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Experimental investigation based on design of experiment during EDMprocess of Inconel material (X-750)

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***Abstract*—In the modern era of industrialization, high accuracy and precision are essential factors in different important and complex shapes of instruments and machinery. So unconventional machining processes like Electric Discharge Machining (EDM) are used for machining complex shapes and contours. The current work is based on Electric Discharge Machining (EDM), which is used to machine difficult-to-machine materials. The Inconel X-750 material has several applications used in various areas. For precise material, machining results are influenced by different input factors like the current, voltage, pulse on time, and duty cycle. These are controlled using Taguchi optimization techniques based on an experimental design approach. So, this work aims to obtain the optimum settings for Inconel X-750 using the Taguchi method of design. In this work, input current, input voltage, duty cycle, and pulse on time as the input factors. Material removal rate and surface roughness were selected as the response.**

***Index Terms*—EDM, Aluminium, Taguchi, MRR, Surface roughness.**

I. INTRODUCTION

In 1770 it was first discovered by Joseph Priestly and was developed commercially during the 1970s. Then wire EDM came into the picture and was used broadly, which helped develop the metal working industry. EDM is now very commonly employed in mold, die, and tool-making industries to machine heat-treated steel. After heat treatment, it isn't easy to machine the tool steel using conventional processes. In the EDM process, electricity generates an electrical spark, and material removal occurs due to heat produced from the spark. The thermal energy from the spark melts and vaporizes small particles from the material of the workpiece. Then these are flushed away from the gap by the continuous flow of the dielectric fluid. Materials that are machined by EDM process must be electrically conducting. Spark on-time (Ton): period for which the current is permitted to flow per cycle. MRR is directly proportional to the net energy applied during this time. This energy is influenced by the Ton & peak current. Spark off-time (T off): period (μ-s) between the sparks. It permits the molten material to solidify & to be washed out of the arc gap. This parameter also influences the cut speed & stability. Thus, there are chances of unstable arcs being produced for too short of time. Arc gap: The distance between the work piece & electrode during EDM machining. It can also be termed a spark gap. A Servo system is provided to maintain this gap.

II. LITURATURE REVIEW

Uhlmann et al. [1] studied the applications of tungsten carbide electrodes in EDM. SLM (selective laser machining) was used for complex electrode geometry. SLM is an alternative to conventional tool electrode manufacturing. Tungsten carbide is very important due to its machinability by SLM machinability in EDM. It can be concluded that applied voltage energy density affects cobalt content and the conductivity of SLM processed tool electrodes. Abdullah et al. [2] experimented on WEDM taking one-directional CFRP composite using brass coated with zinc of wire 25mm diameter. Using L_{18} Taguchi experimental design varying gap voltage (120 to 140), pulse on-time (0.8-1 μs), ignition current (3-5A) & pulse off-time (4-8μs) to find out MRR, kerf width top, and bottom & work piece edge damage. They conclude that process parameters and electrode material are suitable in

WEDM of unidirectional CFRP composite and found the highest MRR of 2.44mm^3/min achieved at 5A, on-time 1µs, off-time 4µs, and 120V gap voltage. Ebisu et al. [3] studied the effect of jet flushing on the accuracy of the corner shape in wire EDM through CFD analysis. They simulated the field flow and debris movement in the kerf of the machine during the cut at the corner shape in the first cut wire EDM. Also, by structural analysis or effects of loads on the wire, they find out deflection in the wire through CFD analysis of hydrodynamics force in stress distribution. The study concludes that when the cutting direction at the corner changes during corner shape machining, the flow & pressure field of the jet changes significantly around the wire. Just after the corner below the wire area, the disappearance of debris stagnation occurs & influence of hydrodynamic force and discharge explosive is large with flushing of jet on the deflection of wire. Gohil et al. [4] studied EDT, which is another only type of EDM on the alloy of TI-6Al-4V. The main aim of this experiment was to find out the importance of different machining parameters such as peak current and gap voltage spindle speed, T_{on}& flushing pressure accomplishment calculated at reverse polarity. Taguchi-GRA is used to optimize MRR & surface roughness at the same time. Through Grey analysis, optimum process parameters are- T_{on} (5µs), Voltage gap 40V, max current 5A, flushing pressure 0kg/cm^2 & spindle speed 40 RPM. It is found that voltage & FP influence MRR & surface roughness more. This experiment found that the Grey-Taguchi method is most convenient for optimizing EDM turning of alloy Ti-6Al-4V.

Dabade et al. [5] used Taguchi optimization in WEDM of Inconel 718 alloy design of experiment using Taguchi and ANOVA applied for MRR and SR values. The T_{on} is the most effective parameter in all performance measures such as surface roughness, MRR, Kerf width, and Dimensional divergence at 95% confidence level with 83.20 %, 57.9 %, 54.4% & 36.13 % . Increasing duration of pulse outcome of high energy discharge & discharge current increase outcome of increase of discharge energy which impinges SR by the increase in diameter & discharge crater depth. SR shows improvement in increasing gap voltage, T_{off} & wire tension. However, servo voltage and wire feed are least significant if kerf width is considered. The dimensional deviation is also affected due to an increase in peak current, wire feed, pulse off time, and gap voltage. An increase in wire tension &pulse off time improves dimensional deviation. Roy et al. [6] performed experiments to compare MRR of EN41 & EN19. I_d, T_{on}, T_{off}, and V_d were selected for process parameters, and MRR was selected for the output parameter. Taguchi was used for optimization to estimate the most suitable inputs for optimum output. It was evident from the experiment results that for EN19 & EN41 material, discharge current has a greater effect than other input parameters over MRR. Optimal values of inputs to get the best possible MRR for the EN19 were V_d 40 V, discharge current 24 A, T_{on} 400 µs, and T_{off} 2300 µs, while for EN19 material, these values were 40 V, 24 A, 400 µs & 2100 µs resp. Experimental data indicated that for both the materials, i.e., EN41 & EN19, values of MRR for any combination of parameters were greater for the EN41 than EN19, because carbon percentage decreases for EN19 to EN41, which helps in easy removal of material.

Kumar et al. [7] performed experiments to investigate the effects of various input parameters such as I_d, discharge voltage, T_{on}& T_{off} on the R_a of EN41. They took five different outputs related to surface roughness, i.e., R_a, R_q, R_{sk}, R_{ku}, &$R_{sm,}$ and optimized them. The experiments demonstrated that discharge current has more influence over the R_a of EN41. Other parameters have very less effect on the surface roughness of the material & hence are neglected. Balasubramanian et al. [8] took EN8 & D3 steel materials as work pieces and performed machining on these two materials. I_{peak}, I_{on}, the diameter of the tool &F_p were selected as input process parameters, and MRR, TWR & SR were considered output. Sintered powder metallurgy copper & cast copper were used as electrodes for machining. Response surface methodology was used to analyze the parameters. The results from the experiments demonstrated that the coefficient of the determinant (R^2) was more than 0.9 for both materials. For both the materials, i.e., EN8 and D3, the mean MRR was high, and TWR was low for the cast electrode compared to the sintered electrode. Das et al. [9] performed EDM on EN31 to obtain the best combination of input parameters for optimal MRR and R_a. ABC algorithm opted for optimization. T_{on},

T_{off}, voltage & I_d were selected as input parameters. The ABC algorithm optimal combination of input parameters was obtained, and corresponding to the input parameters, the value of maximum MRR and minimum Ra were found. It was seen that increasing pulse on time and current MRR and surface roughness increases. Sahu et al. [10] conducted experiments on EDM for the different combinations of input process parameters. I_d, T_{on}, τ F_p were considered for input process parameters, while MRR, TWR, Ra, and circularity (r_1/r_2) were considered as outputs. RSM was adopted to establish the contribution of different input process parameters to outputs. It was concluded based on the results that maximum productivity and quality were achieved at discharge current = 7 Amp, pulse on-time = 200 µs, duty factor = 90 %, & flushing pressure = 0.4 kg/cm^2. For these values of input parameters, the values the outputs from the experiments were obtained as material removal rate = 13.96 mm^3/min, tool wear rate = 0.0201 mm^3/min, surface roughness = 4.93 µm, and r_2/r_1 = 0.8401. Durairaj et al. [11] conducted experiments to optimize parameters in WEDM for the SS304 material. The objective of the experiments was to minimize Ra and kerf width. Stainless steel 304 was used for the work piece material & wire of brass of 0.25mm diameter was used as the tool material, and for dielectric fluid, distilled water was used. Input parameters were V_d, wire feed, $T_{on,}$ and T_{off}. Using grey relational theory for multi-objective optimization best combination was obtained for surface roughness and kerf width. It was concluded that pulse on time has a greater impact on surface roughness and kerf width in grey relational analysis and Taguchi optimization.

From state-of-the-art knowledge relevant to EDM machining on aluminum alloy Inconel X-750 materials have less effort. In this regard, the current study efforts on the Inconel X-750 in EDM process for the MRR, and Ra over the parametric constraints spark current (I), gap voltage (V), pulse on time (P), and % duty cycle (D). For conducting an experiment and optimization investigation, the Taguchi experiment is accomplished. Analysis of variance (ANOVA) has been used to develop a regression model to check the experimental feasibility. This concept might be beneficial for selecting process parameters during EDM machining to increase process productivity.The research gap finding in the machining of EDM the objective of the present work is the machining (EDM process) of Inconel X-750 to investigate on response MRR, and Ra over the parametric constraints spark current (I), gap voltage (V), pulse on time (P), and % duty cycle (D). Taguchi-based optimization in EDM of Inconel-X750 is proposed.

III. EXPERIMENTATION

After going to the extensive research papers, we found that different researchers got different results while machining different work materials. That result gave an insight that there are still some materials of recent alloys of nickel that have not been machined to a great extent. There is still a hope that there exist some tool materials like copper mixed tellurium that can finish the surface better than the other materials, and the same is being investigated to work. So, we have selected Inconel X-750 as our work material (as displayed in Fig. 1). Similarly, copper has been selected for tool material due to their excellent conductivity and better machining capability. It is nickel-chromium precipitated harden the alloy. It has high tensile & creep-rupture properties. The addition of aluminum & titanium is done to increase mechanical properties at high temperatures up to 704 ºC. Electrical discharge machining can shape very hard materials & deep holes in electrically conducting materials irrespective of shape, hardness & toughness, so EDM can machine Inconel X750 which is very difficult to machine by traditional machining. It has high-temperature applications in rocket engines, gas turbines, rocket engines (thrust chambers), aircraft applications, nuclear reactors, and pressure vessels. It also has good formability & excellent high-temperature resistance. Due to good corrosion, and temperature resistance, it offers a highly stressed environment & used in gas turbines & aircraft. The materials Density: 8.276 g/cm³, Melting range: 1393-1427°C, Poisson's ratio: 0.3, Electrical resistivity: 1.22 x 10-6 Ω-m, Chemical analysis, Ni-70%, Cr-14-17%, and Fe-5-9%. The L_9 orthogonal array was chosen for the experimentation based on these inputs. Each row of the OA indicates a collection of input process parameter values used in a certain experiment. Thus, nine experiments were required for one phase of the study. Also, Taguchi strongly recommends that rows are selected randomly, and each run be repeated three times. The output response measurement of MRR and surface roughness. The machining setup is displayed in Fig. 1.

Fig. 1. ZNC EDM Machine (105/06-07)

IV. METHODOLOGY

Taguchi is an optimization technique that enhances the quality of processes & products and lowers their costs with minimum work & resources. Taguchi achieves such high quality by making the performance of processes & products immune to changes in factors like materials, machinery, labor &conditions. Taguchi’s theory is based on the following three concepts. Quality must be designed in the product & it should not be inspected into it. Minimum deviations achieve quality from the target. The process design should be so that it is unaffected by uncontrollable environment variables. Losses and deviations from standards should be considered when calculating quality costs. Taguchi found that quality improvement is not achievable through inspection, salvaging & screening. Taguchi proposes 3 stage process system, parameter & tolerance design. Taguchi is a controlled mechanism for evaluation & implementation of enhancement in processes or products. These improvements are based on improvising the required characteristics by studying the key variables desirable for the process and optimizing the procedure to give the best results. Therefore, Taguchi recommends the orthogonal array (OA) out of experiments. Selecting the most appropriate Orthogonal Array and assigning the parameters and interactions of interest to relevant columns is the first step in designing an experiment. This is made easier by Taguchi's suggestion to use a linear graph and triangular tables. In these arrays, Columns are orthogonal. So, for any pair, all combinations of levels occur, and they occur an equal no of times. The number of orthogonal array rows corresponds to the number of experiments.The number of columns represents the maximum number of factors studied using the array.Taguchi has basic arrays known as standard orthogonal arrays. Based on levels & factors, it is possible to choose one of these for the particular requirement.Assign a priority level to each input and output process variable to be monitored.Choose an orthogonal array (OA) and design its columns with the relevant parameters (parameters).To determine the response, conduct tests at the different levels listed in Table 1.Find the best possible set of input parameters by analyzing the consequences of each factor on the outcome. Find the optimum possible performance characteristics. The Machined surface of the sample displayed in Fig. 2. Figure 3 presents the experiment and corresponding response (MRR and SR) measurement value.

Table 1 Constraints and their levels

S. No.	Parameters	Unit	Level
1	Input current (I)	Amp	8-16
2	Pulse on time (P)	μs	200-400
3	Duty cycle (D)	-	8-10
4	Voltage (V)	Volt	50-70

Fig. 2. Machined surface

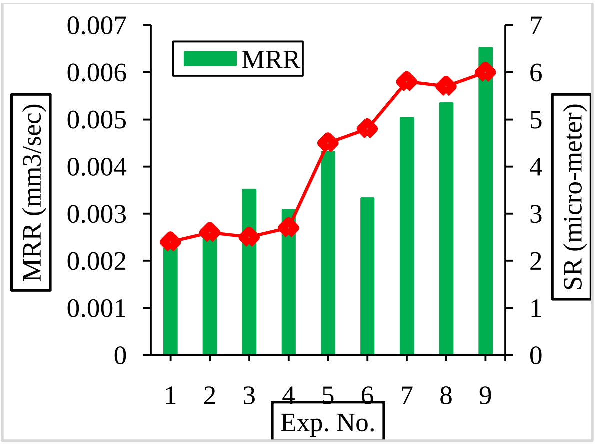

Fig. 3. Response surface corresponding experiment

V. RESULT AND DISCUSSION

The total number of experiments required to run all possible combinations of all the levels for each factor. Fractional factorial design is a portion of the total combination. If orthogonality is maintained, the fractional factorial matrices are called orthogonal arrays. The elementary robust design principle is to enhance the product quality by reducing the effect of the reasons for variation without eliminating causes. It can be achieved by optimizing process & product design to make the performance insensitive to the various causes. It is also termed parameter design. A robust design approach helps to generate required information with much fewer experimental attempts. It is quite difficult to obtain related data about the process parameters, so any changes are avoided during manufacturing and customer use. Mainly two tasks to be executed in robust design: Establish a prime quality indicator to assess the impact of change in a particular parameter on the product performance. With the least amount of time and money, obtain reliable information about the process parameters. This is achieved by using (S-N) ratio quality measures and orthogonal arrays to analyze design parameters simultaneously.

To determine the optimum combination of controllable factors that are given the best value of the desired response. Taguchi's experimental design are the most commonly used process optimization techniques. The optimization technique involved term of statistical. ANOM is a mathematical approach used to analyze data to determine its relevance and significant elements [12]. Results and optimal settings for the approaches are very similar in terms of their effectiveness. MRR and SR are affected by process constraints. Also, the performed analysis maximum delta value is 0.002866 for MRR and 3.333 for SR.Model summaries of response and affecting parameters are included in Table 2 to examine the results more clearly. ANOM was used to examine the influence of machining parameters on the developed indices. The results are accurate with little deviation. The essential factors are the input voltage, pulse off moment, and input voltage. The most influencing factor is input current to MRR as well as SR. The input current, pulse on time, voltage and duty cycle has the impact on response (MRR, and SR).

Machining Inconel X-750, a Taguchi technique, is employed to combine contradictory reactions during the operation. L_9 Taguchi orthogonal data demonstrates that experimental number 9 has the greatest value of MRR (value 0.006529 mm^3/sec) and experiment number 1 for SR (2.4 µm). With highest value experiment number 9 and 1 yields the best results in terms of optimal MRR and SR. On experimental runs, Fig. 4 and Fig. 5 displays the S/N ratio optimal plot ranking. From Fig. 4, Taguchi S/N ratio, best settings for MRR are I-16, P-400, D-10, V-50 with optimal value 0.00676. Similar, for the SR are the best condition is I-8, P-200, D-9, V-70 and optimal value 1.2 µm (Fig. 5). As shown in Table 3, predicted the optimum value confirmed with compared to the OA (run order 9, which corresponds to the parametric setup). The preferred solution value for MRR (3.565%) and SR (50%) has improved (as demonstrate in Table 3).

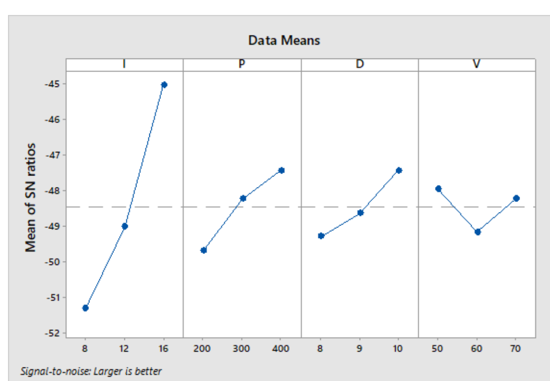

Fig. 4. S/N ratio plot for MRR

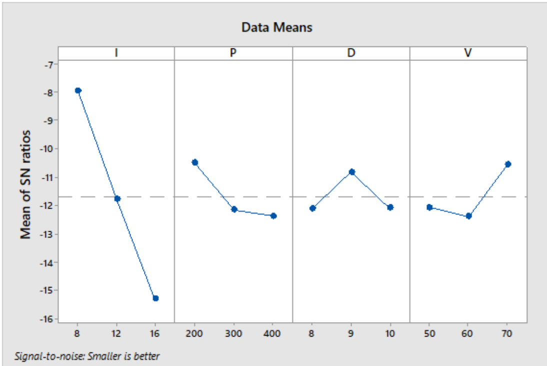

Fig. 5. S/N ratio plot for SR

Table 2 Response table for means for response

Level	MRR				SR			
	I	P	D	V	I	P	D	V
1	0.0027	0.0034	0.0036	0.0043	2.50	3.63	4.30	4.30
2	0.0035	0.0040	0.0040	0.0036	4.00	4.26	3.76	4.40
3	0.0056	0.0044	0.0042	0.0039	5.83	4.43	4.26	3.63
Delta	0.0028	0.0009	0.0006	0.0007	3.33	0.80	0.53	0.76
Rank	1	2	4	3	1	2	4	3

Table 3 Optimal confirmation

Response	OA condition	OA value	Optimal condition	Optimal value	% Imp
MRR	Exp. 9	0.006519	I-3, P-3, D-3, V-1	0.00676	3.565
SR	Exp. 1	2.4	I-1, P-1, D-2, V-3	1.2	50

VI. CONCLUSION

The conclusion of this paper is summarized in the following points:

- Input current (I) is most significant for material removal rate than voltage and pulse on time. The material removal rate is least affected by the duty cycle. The duty cycle contribution is so low that it can be neglected for the material removal rate.
- Surface roughness is nearly independent of the duty cycle and is mainly affected by current than by pulse on time followed by voltage.
- Material removal rate increases when current 12 amp to 16 amp, MRR suddenly increases when pulse on-time increases from 300 µsec to 400 µsec.
- The optimum set of parameters is given by I=16A, P=400µs, D=10, and Voltage=50 for MRR found. This optimal setting gives us the maximum MRR found (0.00676 mm^3/s). It has confirmed with compared to OA of the experiment (3.565%).
- The optimum set of parameters is given by I=16A, P=400µs, D=10, and Voltage=50 for SR found. This optimal setting gives us the minimum SR found (1.2). It has confirmed with compared to OA of the experiment (50%).

The applications of robust design are not limited to the engineering field. The technique has been successfully employed for business and optimization profile planning. The approach of robust design provides simultaneous enhancement of quality, performance, cost, and engineering productivity. Optimization can be described as finding an alternative with the best cost efficient or most obtainable performance under the given set of constraints, maximizing desired factors and minimizing undesired ones. It is a method of finding the setting that will give maximum and minimum response values. In this, controlled factors are determined that will affect the desired response. Also, the minimizes the effect of uncontrollable or noise factors.

CONFLICT OF INTEREST

Authors confirm there are no conflict of interest.

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