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Assessment of Influence of the Process Parameters on Electrochemical Micromachining of 15-5 PH Stainless Steel

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This Research work mainly focuses on optimizing the Electro chemical Machining input parameters like Current, Voltage, Electrolyte Concentration and Inter Electrode Gap applied for micro-drilling operation in a 15-5 PH Stainless steel substrate.Taguchi's L_{27} orthogonal array and grey relation analysis techniques are deployed for multi -objective optimization in order to maximize the Material Removal Rate and minimize the overcut and Surface roughness. Based on the analysis, it is evident that input current plays a dominant role which affects the output parameters.Finally, the optimum reported values of Material Removal Rate, Overcut and surface roughness are 3.852 g/min , 0.128mm and 1.53µm respectively.

Keywords: Material Removal Rate(MRR), Surface Roughness(SR), Orthogonal Array(OA), Electro chemical machining(ECM), Inter Electrode gap(IEG) and Grey Relational Grade(GRG).

1. INTRODUCTION

Electrochemical Machining (ECM) is a non-traditional machining process which helps in removing the metal from the workpiece. The current passes through the tool that is used as cathode and the workpiece that is used as anode by means of an electrolyte solution. ECM is able to machine complicated shapes and profiles.The need of high precision machining with better surface finishing characteristics is highly utilized in aerospace, submarine and automobile industries.15-5 PH Stainless steel is mainly used in automobile industries to provide micro holes needed for specific applications with good surface finish quality characteristics.Moreover, 15-5 PH stainless steel is an electrically conductive material to machine this process. The machinability of the 15-5 PH Stainless steel workpiece materials mainly depends on mechanical and physical properties and yields better corrosion resistance and attains good accuracy. Several pieces can be cut using a single tool without any loss in its shape and structure because of the copper cathode which has high thermal and electrical conductivity [2].

Nayak [3] performed simulation investigation with the aid of GRA and taguchi's L_{27} orthogonal array concept to optimize the feed rate and voltage parameters followed by experimental validation. Da [4] concluded that the electrolyte concentration plays a major contribution in the magnitudes of MRR and surface roughness. The results were derived with the aid of ANNOVA simulation.Further, SEM images were also captured to potray the characteristics of surface morphology.. An interesting assessment were reported by Lu [5] wherein it has been concluded that good type cathodes could be deployed for machining workpieces with complex geometries. Choi [6] have investigated that the finite element simulation on Invar allo machining was performed to asses the importance of current density in ECM.The results are suggesting that precise machining could be performed by adjusting the current density.

Manivannan [7] considered the process parameters which includes current, pulse on time, feed rate and gap voltage and response parameters as Electrode wear rate, overcut and MRR using Micro Electric Discharge Machining. SEM images have been used to study the qualities of the micro holes. The result of the experimental values shows that the overall performance of the micro-Electric Discharge Machining has improved using TOPSIS method. Also it is concluded that the feed rate and the current were the most significant factors on Micro EDM during the study on process parameters using TOPSIS method. Goud [8] proposed the drilling of the micro holes incorporated in the workpiece material as quartz glass and the cathode taken as stainless steel to carry out the performance studies using electrochemical discharge machining. by Taguchi method of L9 orthogonal array experiments and also, to obtain the optimum parameters, Grey Relational analysis approach was used and the result displays that the MRR increases when the width of overcut decreases. Feed rate is the most important factor for machining the quartz glass . Performance studies on Nitinol shape memory alloys were investigated by Lee [9] The various input parameters utilized for Electrochemical polishing process were studied and the most optimal machining conditions were established clearly.

Tiwari [10] have developed a mathematical model by using regression analysis with L_{27} orthogonal Array for machining processes as with three levels of input parameters. And overcut as response parameter The results shown that the Voltage plays a significant role with the response overcut factors. Tang [11] analysed the machining process by varying electrolyte concentration with process parameters.Finally conclude the increase in the tool feed rate with constant voltage results shows the increase in Material Removal Rate and the decrease in the surface roughness and side gap. Thanigaivelan [12] investigated with the stainless steel 304 sheets. Machining rate is the influenced response parameter for using the shape of the truncated cone tip electrode. And different cathode chosen were conical tip electrode and truncated cone tip electrode.Better optimal result got with conical tip electrode with lesser overcut in the machining processes. Manikandan [13] investigated the multi objective optimization technique using Electro Chemical Machining for the workpiece of Inconel 625 material. The researchers show the three input variables like Electrolyte Concentration, Flow rate and Feed rate as well as the corresponding output measures as MRR, SR and Overcut. Finally, the researcher concludes that the Feed rate plays a major role in penetrating the micro holes in Electro chemical drilling. Sathish [14] propose the micro holes are drilled and passed out through stainless steel using Electro Chemical Machining processes for the input parameters like voltage, feed rate and duty ratio. The researchers have taken Overcut, MRR and Conicity as response parameters and have finally evaluated them after observing the special effects of output responses with corresponding input parameters. Hence, Conicity has also been analysed with VMS images. Gobikrishnan [15] examined the drilling investigations on Inconel 625 material with the process parameters like Electrolyte Concentration. Voltage and Current by using L_9 orthogonal array. SEM images have been used to study the micro holes. Finally, researchers concluded the current is the most predominant parameter to remove the metal from the work piece.

Yadav [16] propose that the Alumina epoxy Nano composite is a special class of composites and so it is difficult to machine. The authors consider the kerf characteristics in Alumina epoxy Nano composite by Wire electrochemical spark cutting (WECSC) processes and confirm that the quality of the cut can be measured by using kerf characteristics. The researchers investigate the input factors like wire velocity, applied voltage, electrolyte concentration, pulse on time and off time and conclude that the influencing parameters of Alumina epoxy Nano composite are wire velocity, concentration of electrolyte and applied voltage. Kumar[17] inspected the drilling of AISI D2 tool with different process of electrode by using electrical discharge machining processes. Further, the researchers have experimentally concluded the Electrode wear ratio and the surface roughness have considerably reduced by using Cryogenic cooled electrode compared with conventional electrical discharge machining. Finally, the results of the experiments shows that the Cryogenic cooled electrode is better than that of Conventional electrical discharge machining. Avinash [18] investigated the two different alloys such as Ti-6Al-7Nb and Ti-6Al-4V and studied the corrosion resistance performance using micro-milling operation. The researchers have used L9 orthogonal array with tungsten carbide were used for machining operation. The process parameters are cutting speed, feed per tooth and depth of cut. Using the parameters, corrosion behaviour is also analysed. A minimal corrosion rate has been obtained for both Ti-6Al-4V and Ti-6Al-7Nb material. Finally, the researchers conclude that the Ti-6Al-7Nb alloy has got a less rate of corrosion by forming TiO2. Madhankumar [19] investigated the stainless steel electrode with Inconel 625 material by using Taguchi based analysis approach with difeerent machining parameters.. The researchers have used the process parameters such as concentration, voltage and feed rate. The response factors obtained are Overcut, MRR and SR. ANOVA has also been involved to study the multi performance characteristics of the machining processes. Finally, the authors conclude that the voltage is the most predominant characteristic for the machining performance. Davydov [20] suggests the machining of Titanium alloy leads to the higher metal removal rate and the optimum usage of constant electrolyte solution, where Electrochemical Machining is preferred. The researchers investigated that the many electrolytes concentration is used in titanium alloy to study the performance of materials behaviour and it is applied in the Electrochemical Machining process. Nacl is the most used electrolyte solution for the better machining process as it costs less and has better machining performance efficiency. Finally, the researchers conclude that the machining of titanium alloy in Electrochemical machining gives better material removal rate and provides good result compared to traditional machining process where it can be used in the several applications such as aircraft and in the field of biomedicine. Mouliprasanth [21] suggests that the Nitinol alloy material is the hardest material which is difficult to cut in the traditional machining processes because of their shape memory effect, thereby Micro Electro chemical Machining processes are used. To make the micro holes in NiTi alloy with 0.25mm thickness and variant electrolyte solution is used as passivating and Non-Passivating Electrolyte for the behaviour of studying machining performance characteristics. The machining input factors such as feed rate, duty cycle and voltage and the output parameters like Conicity, circularity, overcut and Material Removal rate. The researchers concludes that the using of passive electrolyte solution in the machining of Nitinol alloy material which gives the higher Material Removal Rate. In addition, it also gives the better surface finish and accuracy of using the nitrate solutions. Dabrowski [22] has developed the numerical model for two-dimensional flow of electrolyte concentration in the IEG where Electrochemical Machining process is used. Finally, the researchers conclude that the results are compared with experimental data continuous Electrochemical Machining process with a Vibrating Tool Micro Electrochemical Machining process. Hence, the researchers get their results more accurately with less vibration frequencies. Consequently, higher frequencies vibration leads to least accuracy and surface finishes. Kumar [23] investigated that the Electrochemical Machining processes using various machining parameters and find out the output responses as diametrical overcut. The researchers developed the Micro Electrochemical Machining process to drill the micro holes using insulated electrode with Bare and flat end electrodes with minimizing of machined stray position in the workpiece material. The researchers have done the modelling and simulation for the different machining parameters to obtain the optimum values using COMSOL Multiphysics V4.2a software and finally conclude that using of Insulated electrode for machining purpose gives the minimum abandoned current affected zone and also produces minimum diametrical overcut and gives better accuracy and surface finished holes for the required shape. Few other optimization studies were also carried out in the area of electro chemical machining.[24, 25]. Zhou developed the rotating tool for machining the workpiece in an Electrochemical Machining setup to get the desired curved surface with the best qualities. The researchers conclude that the machining gap plays a key role in the performance characteristics and the numerical simulations were carried out [26]. The researchers investigated the Laser drilling with jet Electrochemical machining with the usage of 321 Stainless steel workpiece materials. When using laser drilling for machining, the entrance part of the hole is clean and free of blotches, and the surface area has less pitting; additionally, better accuracy is achieved with fewer defects in the workpiece materials[27, 28].

From the literature survey, it has been observed that many researchers have reported on various materials like Titanium alloy material, Inconel alloy material, high nickel and cobalt materials. But, only a few researchers have reported on Stainless steel material. None of the researchers have done an experimental investigation on 15-5 PH stainless steel on Electro chemical machining for optimizing the machining performance characteristics. This research mainly focuses on optimizing the parameters of Electro Chemical Maching with different dependent variables. The main focus of the ECM process is to get the maximum Material Removal Rate (MRR). On the other hand, Overcut plays a vital role in the machining process. The present study concludes that Current acts as the most important factor for attaining the machining performance characteristics. Hence, the researchers moving into multi objective optimization, use Grey Rational analysis (GRA) to optimize the functioning parameters and to get the optimum processed values. To carry out the experiments, an orthogonal array (L_{27}) has been used in this study to get the desired output machining performance characteristics. Thus, the objective of the present study is to enhance the machining input factors including the Current, Voltage, Electrolyte concentration and IEG by using Grey Relational Analysis

2 GREY RELATIONAL ANALYSIS

Taguchi method is a powerful technique for developing superior quality and cost-based systems of experiments for an Orthogonal Array (OA), which has a shortened variance for optimal operation values to configure the process of control factors. Taguchi method is suitable for optimisation of a sole reaction, but the performance of multi optimisation features is dissimilar from machining performance features. Following steps are adopted for the grey relational Analysis procedure

Step 1: For MRR, 'Higher the better' is the desired characteristic used. Hence as a criterion, the Material Removal Rate must be maximized. Normalisation using MRR is

$$\mathrm{Z_k} = \frac{\mathrm{y_k} - \min(\mathrm{k})}{\max(\mathrm{k}) - \min(\mathrm{k})} \qquad (1)$$

Step 2: For Overcut, 'Lower the better' is the desired characteristic used. So, overcut must be minimized. Normalisation using Overcut is

$$Z_k = \frac{\max(k) - y_k}{\max(k) - \min(k)} \qquad (2)$$

where $\mathrm{Z_k}$ shows the value for Grey Relational generation. Max (k) relates to maximum value of k and min(k) relates to minimum value of k for their kth response. The response of (k=1, 2, 3….27) for the reaction variables. For a better performance characteristic, they should have larger normalized values.

Step 3: The equation (3) is calculated for Grey Relational coefficient Ø(k)

$$\text{Ø}_k = \frac{\Delta_{min} - \omega\Delta_{max}}{\Delta(k) + \omega\Delta_{max}} \qquad (3)$$

where $\Delta_{\min}$ & $\boldsymbol{\Delta_{\max}}$ are the maximum and minimum values of normalized results for the Kth response and ω is the differentiating factor where the values are in the range of $0 \leq \omega \leq 1$. The recommended values of the differentiating factor ω is taken as 0.5. So, ω is approximately taken as 0.5 for the analysis of the current study

Step 4: The Grey Relational Grade is considered as total output techniques for multi responses parameters like Overcut and Material Removal Rate. In the equation (4), the Grey Relational grade of every experiment has been calculated as given below:

$$\gamma = \frac{1}{n}\sum_{k=1}^{n} \text{Ø}(\mathrm{k}) \qquad (4)$$

where 'n' denotes the machining process variables. From experiments, it has been observed that the maximum value of GRG shows highest sequence as order of 1. The symbol γ denotes the relationship between the comparative order and the reference order. Then, the most significant value for Grey Relational Grade is attained, when corresponding value of order is 1.

3. MATERIALS AND METHODS

3.1 Selection of Materials

15-5 PH Stainless Steel is a hardening stainless steel and mainly used in the aerospace field, food processing, metalworking and petrochemical industries. The 15-5 PH stainless steel material provides excellent mechanical properties such as high corrosion resistance, good strength and a high degree of hardness. Compared to the strengthened nickel alloys and non-ferrous alloys, it is more effective to use. Therefore, 15-5 PH stainless steel has been chosen as the work piece material for the present study. The chemical configuration of the 15-5 PH stainless steel material is configured in Table1. The work piece material, which is made up of circular sections of 50mm in diameter, and 0.6mm in thickness was chosen for this research study.

Table 1. Chemical configuration for 15-5 PH stainless steel

C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Ti	Co	Al
0.023	0.43	0.63	0.022	0.001	4.70	15.40	0.092	3.21	0.001	0.057	0.02

The copper tool plays an essential role in machining the work piece and generally, it has high electrical conductivity for the passage of current. Hence copper tool material is used for this study. The tool is coated with an epoxy powder resin on either side of the tool position because the lower contact area of the machine passes the current to the work piece. Therefore, the current passes straight through the base of the tool to the work piece, which helps in preventing the passage of current in large areas of machining. Sodium chloride is rapidly dissolved in water and reacts with other solvents. The preparation of sodium chloride solution plays an important role in Material Removal Rate for removing the work piece. Therefore, Sodium chloride electrolyte solution is used for machining in the present investigation. Various levels of concentration like 40g/lit, 45g/lit, and 50g/lit have been used in this experiment for machining.

3.2 Design of Experiment

The present investigation involves four controllable factors like Current, Electrolyte Concentration, Voltage, and Inter-electrode gap. and three levels with four process parameters are used for machining. In this investigation, L_{27} orthogonal arrays (OA) are used in the Design of Experiments (DOE) with the support of Minitab software for operating the experiments. Many trials and errors have been done and finally the SR, Overcut and MRR were calculated. The machining parameters and their level of factors are tabulated in table 2. The experimental work proceeses through 27 runs with three levels were chosen for the experiments.

Table 2. The Various Levels and parameters of machining.

Parameters and Units	Symbols	Level 1	Level 2	Level 3
Current(A)	A	5	6	7
Voltage(V)	B	15	17	19
Electrolyte Concentration(g/lit)	C	40	45	50
Inter Electrode gap(mm)	D	0.2	0.25	0.3

3.3 Experimental Procedure

The Electrochemical machining set up consists of Machining chamber, Tool feeding arrangement, nozzle, Stepper motor, Pulse generator, and Filter. The work piece is considered as Anode and tightly fixed inside the chamber and the tool is considered as Cathode, rigidly fixed in the main screw, which is supported by a stepper motor. A current sensing circuit connects the stepper motor controller circuit and the tool to prevent short circuits in the machining set up. The tool is moved in the forward direction to reach the work piece, and the constant gap is maintained between Anode and Cathode because it is a not-touchable process. The input variables like current, Voltage, pulse on time and off time are speckled by the control panel. The electrolyte concentration has been poured into the bath, and the work piece is dipped in an electrolyte solution. The electrolyte is passed through the tank and a filter which removes the polluted material from the electrolyte. In an evacuated bath, the electrolyte solution is stored for the machining processes. The material is separated in the form of mud, and it is precipitated in the filter followed by chemical reaction that takes place by means of current and electrolyte solution. By this technique, the hardest material can give a complex profile in a distinct machining operation.

3.4 Machining Characterisation

3.4.1 Measurement of Material Removal Rate and Overcut

The Material Removal Rate can be calculated as the weight has been calculated during earlier machining and later machining of the component at the respective time. The formula of the Material Removal Rate can be shown in the equation. Overcut may be defined as the difference between machined hole dimension and the dimension of the tool electrode. The Overcut can be calculated by using the formula given in the equation (6).

3.4.2 Measurement of Material Removal Rate (MRR)

The MRR in the ECM processes is higher than any of the un-conventional machining processes. The Material Removal Rate can be formulated by taking the weight of the drilled work piece and the weight of the undrilled workpiece with respect to the time duration of the respective machined workpiece. So, the weight of the work piece is taken by means of a weight balancing machine with their respective accuracy. The pulse rectifier calculates the time duration of the drilled hole. The equation (5) can be used for calculating the MRR.

Material Removal Rate= $\frac{P-Q}{R}$ (5)

Where P=weight of the work piece before machining

Q=Weight of the work piece after machining

R=Machining Time

3.4.3. Measurement of Surface Roughness (SR)

The surface roughness of the drilled work piece material can be measured by means of Mitutoyo Surftest 201.The results are obtained by taking the average value of three measurements taken in the different positions of the measured instrument. Surface roughness is prepared in the transverse direction on the work piece material (15-5 PH Stainless Steel). This is repeated three times and the average of the three times of dimensions is noted. The measurement of the profile is digitized, and the readings are taken with the accurate measurements.

3.4 .4 Measurement of Overcut

Overcut is defined as the difference between machined hole dimension and the dimension of the tool electrode as the size of the hole is produced in the work piece material during the machining process. Overcut is the most predominant parameter to reduce the machining accuracy. In this study, Taguchi's techniques are used to reduce the Overcut by using optimal input factors like Voltage, Electrolyte Concentration, current and IEG to get the optimal values which are determined for 15-5 PH Stainless steel work piece material.

Overcut = Dimension of the machined hole – Dimension of the tool electrode (6)

4. RESULTS AND DISCUSSION

The work involves three levels and four process parameters used for machining processes. The four controllable factors are Current, Electrolyte Concentration, Voltage, and Inter-electrode gap. In this investigation, L_{27} orthogonal arrays (OA) are used with the support of Minitab software for operating the experiments. For L_{27} orthogonal Array (OA), the three-level factors can be used to provide the response factors like SR, Overcut and MRR. For the twenty-seven experimental values and the corresponding output responses, values are shown in the table 3.

Table 3. Design of Experimental Values and output values of Response parameters results

Exp.No	A	B	C	D	Output Responses		
					MRR	Surface Roughness	Overcut
1	5	15	40	0.20	2.662	1.97	0.756
2	5	15	45	0.25	2.732	2.35	0.725
3	5	15	50	0.30	2.812	1.98	0.702
4	5	17	40	0.25	2.594	2.24	0.756
5	5	17	45	0.30	2.801	2.43	0.795
6	5	17	50	0.20	2.915	2.30	0.856
7	5	19	40	0.30	2.676	2.48	0.895
8	5	19	45	0.20	2.885	2.91	0.978
9	5	19	50	0.25	2.942	2.73	0.904
10	6	15	40	0.25	2.788	2.81	0.453
11	6	15	45	0.30	2.926	2.95	0.426
12	6	15	50	0.20	3.172	2.88	0.513
13	6	17	40	0.30	2.879	3.41	0.526
14	6	17	45	0.20	3.147	3.32	0.578
15	6	17	50	0.25	3.144	3.15	0.595
16	6	19	40	0.20	2.946	3.37	0.625
17	6	19	45	0.25	3.312	4.26	0.461
18	6	19	50	0.30	3.189	3.39	0.571
19	7	15	40	0.30	3.034	4.01	0.185
20	7	15	45	0.20	3.156	4.45	0.179
21	7	15	50	0.25	3.335	4.27	0.16
22	7	17	40	0.20	3.146	4.34	0.256
23	7	17	45	0.25	3.314	5.15	0.279
24	7	17	50	0.30	3.390	4.35	0.295
25	7	19	40	0.25	3.226	4.77	0.276
26	7	19	45	0.30	3.412	5.22	0.256
27	7	19	50	0.20	3.456	4.83	0.389

4.1 Process Parameters of Material Removal Rate for 15-5 PH Stainless Steel

The focus for Micro Electro Chemical Machining process is to get the higher Material Removal Rate with lower Overcut and Surface Roughness parameters. In the present investigation, Table 4 shows that MRR increases when there is a gradual rise in current from 5 to 7A. It also shows that MRR increases when the voltage increases from 15 to 17V. The table 4 shows that the Material Removal Rate increases when the electrolyte concentration increases from 40 to 50 g/lit, but with the further parameters of IEG, the Material Removal Rate decreases when the IEG increases from 0.20 to 0.30 mm [19]. The productivity of Micro Electro chemical Machining process can be determined by MRR with the help of the influence of machining input parameters like current, Electrolyte Concentration, Voltage and IEG for the work piece material of 15-5 PH stainless steel.[13].

4.2 Response Analysis for Material Removal Rate of 15-5 PH Stainless Steel

Table 4. Response Table for Material Removal rate of 15-5 PH stainless Steel

Levels	Means				S/N Ratio			
	Current (A) (A)	Voltage (V) (B)	Electrolyte Concentration (g/lit) (C)	Inter Electrode Gap (mm) (D)	Current (A) (A)	Voltage (V) (B)	Electrolyte Concentration (g/lit) (C)	Inter Electrode Gap(mm) (D)
1	2.780	2.957	2.883	3.054	8.873	9.395	9.175	9.675
2	3.056	3.037	3.076	3.043	9.690	9.620	9.735	9.631
3	3.274	3.116	3.151	3.013	10.295	9.843	9.948	9.552
Delta	0.494	0.159	0.267	0.041	1.422	0.448	0.773	0.124
Rank	1	3	2	4	1	3	2	4

Response analysis for MRR of Micro Electro Chemical machining for 15-5 PH stainless steel is given in table 4. It is experimental from the analysis of response table values to get the optimum process parameters for better MRR , which is A3B3C3D1. This means that the Current is 7A, voltage is 19V, Electrolyte concentration is 50 g/lit and IEG is 0.2 mm. Current is the maximum predominant factor for MRR followed by the Electrolyte Concentration, Voltage and Inter Electrode Gap respectively. The variation in material removal rate is nearly identical to analyses with similar setup. [15]. It is observed that the difference (delta) has higher values and gets the first rank for Current parameters followed by the remaining process parameters and thus have the most influence factors over Micro Electro Chemical Machining performance characteristics.[19]

4.3 Process Parameters of Surface Roughness for 15-5 PH Stainless Steel

For the present study, it is determined from Table 5, shows that the surface roughness of the drilled surface decreases when there is a gradual decrease in current from 5 to 7A. It also shows that the SR of the machined surface decreases again due to the lower potential difference and with the decrease of voltage from 15 to 17 V. From the table, it has been observed that the surface roughness first decreases when the concentration of electrolyte is increased from 40 to 50 g/lit. Taking the initial level of electrolyte concentration does not show the variation , but the level of concentration increases first, then decreases and then increases again with the highest level of electrolyte concentration because, for the unconventional machining process, especially for the Electro Chemical Machining Process, electrolyte concentration levels are important for the machined surface of the drilled hole. When the concentration of electrolyte increases, the excess of ions that exist in the IEG helps to remove the undesirable material and thus leads to poor surface finish owing to the increase in surface roughness as shown in table 5. In similar analyses, the increases in IEG lead to a decrease in surface roughness. [3]. But, due to the other parameters of the inter electrode gap, the surface roughness decreases first and the level of the gap increases and again it fluctuates from decrease to increase according to the process parameter, IEG, from 0.20 to 0.30 mm. The increase in the inter electrode gap takes the affinity away from the gap between work piece and tool as the flow of current in the gap increases from machining processes. Therefore, greater flow of current density in the gap yields lesser surface roughness. Less concentration of electrolyte leads to higher roughness of the drilled exterior area because of ions diminishing in the machining path of the electrolyte.[3, 13]

4.4. Response Analysis for Surface Roughness of 15-5 PH Stainless Steel

Table 5. Response Table for Surface Roughness of 15-5 PH stainless Steel

Levels	Means				S/N Ratio			
	Current (A) (A)	Voltage (V) (B)	Electrolyte Concentration (g/lit) (C)	Inter Electrode Gap(mm) (D)	Current (A) (A)	Voltage (V) (B)	Electrolyte Concentration (g/lit)(C)	Inter Electrode Gap (mm) (D)
1	2.377	3.074	3.267	3.374	-7.454	-9.382	-9.928	-10.218
2	3.282	3.410	3.671	3.526	-10.261	-10.306	-10.931	-10.566
3	4.599	3.773	3.320	3.358	-13.222	-11.249	-10.078	-10.153
Delta	2.222	0.699	0.404	0.168	5.768	1.866	1.003	0.413
Rank	1	2	3	4	1	2	3	4

Response analysis for SR of Micro Electro Chemical machining for 15-5 PH stainless steel is tabulated in table 5. It is experimental from the analysis of response table to get the optimum response factors for surface roughness which is A1B1C1D3. This means that the Current is 5A, voltage is 15V, Electrolyte concentration is 40g/lit and inter electrode gap is 0.3mm. Current is the greatest predominant parameter for SR followed by Voltage, Electrolyte Concentration, and IEG respectively. It is observed that the difference (delta) is extreme and gets the first rank for the Current parameters followed by the remaining process parameters and thus has the most influential factors over Micro Electro Chemical Machining performance characteristics.[3]

4.5. Process Parameters of Overcut for 15-5 PH Stainless Steel

Table 6 indicates that the overcut increases when the level of current increases from 5 to 7A. It also shows that the overcut decreases when the corresponding voltage values increase from 15 to 17V. From the table 6, it is observed that the overcut increases first from 40 to 45 g/lit and decreases with the rising level of electrolyte concentration from 45 to 50 g/lit which shows that the increasing level of electrolyte concentration erode the work piece material [10]. This leads to a higher machined hole surface compared to the diameter of the tool electrode materials. But, due to the other parameters of the inter electrode gap, overcut increases when IEG increases from 0.20 to 0.25 mm and again it decreases when the level of IEG increases from 0.25 to 0.3mm. The productivity of the Micro ECM process can be determined by overcut with the help of the influence of machining input factors like current, Voltage, Electrolyte Concentration and Inter Electrode Gap for 15-5 PH stainless steel.

4.6 Response Analysis for Overcut of 15-5 PH Stainless Steel

Table 6. Response Table for Overcut of 15-5 PH stainless Steel

Levels	Means				S/N Ratio			
	Current (A) (A)	Voltage (V) (B)	Electrolyte Concentration (g/lit) (C)	Inter Electrode Gap (mm) (D)	Current (A) (A)	Voltage (V) (B)	Electrolyte Concentration (g/lit) (C)	Inter Electrode Gap(mm) (D)
1	0.8186	0.4554	0.5253	0.5700	1.789	8.211	6.671	5.955
2	0.5276	0.5484	0.5197	0.5121	5.624	6.017	6.860	6.933
3	0.2528	0.5950	0.5539	0.5168	12.251	5.436	6.133	6.776
Delta	0.5658	0.1396	0.0342	0.0579	10.462	2.775	0.727	0.978
Rank	1	2	4	3	1	2	4	3

Response analysis for overcut of Micro Electro Chemical machining for 15-5 PH stainless steel is given in table 6. It is experimental from the analysis of the response table to get the optimum process parameters for Overcut, which is A3B1C3D2. This means that the Current is 7A, voltage is 15V, Electrolyte concentration is 50 g/lit and inter electrode gap is 0.25mm. Current is the leading parameter for overcut and it is followed by Voltage, IEG and Electrolyte Concentration respectively [19]. It is observed that the difference (delta) is maximum and that it gets the first rank for Current parameters followed by the remaining process parameters and thus have the most influential factors over Micro Electro Chemical Machining performance characteristics [13].

4.7. Analysis Of Variance (ANOVA)

In this investigation, L27 orthogonal arrays (OA) are used with the support of Minitab software for operating the experiments and for calculating the Analysis of Variance (ANOVA). ANOVA is calculated for the following response factors like SR, overcut and MRR with the four controllable factors like Current, Electrolyte Concentration, Voltage and Inter-electrode gap.

Table 7. ANOVA of Electro Chemical Machining for 15-5 PH stainless Steel

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Material Removal Rate							
Current	2	1.10511	67.81%	1.10511	0.552554	161.79	0.000
Voltage	2	0.11313	6.94%	0.11313	0.056565	16.56	0.000
Electrolyte Concentration	2	0.34203	20.99%	0.34203	0.171016	50.07	0.000
Inter Electrode Gap	2	0.00798	0.49%	0.00798	0.003989	1.17	0.334

Error	18	0.06147	3.77%	0.06147	0.003415	-	-
Total	26	1.62972	100.00%	-	-	-	-
Surface Roughness							
Current	2	22.4757	86.01%	22.4757	11.2379	467.38	0.000
Voltage	2	2.1992	8.42%	2.1992	1.0996	45.73	0.000
Electrolyte Concentration	2	0.8691	3.33%	0.8691	0.4345	18.07	0.000
Inter Electrode Gap	2	0.1538	0.59%	0.1538	0.0769	3.20	0.065
Error	18	0.4328	1.66%	0.4328	0.0240	-	-
Total	26	26.1306	100.00%	-	-	-	-
Overcut							
Current	2	1.44086	90.58%	1.44086	0.720432	377.38	0.000
Voltage	2	0.09088	5.71%	0.09088	0.045438	23.80	0.000
Electrolyte Concentration	2	0.00606	0.38%	0.00606	0.003028	1.59	0.232
Inter Electrode Gap	2	0.01862	1.17%	0.01862	0.009308	4.88	0.020
Error	18	0.03436	2.16%	0.03436	0.001909	-	-
Total	26	1.59078	100.00%	-	-	-	-

Table 7 represents the Analysis of variance for the response factors like SR, Overcut and MRR. The point to be observed from table 7 is that current is the maximum predominant factor for MRR and that it is followed by the Electrolyte Concentration, Voltage, and Inter Electrode Gap respectively. For the Surface Roughness, the calculated ANOVA shows that current is the greatest predominant parameter for SR and followed by the Voltage, Electrolyte Concentration and IEG respectively. As given in table 7, the calculated ANOVA implies that Current is the most leading parameter for overcut followed by the Voltage, IEG and Electrolyte Concentration respectively [13]. It is clearly shown that Current is the greatest predominant parameter, and contribution wise, it shows the maximum for all the response factors like SR, Overcut and MRR as 67.81%, 86.01% and 90.58% [19]. For getting the lower P-value below 0.05, table 7 shows the strong confirmation against the result values for choosing accurate levels and process parameters for the given machining processes [10].

4.8. Multiple Regression Analysis Of Electro Chemical Machining Processes For 15-5 PH Stainless Steel

A parametric relationship has been developed among the Micro Electro-Chemical Machining parameters. The preferred performance measures are calculated, and the values are established from the experimentation values. The observed relations, which are pretending to be the Micro Electro-Chemical Machining processes , are developed by multiple regression analysis. The regression analysis equations have been developed to examine the relationships between the response parameters (MRR, SR and overcut) and process parameter variables (current, voltage, IEG and electrolyte concentration). It is one of the most common techniques used to calculate the performance of response output parameters and input variables of machining parameters. The regression equations are generated with the help of Minitab 19 for Material Removal Rate, Surface Roughness and Overcut. It is shown in the below equations:

$$\text{MRR(g/min)} = -4.88 + (0.278 \times A) - (0.013 \times B) + (0.2699 \times C) - (3.57 \times D) - (0.0288 \times A2) + (0.00001 \times B2) - (0.002364 \times C2) - (3.78 \times D2) + (0.01194\, A \times B) - (0.00025\, A \times C) + (0.489\, A \times D) - (0.00141\, B \times C) + (0.176\, B \times D) - (0.0196\, C \times D) \quad (7)$$

Surface Roughness (µm) = -31.8 – (1.71 x A) - (0.095 x B) + (1.436 x C) + (33.2 x D) + (0.2056 x A2) + (0.0035 x B2) - (0.01511 x C2) - (63.8 x D2)+ (0.0177 A x B) - (0.0013 A x C) + (0.45 A x D) - (0.00064 B x C) + (0.300 B x D) - (0.205 C x D) (8)

Overcut (mm) = 2.05 – (0.385 x A) + (0.284 x B) – (0.0795 x C) - (3.66 x D) + (0.0081 x A2) - (0.00581 x B2) + (0.000798 x C2) + (12.51 x D2)- (0.00699 A x B) +(0.00188 A x C) + (0.157 A x D) + (0.00053 B x C) – (0.136 B x D) - (0.0390 C x D) (9)

where ‘A’ denotes Current (A), ’B’ Voltage (V), C Electrolyte Concentration (g/lit) and ‘D’ Inter electrode gap (mm). The R^2 values of multiple regression analysis model of Micro Electro Chemical Machining of 15-5 PH stainless steel material is given in the table. It is also proved that the values are developed, and multiple regression models are fit for the further calculations [13, 19]

Table 8. R^2 values of different multiple regression developed models for Electro Chemical Machining of 15-5 PH stainless Steel

Regression Model	R^2 Values		
	MRR	SR	Overcut
Linear	94.60	93.51	97.09
Linear+ Squares	96.23	98.34	97.84
Linear+ Interactions	95.68	93.71	97.60
Full Quadratic (Linear + squares + Interactions)	97.30	98.54	98.35

4.9. Multi Objective Optimization For Performance Measures Using Grey Relational Analysis

Table 9. Grey Relational grade (GRG) and Corresponding rank values for Electrochemical Machining of 15-5 PH Stainless Steel

S.No	GRG and corresponding rank values				
	Material Removal Rate	Surface Roughness	Overcut	Grey Relational Grade	Rank
1	0.35184	0.40697	0.33333	0.36405	26
2	0.37316	0.41992	0.36151	0.38486	24
3	0.40093	0.43007	0.33402	0.38834	22
4	0.33333	0.40697	0.35288	0.36439	25
5	0.39687	0.39176	0.36806	0.38557	23
6	0.44342	0.37014	0.35754	0.39036	21
7	0.35590	0.35752	0.37228	0.36190	27
8	0.43014	0.33333	0.41296	0.39214	20
9	0.45608	0.35473	0.39490	0.40190	19
10	0.39217	0.58262	0.40273	0.45917	18
11	0.44849	0.60593	0.41720	0.49054	15
12	0.60280	0.53675	0.40984	0.51646	12
13	0.42758	0.52774	0.47307	0.47613	16
14	0.58243	0.49456	0.46099	0.51266	13
15	0.58008	0.48460	0.43978	0.50149	14
16	0.45802	0.46796	0.46763	0.46454	17

17	0.74957	0.57606	0.62863	0.65142	10
18	0.61748	0.49878	0.47033	0.52886	11
19	0.50528	0.94240	0.57319	0.67362	9
20	0.58960	0.95561	0.67850	0.74124	6
21	0.78080	1.00000	0.63107	0.80396	4
22	0.58165	0.80990	0.64870	0.68008	8
23	0.75218	0.77462	0.95870	0.82850	2
24	0.86720	0.75184	0.65130	0.75678	5
25	0.65204	0.77905	0.78313	0.73807	7
26	0.90737	0.80990	1.00000	0.90576	1
27	1.00000	0.64107	0.80645	0.81584	3

The Optimum Process Parameters for the Grey Relational Coefficient and Grey Relational Grades for Micro Electro chemical Machining of 15-5 PH Stainless steel have been calculated in the Equations (5) and (6). Hence, the Grey Relational Grades and corresponding rank values are presented in table 9. After the calculation of GRG values, the highest rank is given to the highest-Grade values, and it is shown in table 9. Among the 27 trails, Experiment No.26 attains the highest GRG values which show that the equivalent set of machining parameters variables has the multi performance characteristics compared to all the set of readings which are calculated in this study. The highest GRG value shows that the optimum setting level for the process parameters variables are shown and thus competes with the multi performance features for the machining performance [13, 19].

4.9.1 Optimum Level parameters for Electrochemical Machining of 15-5 PH Stainless Steel

Taguchi's analysis of L27 orthogonal array used for the Micro Electro chemical Machining of 15-5 PH Stainless Steel performance characteristics is tabulated in response table 10. Figure 1 clearly shows the fluctuation of Grey Relational Grade with the corresponding experimental trail numbers.[3, 19]. Grey Relation Grade value slightly increases and decreases due to the effect of input machining parameters for the corresponding run number which is shown in figure 1. It is determined from the analysis that the MRR gradually improves when there is an increase in the levels of current parameters. From the result of the experimental analysis, it can be concluded that the best possible set of machining parameters variable is A3B3C2D2 which indicates that the current is 7A, Voltage is 19V, Electrolyte Concentration is 45 g/lit and Inter Electrode Gap is 0.25mm [13].

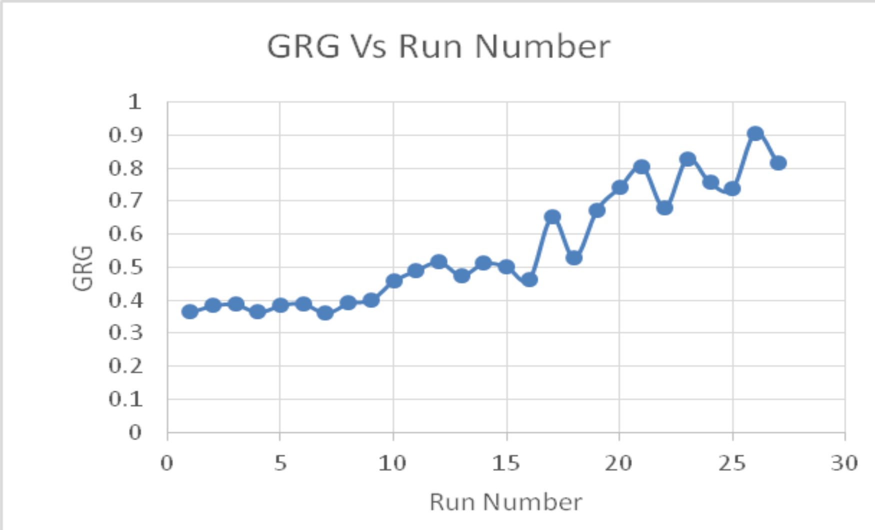

Figure 1. Response Graph for GRG Vs Run Number

Table 10. Response Table for Grey Relational grade (GRG) on Electrochemical Machining of 15-5 PH Stainless Steel

Levels	Means				S/N Ratio			
	Current (A) (A)	Voltage (V) (B)	Electrolyte Concentration (g/lit) (C)	Inter Electrode Gap (mm) (D)	Current (A) (A)	Voltage (V) (B)	Electrolyte Concentration (g/lit)(C)	Inter Electrode Gap (mm) (D)
1	0.3815	0.5358	0.5091	0.5419	-8.376	-5.767	-6.184	-5.666
2	0.5113	0.5440	0.5881	0.5704	-5.872	-5.652	-5.057	-5.292
3	0.7715	0.5845	0.5671	0.5519	-2.289	-5.118	-5.295	-5.578
Delta	0.3900	0.0487	0.0790	0.0285	6.087	0.649	1.127	0.375
Rank	1	3	2	4	1	3	2	4

Current is the most leading parameter, which is followed by the Electrolyte Concentration, Voltage, and Inter Electrode Gap. The dominant input parameters are responsible for getting the higher MRR and lessen the Overcut and SR which are found in the response table for GRG on Electrochemical Machining of 15-5 PH Stainless Steel and they have been tabulated in table 10 [19].

It is observed that the difference (delta) in getting higher values is maximum for Current parameters followed by the remaining process parameters and thus they have the most influential factors over Micro Electro Chemical Machining performance characteristics [13]. Inter Electrode Gap has the least impact over Micro Electro Chemical Machining performance characteristics [3].

4.9.2 ANOVA for Electrochemical Machining of 15-5 PH Stainless Steel

Table 11. Results of Analysis of Variance on GRG for Electro Chemical Machining of 15-5 PH stainless Steel

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Current	2	0.710142	90.70%	0.710142	0.355071	239.63	0.000
Voltage	2	0.012233	1.56%	0.012233	0.006116	4.13	0.033
Electrolyte Concentration	2	0.030122	3.85%	0.030122	0.015061	10.16	0.001
Inter Electrode Gap	2	0.003759	0.48%	0.003759	0.001880	1.27	0.305
Error	18	0.026671	3.41%	0.026671	0.001482	-	-
Total	26	0.782927	100.00%	-	-	-	-

Analysis of variance for multi performance optimization for the Micro Electro chemical Machining of 15-5 PH Stainless Steel is presented in table 11. The analysis of the results indicate that the Current is a major parameter, followed by the Electrolyte Concentration, Voltage and IEG. In table 11, it can be observed that the most influential parameter contributing towards the GRG optimum value is current and Electrolyte Concentration with a percentage contribution of 90.70% and 3.85% respectively. The results are confirmed to have a similar relationship with Taguchi's analysis as shown by the ANOVA analysis [13, 19].

4.9.3 Confirmation Test for Electrochemical Machining of 15-5 PH Stainless Steel

Table 12. Confirmation test results for Electro Chemical Machining of 15-5 PH stainless Steel

Setting level	Initial setting A1B1C1D1	Optimum machining parameters A3B3C2D2
MRR(g/min)	2.662	3.852
Surface Roughness (μm)	1.97	1.53
Overcut	0.756	0.128
Grey Relational Grade	0.36405	0.90576
Improvement on GRG	0.54171	

The confirmation experiment is crucial for concluding the results of the Taguchi-based Grey analysis techniques. The result attained from the multi characteristics is tested by showing the confirmative test values and using the levels of process factors A3B3C2D2, which means that the current is 7A, Voltage is 19V, Electrolyte Concentration is 45g/lit and Inter Electrode Gap is 0.25mm. Current is the major leading parameter, followed by the Electrolyte Concentration, Voltage and Inter Electrode Gap. From the table 10, it is observed that the current increases from 5 to 7A and also voltage increases from 15 to 17V. Further, concentration of electrolyte increases from 40 to 45 g/lit and decreases from 45 to 50 g/lit. But, the other parameters of IEG increases gap from 0.20 to 0.25 mm and again it decreases from 0.25 to 0.30mm. Also, it is noted that there is an increase in the Grey Relation Grade with an increase of current and voltage [3]. The similar result obtained from the Grey Relation Grade increases with current and voltage inceases [19]. Confirmation experiment results are carried out and also confirm the analysis from the optimum condition outcomes for the Overcut, Surface Roughness and Material Removal Rate have been achieved through the experiment. The comparison between the first setting level and the best level of machining parameters are presented in table 11. From the output of the analysis from the table 11, it is understood that the optimum parameter helps to improve the machining characteristics for the 15-5 PH stainless steel material.

5. CONCLUSIONS

This paper details about the multi objective optimization of Micro ECM of 15-5 PH stainless steel using Taguchi based GRA approach. The important points to be concluded for these 27 experimental runs from the result analysis are as follow:

- Current is the most predominant parameter for attaining the optimum of multi objective performance characteristics during the machining processes.
- The R^2 values for established regression model (97.30% for MRR, 98.54% for SR and 98.35 % for overcut) prove that the results can be applied for further calculation values.
- The multi objective techniques for the input parameters are considered as current with 7A, Voltage 19V, Electrolyte Concentration 45g/lit and Inter Electrode Gap 0.25mm. This parameter has produced a better multi performance characteristic and this is also validated from the results which are MRR, Minimum Overcut and SR respectively from the experiment results.
- The optimum machining output performance characteristics for Micro ECM of 15-5 PH stainless steel for GRG has been found to be that MRR is 3.852g/min, SR is 1.53µm and Overcut is 0.128mm.
- The confirmation test concludes that there is a significant development in the multi performance optimization of Grey Relational Grade as 0.54171 for the investigational result values.

The significant findings of this research work will facilitate the industries for the improvement of its existing efficiency and quality of the product using Micro electro chemical machining process.

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