the optimum condition of response parameter for its own parameter. Influence of each parameter on the response parameter can be identified by the main effect plot. The Analysis Of Variance (ANOVA) will help to know the percentage contribution for each process parameter toward the response parameter.

Thus through ANOVA parameter need to control can be identified. As per Taguchi suggestion analysis for any experiment can be done in two way. The flow chart of experimentation is shown in fig. 3.1.

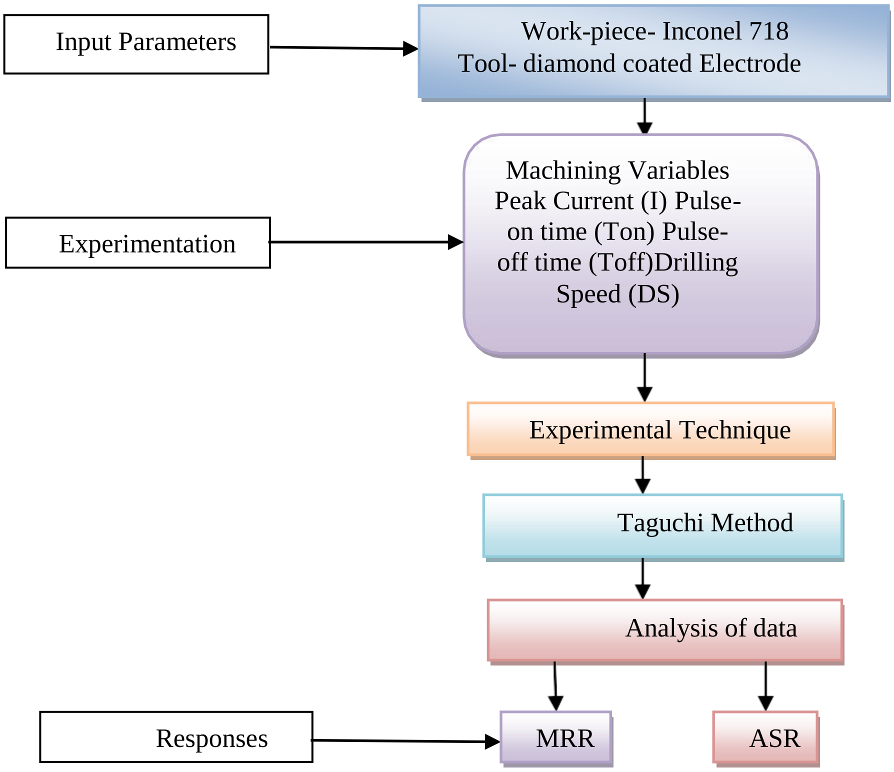

Figure 3.1 Flow Chart of Experimental work

According to Taguchi first approach, the analysis through main effects and ANOVA is done for every single run or for an average repetitive run. According to the second approach by Taguchi, there is need to measure S/N ratio for each experiment. The S/N ratio for each experiment is existing quality measurement related to losing function. As the S/N ratio maximizes the loss function will minimize. The S/N ratio provides a best operating condition for obtaining the best result. The S/N ratio can treat as response parameter. Taguchi recommends using an outer orthogonal array for forcefully introducing noise in experiments. Generally this process of subject to much noise factor which in combination influence. The outcome of each EDM process parameter on the selected response parameter been studied by main effect plot of raw data [33].

IV. EXPERIMENTAL WORK

A. Description of Experimental set-up

The experiments were conducted using EDM die-sinking machine of PRESSMACH (Model: G30) with self developed drilling set up installed at Workshop of IIMT College of Engineering, Greater Noida, UP, India, as shown in Fig. 4.1 and Fig. 4.2 respectively.

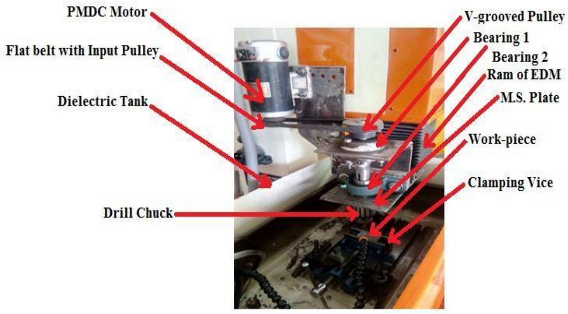

Figure 4.1: Die Sinking EDM of PRESSMACH (Model: G30) Figure 4.2: ExperimentalSetup

The specifications of the EDM die-sinking machine tool of PRESSMACH (Model: G30)used for conducting the experiments are enlisted below in Table 4.1.

Table 4.1: specification of die-sinking electric discharge machine (EDM) tool

Parameter	Unit	Specifications
Work Table Table Size(L*B) Table Travel Longitudinal (x-axis) Cross (y-axis)	 mm mm mm	 350*220 220 130
Work Piece Max. height Max. weight	 Mm Kg	 150 100

The tool was made up of electrolytic pure copper with a diameter of 0.8 mm and rectangular plates of dimension (54×24) mm2 with thickness 5 mm was used as work- piece materials. Commercial grade EDM oil (SEO25) was used during the process. The side flushing pressure of 0.3kgf/cm2 was used in this present research work.

During EDDD process, pulse-on time, current, pulse-off time and drill rotational speed were considered as input process parameters. Both diamond coated drill tool (Fig. 4.3) and work-piece were submerged in dielectric fluid. The variac was connected in-line with DC motor (0.25h.p, 1500 r.p.m) to control drill speed. Specimen was held in vice and levelled horizontal. After exhaustive trial experimentation, input process parameters range was determined. On the basis of pilot experiment, the acceptable ranges of process parameters were decided to perform final experimentation. The change in surface roughness (SR) and metal removal rate (MRR) were investigated by performing each experimental run by measuring “Ra” value using surface roughness tester and the loss in weight of machined work-piece in total time elapsed in machining was calculated to find out metal removal rate (MRR) for that experimental run.

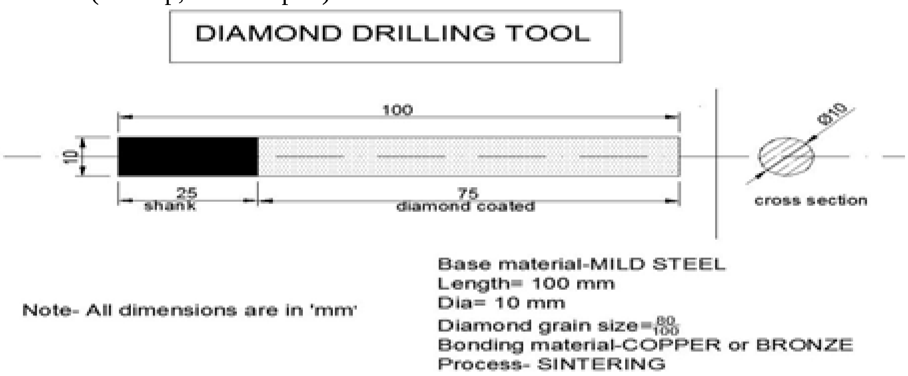

Figure 4.3: Geometry of diamond coated drilling tool

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B. Selection of Work-piece Material

The work piece material used for the work was Inconel 718.

- It is a high carbon alloy steel with high degree of hardness, and abrasion resistance.
- It is a nickel-based super alloy that is well suited for applications requiring high strength in temperature ranges from cryogenic up to 1400°F.
- It also exhibits excellent tensile and impact strength.
- Large cutting forces are required during machining which may result in tool factor and high cutting temperatures.

C. Preparation of Test Specimen

The sample of cuboidal shape has been cut for machining as per present experimentalwork. A close view of the preparation of test specimen being is shown in Figure 4.4.

Figure 4.4: Preparation of Test Specimen

D. Steps involved in conducting the experiment

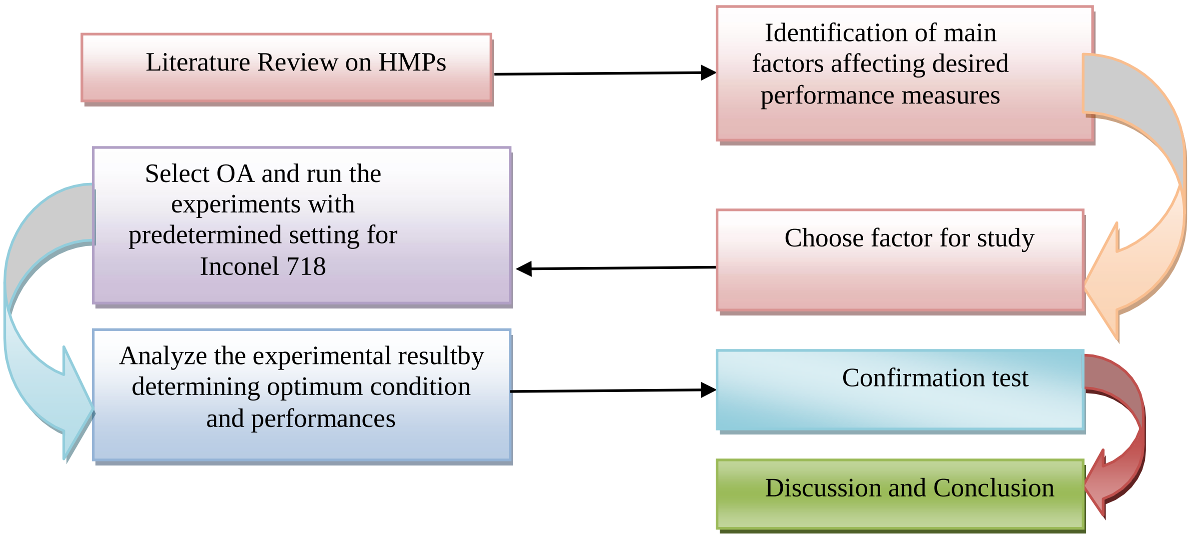

Figure 4.5: Flow chart for conducting experiment

The flow chart for conducting experiment in present work is shown in fig. 4.5. Theworkpiece after being cut is shown in the Fig.4.6.

Figure 4.6: Workpiece (Inconel 718) after being cut

The composition of material was tested on Scanning Electron Microscope (SEM). The chemical compositions and geometry of the sample used for flat work-piece materials used in present work are given in Table 4.2.

Table 4.2: Details of workpiece

Workpiece Material		Inconel 718	
Chemical Composition inPercentage by Weight		N	52.5
		C	19
		C	0.3
		M	3.05
		N	5.125
		C	0.08
		M	0.35
		P	0.015
		S	0.015
		Si	0.35
		Ti	0.9
		A	0.50
		C	1.00
		B	0.006
		F	16.809
Flat Workpiece		54 mm	
	Width	24 mm	
	Thickness	5 mm	

E. Trial Run of the Planned Experiments

The main reason for the trial run was to find a range of input parameter and each combination of factors are run on the machine for a short duration to ensure a successful run in the full fledge experiments.

F. Selection of factors and their levels for final run

The three level of each four control factor has taken into consideration. The control factor is peak current, pulse-on time, pulse-off time and drilling speed. Their level is shown in Table 4.3 with symbol used for each factor.

Table 4.3: EDDD process parameters and their values at different levels

Process Parameters ↓	Symbolused	→ Levels and Values ↓		
		1	**2**	**3**
Peak current	I_p (A)	3	5	7
Pulse on time	T_{on}(μs)	100	150	200
Pulse off time	T_{off}(μs)	50	75	100
Drill speed	DS (RPM)	725	825	925

Figure 4.7 have shown the specimen after drilled by diamond coated drill using electric discharge diamond drilling process.

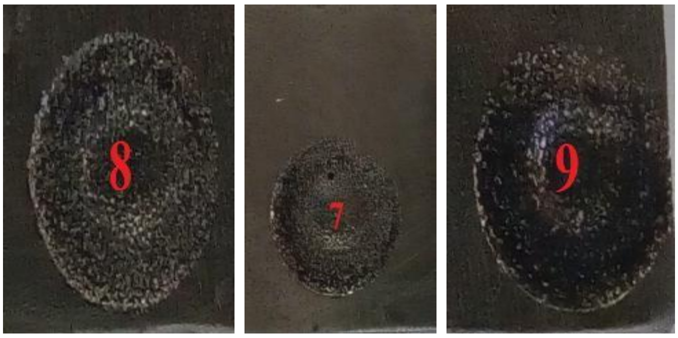

Figure 4.7: Work-pieces after Electric Discharge Diamond Drilling (EDDD)

G. Measurement of Response Variable

The description of the measurement of response variable has been brief in the following paragraph.

1) Measurement of metal removal rate (MRR)

For EDDD, metal removal rate (MRR) is a desirable characteristic and it should be as high as possible to give least machine cycle time leading to increased productivity. In the present study, an amount of metal removed after 15-minutes was calculated by weight difference of metal after and before the EDD machining by using precision electronic weight balance having 0.1 mg resolution. The metal removal rate is calculatedby using the empirical formula given in equation 7:

$$MRR(gm/min)=(W_i-W_f)/t_m \ldots\ldots\ldots\ldots(7)$$

Where,
W_f = the final weight of work material,
W_i = the initial weight,
t_m= machining time inminutes.

WT_f = the final weight of the tool (in gm.) after machining and
WT_i = the initial weight of the tool before machining

2) Measurement of average surface roughness (ASR)

Surface roughness is a component of surface texture of a surface. It is computed by the deviations in the direction of the normal of a real surface from its ideal form. If the deviation is large, the surface will be rough and vice versa. Roughness is typically considered to be the high-frequency, short-wavelength component of a measured surface. It is denoted by µm.

Figure 4.8: Surface roughness Tester (Mitutoyo SJ-301)

Surface roughness was measured by Mitutoyo SJ-301 as shown in Fig.4.8. It measures average roughness by comparing all the peaks and valleys to the mean line, and then averaging them all over the entire cut-off length. Stylus is dragged across the surface of the workpiece to give the average value of the peaks and valley on the surface. Hence, it provides surface roughness (Ra) of the worked surface.

V. RESULTS ANALYSIS AND DISCUSSION

This chapter presents experimental result analysis on electric discharge diamond drilling (EDDD) of Inconel 718, analysis and discussion were focused on metal removal rate (MRR) and average surface roughness (ASR). In the present work an optimization of process parameters of EDDD of Inconel718 using Taguchi method have been studied. The experimental studies were conducted by varying peak current, pulse-on time, pulse- off time and drill speed. The machining parameter settings were finalized using Taguchi method. The degree of importance of process parameters on MRR and ASR are determined by analysis of variance (ANOVA). The optimum process parameters corresponding to selected response variables were obtained using analysis of single-to-noise ratio. Confirmation run will be conducted to compare predicted and experimented results. The sequence of this chapter covered; Experimental results of EDDD of Inconel 718, data analysis using Taguchi method and Confirmation test.

A. Experimental results of EDDD of Inconel 718

Table 5.1 present the experimental result for EDDD of Inconel 718 in terms of MRR and ASR. For Each trial condition, two repetitions were run and the average data were calculated. In Table 5.1, the metal removal rate (MRR) for each test specimen was computed using equation 7. The average surface roughness was measured by using a surface roughness tester ((Mitutoyo SJ-301) shown in fig. 4.8.

Table 5.1: Experimental results of EDDD of Inconel 718 using L9 OA

Expt. Run	I	Ton	Toff	DS	MRR (gm/min.)	ASR (µm)
	(A)	(µs)	(µs)	(RPM)		
1	1	1	1	1	0.0076	3.89
2	1	2	2	2	0.0084	3.74
3	1	3	3	3	0.0044	3.72
4	2	1	2	3	0.0046	4.20
5	2	2	3	1	0.0040	4.97
6	2	3	1	2	0.0025	6.47
7	3	1	3	2	0.0106	3.20
8	3	2	1	3	0.0082	5.80
9	3	3	2	1	0.0077	6.30

B. Data analysis using Taguchi Method

The experimental data has been analyzed using Taguchi method where information such as main effects, percentage contribution of each factor (using ANOVA) and estimation of the optimum result can be produced. The data analysis was conducted separately for the two response variables-material removal rate (MRR) and surface roughness. In this present thesis work, the Taguchi method of analysis was conducted with the help of software (MINITAB16).

1) Data analysis for metal removal rate (MRR) and average surface roughness (ASR)

In this section, the effect of independent EDDD process parameters (peak current, pulse on time, pulse off time and drill speed) on the selected response characteristics (MRR and surface roughness) will be discussed. The average values of response characteristics and S/N ratio (dB) for each parameter at all levels are calculated from Table 5.3 and 5.4 and 5.5. Finding the optimum value of the cutting speed using MINITLAB 16, we get the response table for the mean of MRR and plotting the graph for which the S/N ratio larger is better.

a) Signal to noise (S/N) ratio for MRR

The data of MRR were transformed into S/N ratio using equation 1. Table 5.2 shows the S/N ratio for average response of MRR.

Table 5.2 Response Table for Signal to Noise Ratio for MRR (Larger is better)

Average Response Table (MRR) for SN Ratio				
Factors	I(A)	Ton(μs)	Toff (μs)	DS(RPM)
Level 1	-43.79	-42.99	-45.5	-44.32
Level2	-48.91	-43.73	-43.51	-44.35
Level 3	-41.16	-47.15	-44.86	-45.2
Difference	7.75	4.16	1.99	0.88
Rank	1	2	3	4

b) Main effects plots for MRR

Main effects for each factor have shown in Table 5.1. Since each process parameter has three levels, the average effects of each level is shown under the three rows marked Level1, Level2 and Level3 respectively.

The main effects are the difference between the average effect at level having maximum value and the level having the minimum value and which is finally shown in fourth row leveled 'Difference'. A minus sign indicates an increase in noise as the factor changes their levels whereas a positive value indicates a decrease in noise respectively for negative value. In order to understand in a better way, the data were plotted into graph asshown in fig. 5.1and fig. 5.2. In S/N ratio analysis, the greater value of S/N represents a more desirable condition.

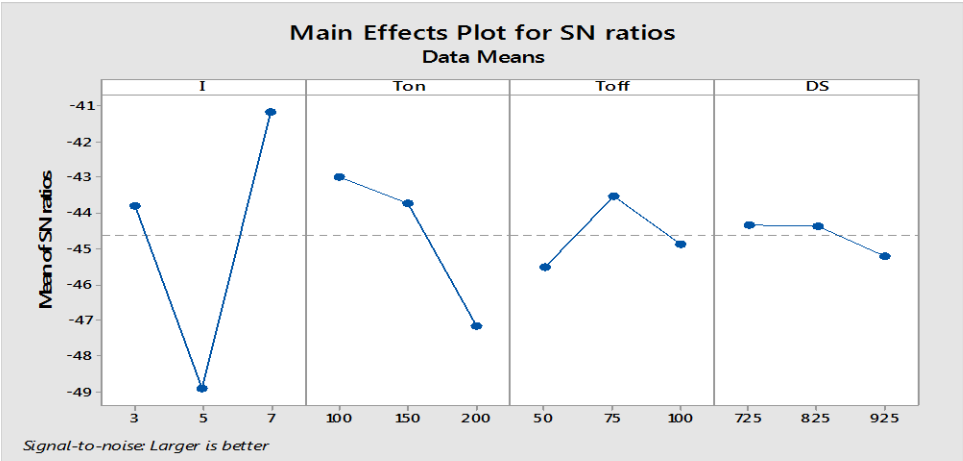

Figure 5.1: Main effects plot for S/N ratio for MRR

Table 5.3 Response Table for Means of MRR

Average Response Table (MRR) for Mean				
Factors	I(A)	Ton(µs)	Toff (µs)	DS(RPM)
Level 1	0.0067	0.00755	0.006	0.00633
Level2	0.0037	0.006867	0.0069	0.007167
Level 3	0.008833	0.004867	0.00633	0.005733
Difference	0.005133	0.002683	0.0009	0.001434
Rank	1	2	4	3

Average value of MRR, calculated from raw data is 0.0337 gm/min. It is clear from *S/N*plots the max. *S/N* ratio occurs correspond to **I3 Ton1 Toff2DS1**.

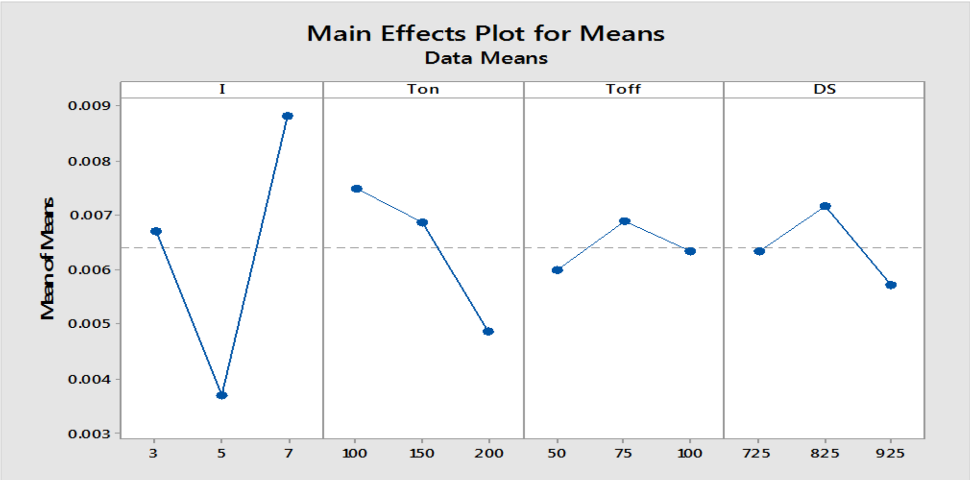

Fig. 5.2 Main effects plot of Mean for MRR

c) Analysis of Variance (ANOVA) for MRR

To determine the statistically significant process parameter, a powerful statistical technique called analysis of variance (ANOVA) was used. Predicted mean (optimum) Value will be corresponds to these factors but the only significant factors would be chosen. The significant factors for MRR are chosen from ANNOVA table shown in Table 5.4. For better understanding, the percentage contribution (%P) of each process parameter in affecting MRR has also been calculated and shown in Table 5.4 below.

Table 5.4 ANOVA Table for Mean Data of MRR

ANOVA Table (MRR) for Mean				
Sources	DOF	SS	MS	% P
I(A)	2	0.00004	0.00002	71.42857143
Ton(µs)	2	0.000011	0.0000055	19.64285714
Toff(µs)	2	0.000002	0.000001	3.571428571
DS(RPM)	2	0.000003	0.0000015	5.357142857
Error	0			
Total	8	0.000056		100

VI. CONCLUSIO AND FUTURE SCOPE

A. Conclusion

The experiments were performed for the drilling of Inconel 718 using rotary copper electrode with influence of dielectric used as spark erosion oil (SEO25). The input parameters were selected as discharge current, pulse ON time, pulse OFF time, and tool speed. These parameters were kept varying as L9 Taguchi approach in order to achieve optimum Material Removal Rate (MRR) and average surface roughness (ASR).
Following conclusions have been drawn after carefully studying the results:

1) The most important parameters affecting metal removal rate (MRR) are peak current (I), pulse-on time (T_{on}) and drill speed where as factors affecting average surface roughness (ASR) are pulse-on time (T_{on}), peak current (I) and pulse-off time (Toff) respectively.
2) The optimum level of input parameters obtained for MRR has been found as Peak current=7amp; Pulse on time-=100µs; Pulse-off time=75µs; Drilling speed=725 RPM.
3) The optimum level of input parameters obtained for MRR has been found as Peak current=3Amp; Pulse on time-=100µs; Pulse-off time=100µs; Drilling speed=825 RPM. 4.) The optimum value of MRR and ASR are 0.005318 gm/min and 1.88 µm.
4) The percentage contribution of most of the significant factor for MRR as per ANOVA table is peak current (I) with 71.428%, pulse-on time (T_{on}) with 19.643% and drill speed with 5.3571% respectively.

The percentage contribution of most of the significant factors for ASR as per ANOVA table is pulse-on time (T_{on}) with 38.223% , peak current (I) with 31.558% , and pulse-off time (T_{off}) with 25.379% respectively.
The percentage error between experimental and predicted values for MRR and ASR is 7.16% and 6.844% respectively.

B. Future Scope

1) The effect of other process parameters like duty factor, grain size of diamond coated drilling tool, flushing pressure of dielectric fluid on responses namely wear rate of tool, material removal rate, and surface roughness during machining can also be experimentally studied during EDDD.
2) The effect of process variables on cutting forces during drilling can be studied in case of EDDD of super alloys.
3) The effect of process variables on thickness of recast layer, heat affected zone (HAZ) and microstructure can be studied in case of EDDD of super alloys.

Other optimization techniques like fuzzy logic, artificial neural network (ANN), multi-optimization techniques can also be used to optimize the process variables in order to improve performance characteristics.

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