A STUDY ON MULTI-OBJECTIVE OPTIMIZATION OF ELECTROCHEMICAL MACHINING (ECM) ON COPPER WORKPIECE BY NON-DOMINATED SORTING GENETIC ALGORITHM (NSGA)

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Abstract

Using the Taguchi approach, this study investigated the influence of various input parameters such as applied voltage, electrolyte concentration, flow velocity, and inter-electrode spacing on machining rate. Using the Non-Dominated Sorting Genetic Algorithm, experiments are carried out on ECM to verify the performance of process parameters on the surface of copper. Minitab17 was used to create a series of tests utilizing the Taguchi L9orthogonal array. The regression equation and analysis of variance (ANOVA) were also done using by Taguchi technique. Machining voltage, flow rate, electrolyte concentration, and material removal rate increase as the machining voltage, flow rate, and electrolyte concentration rise. According to the findings, the interelectrode gap impacts MRR and taper angle parameters. As the interelectrode gap increase, the MRR and taper angle is decreased.

Keywords– MRR, Taper angle, ANOVA, Copper, Taguchi, Non-dominated sorting genetic algorithm

INTRODUCTION

Electrochemical machining is a non-conventional method for machining materials that are difficult to manufacture using typical methods. It is a high-precision material removal machining method with minor tool wear and a smooth surface finish. ECM has several advantages that make this technique more effective than other unconventional machining processes. It is also used for producing complex or intricate shapes**.**H. Hocheng et al.[1]shows that as the value of process parameter (voltage, inter-electrode gap, the electrolyte concentration, and time of electrolysis) increases, MRR increases for SKD61 SS. The time of electrolytes influences the hole's diameter. Z Pandilov et al.[2] they said that it is a contactless procedure with no heat input, and the process is not subject to any of the disadvantages experienced with the traditional machining method. S K Soni et al.[3] used a Taguchi L27 orthogonal array to drill LM6 AL/B4C composites, and the results suggest that electrolyte concentration and voltage are the most critical machining parameters for impacting MRR, overcut, and surface roughness. Abhishek Tiwari et al.[4] used the Non-Dominated Sorting Genetic Algorithm (NSGA-II) to optimize the metal removal rate and surface roughness for electrochemical machining on the EN 19 tool by varying different process parameters such as electrolyte concentration, and voltage, feed rate, and inter-electrode gap. A set of experiments was developed using a Taguchi L27 orthogonal array, and regression was used to determine the connection between the dependent and independent variables and the process parameter, which was examined using ANOVA. A. Mohanty et al.[5] used a Taguchi L9 orthogonal array to evaluate the influence of several machining parameters, including electrolyte concentration, feed rate, and applied voltage on material removal rate, surface roughness, and microstructure for Inconel 825 electrochemical machining. Copper was employed as the tool electrode and an aqueous sodium chloride solution as the electrolyte. ANOVA was used to examine the results of the studies. They concluded that voltage is the most critical process parameter affecting material removal rate and surface roughness. Material removal rate and surface roughness both increase when voltage is increased.

1. Objective

The following are the objectives of this study:

1. Experiment with different process parameters for copperplate machining.
2. Examine the MRR and the Taper Angle.
3. The Non-dominated Sorted Genetic Algorithm was used to optimize the process parameter.

2. Methodology

1. Prepare an ECM testing rig and a copper plate workpiece.
2. Process parameters such as voltage, concentration, IEG, and flow rate are chosen.
3. In several sets of experiments, obtain MRR and Taper angle.
4. Create a Fit Regression model to solve the problem. Through an electrolytic material removal method negatively charged (cathode), a conductive fluid (electrolyte), and a conductive workpiece, a large current is transmitted between an electrode and the component in ECM (anode). Minitab software calculates the material removal rate (MRR) and derives the unique MRR and Taper Angle equation.
5. In Matlab2015, an M-file is created.
6. Using the NSGA optimization tool, optimize the equation.
7. Examine the outcomes.

LITERATURE SURVEY

In ECM, there has been a recent study on the process parameter:-

Taha Ali El-Taweel et al.[1] Wire electrochemical machining (WECM) is a cutting technique in which the cathode (tool) is wire, and the anode is the workpiece. They spoke about whether or not a wire could be used as a tool in the electrochemical turning process (WECT). They assessed the performance of voltage, wire feed rate, wire diameter, workpiece rotating speed, overlap distance on the response parameter, metal removal rate, and surface roughness error. The regression model and variance analysis were investigated using the Response Surface Methodology (RSM) based on the experimental results. The following conclusion was reached based on the findings and discussion:

1. Wire as an electrode can be used to make micro-sized turned parts.
2. The surface roughness rises as the wire feed rate increases, but the roundness error decreases.
3. The productivity of the operation and the geometrical inaccuracy of the generated components both improve when the rotating speed of the workpiece is increased.
4. The following settings were found to be the most effective for optimizing metal removal rate while reducing both surface roughness and roundness error: applied voltage 32.5V, wire feed rate 0.4 mm/min, wire diameter 1.3 mm, overlap distance 0.03 mm, and rotating speed 750 rpm.

D. Chakradhar et al.[2] They use Grey Relation Analysis (GRA) to optimize different output parameters like material removal rate, overcut, cylindricity error, and surface roughness for electrochemical machining of EN-31 steel by varying different machining processes parameters like electrolyte concentration, feed rate, and applied voltage. Grey Relation Analysis was employed to convert a multi-response variable to a single-response grey relation grade. The tool electrode was a copper rod covered with epoxy powder resin, and the electrolyte was an aqueous sodium chloride solution. The influence of several process parameters on output was investigated using an analysis of variance. They conclude that:-

- The feed rate significantly influenced the robustness of ECM.
- The optimal combination that optimizes multiple process parameters is the voltage of 20V, feed rate of 0.32mm/min, and electrolyte content of 15%.
- Grey relation analysis improved several output parameters such as material removal rate, overcut, cylindricity error, and surface roughness.
- Grey relation analysis can be used to increase the pace of material removal.
- Grey Relation Analysis may reduce overcut cylindricity error and surface roughness (GRA).

D. Saravanan et al.[3] They used a Taguchi L18 orthogonal array to design and run tests to determine the best machining parameter for cutting SDSS with electrochemical micromachining. They calculated the percentage contribution of various process parameters to the Material Removal Rate using statistical analysis of variance (MRR). The duty cycle is the most important among the many factors analyzed, accounting for approximately 42% of the MRR. The pulse on-time increases as the duty cycle increases, contributing to greater MRR. It aids in the understanding of the machining parameters for SDSS's ECMM.

V. K. Jain et al.[4] They created an experimental system to mill micro-holes and microchannels, which they developed and built. A sewing needle with a tip diameter of 47um is used to machine these characteristics. They investigated the influence of process parameters on the machined hole diameter, such as feed rate, voltage, pulse duty cycle, and electrolyte concentration, and built a mathematical model. Using the ECMM technique, a straight tool with an 80um diameter is produced from 1000um steel wire. They looked at how the material removal rate changed over time and with changes in wire diameter. They analyzed microfeature measurement and photographic with the help of using a digital microscope.

D. Bahrea et al.[5] They reported how the potential of pulsed electrochemical machining (PECM) for lamellar cast iron machining is studied in terms of machining performance during electrolysis using sodium nitrate (NaNO3) as the electrolyte and stainless steel as the cathode. As a result, the material removal characteristics of lamellar cast iron with PECM are identified using a systematic design of experiments approach and an industrial PECM machine system to maximize the process's efficiency and reduce the number of defined surface qualities generated.

Malapati Manoj Kumar Reddy et al.[6] They used an electrochemical machine to investigate the impact of various process parameters, such as machining voltage, pulse period, electrolyte concentration, and duty cycle ratio, on machining performance criteria, such as machining accuracy and material removal rate, in order to meet micro machining requirements. They look into the most effective zone on copper, which provides excellent machining precision while also allowing for a significant amount of machining speed and material removal rate. According to the experimental results, the inclusion of a short pulse period improves. SEM micrographs are used to examine and compare the surface quality of the machined micro holes.

S.S. Uttarwar et al.[7] They used an electrochemical machine to investigate the impact of various process parameters such as time of electrolysis, current, voltage, electrolyte concentration, feed rate, and pressure on the output parameter material removal rate and surface roughness of SS AISI 304. They argued that variations in current had a significant impact on MRR and that surface roughness reduced as current increased. As a result, it was clear that irregular MRR was more likely to occur at high currents. The results revealed that when the MRR, molar concentration of electrolyte, period of electrolysis, and feed rate increased, so did the electric voltage. On the other hand, the period of electrolysis was the most critical factor in the final surface polish.

B. Ghoshal et al.[8] Electrochemical machining (ECM) is the most appropriate and fastest way of micro tool manufacturing for them. They produced tungsten micro tools under various machining conditions to determine the frequency of tool vibration, the effects of voltage, the amplitude of tungsten tool vibration, the dipping length of the tool into the electrolyte, and the electrolyte concentration.

P.Satishkumar et al.[9] They used a Taguchi L27 orthogonal array to design and run tests to see how different parameters like electrolyte concentration, machining voltage, and frequency affect the overcut and material removal rate when electrochemical micromachining Al 6061-6 percent. They proposed an approach for optimizing machining parameters on drilling Al 6061-6 percent Gr Metal Matrix composites using Electrochemical Micro Machining (EMM) based on Taguchi analysis, determining the optimal level of parameters and validating the same with a confirmation test. They discovered that machining performance might be significantly enhanced compared to the initial parametric setup.

S.Dharmalingam et al.[10] They use Taguchi methodology and Grey relational analysis (GRA) to investigate the influence of machining parameters such as machining voltage, electrolyte concentration, and frequency on the overcut and material removal rate on drilling of Al-6 percent Gr Metal Matrix composites using Electrochemical micromachining (MMC). The ideal values of parameters were found based on the analysis, and the confirmation test validated the same. The confirmation result reveals a significant improvement in overcut, Material Removal Rate, and Grey relational grade, which are increased by 41.17 percent, 08.33 percent, and 81.77 percent, respectively, using grey relational analysis. They discovered that machining performance might be significantly enhanced compared to the initial parametric setup.

Suresh H. Surekar et al.[11] They used an electrochemical machine to investigate the influence of several process parameters on the material removal rate of Hastelloy C-276, including voltage, tool feed rate, and electrolyte flow rate. They hypothesized that the tool feed rate significantly impacts the material removal rate, which increases as the tool feed rate and voltage increase. However, an increase in electrolyte flow rate will cause a decrement in the material removal rate of Hastelloy C-276.

Zhuang Liu et al.[12] They looked into the potential of employing microwire electrochemical machining (ECM) to fabricate micro metal tools in various forms. The tests use a diameter 300 um tungsten rod as an anode, a diameter 20um tungsten wire as a cathode, KOH as an electrolytic solution, and ultra shot pulsed current as a power source. In order to achieve ideal conditions, the effects of pulse on time, wire feeding rate, applied voltage, and solution concentration on overcut and machining stability were investigated. They show that the proposed method can effectively create microtools with complicated forms.

B.Babu et al.[13] They suggested a method for applying EMM to optimize machining settings on drilling Al- Al203- B4C Metal matrix composites. They used a Taguchi orthogonal array and analysis of variance to investigate the effects of machining factors such as machining voltage, electrolyte concentration, and frequency on the overcut and MRR. The Taguchi analysis is used to discover the optimal parameter level, then validated using the confirmation test. They discovered that machining performance might be significantly enhanced compared to the initial parametric setup.

Xu Zhengyang et al.[14] They look at the potential of employing Electrochemical Machining (ECM) to make essential aero-engine components out of a novel burn-resistant alloy (Ti40). Reason for cost savings and increased efficiency over traditional mechanical machining. They discovered that an aqueous combination of sodium chloride (NaCl) and potassium bromide (KBr) offers the best electrolyte and that utilizing a pulsed current of 1 kHz rather than a direct current improves the surface quality of Ti40 workpieces. Operating voltage, cathode feeding rate, electrolyte intake pressure, and electrolyte concentration impact the quality of cavities created by ECM and the total material removal rate. By tweaking these parameters, the surface roughness of 0.371 lm was reached in conjunction with a specific removal rate of more than 3.1mm 3A- min.

Mr. Sumit Bhandaril et al.[15] Particle Swarm Optimization Technique was used to optimize the non-traditional machining (NTM) process for electrochemical machining. The project's primary goal is to determine the best machining parameter values. To a considerable degree, non-traditional or unconventional machining has proven superior to conventional milling.

K. Chandra Sekhar et al.[16] Using micro electrochemical machining, researchers investigated the influence of parameters on material removal rate (u-ECM). The Micro Electrochemical Machining (u-ECM) method was developed in-house to investigate the electrode's performance properties. The workpiece electrode is taken as aluminum, the tool electrode as stainless steel, and NaCl (sodium chloride) as the electrolyte. Micro-hole machining has been carried out on the workpiece with 30% electrolyte concentration using the u-ECM method by controlling the voltage and feed rate.

ELECTROCHEMICAL MACHINING

From the figure of the ECM experimental setup, the ECM machine consist of two electrode one is the anode that is our work material, and the other is the cathode that is a tool. Water with Sodium nitrate is used as an electrolytic solution. During the experiment following chemical reaction takes place

$H2O \rightarrow H^+ + OH^-$

$NaNO_3 \rightarrow Na^+ + NO_3^-$

Negatively charged ions that mean anions (OH^- and NO_3^-) move towards the anode while positively charged ions which mean cations (H^+ and Na^+) move towards the cathode.

Reaction at anode

$Fe \rightarrow Fe^{2+} + 2e^-$

Reaction at cathode

$2H^+ + 2e^- \rightarrow H_2\uparrow$

The ferrous ion combines with the hydroxide ion to form ferrous hydroxide $Fe\ (OH)_2$; a ferrous ion was formed during the reaction. This ferrous hydroxide is complex, and it is insoluble in water and hence appears as a solid precipitate that does not affect the chemical reaction.

$Fe^{2+} + 2NO_3^- \rightarrow Fe\ (NO_3)_2$

$2Na^+ + 2OH^- \rightarrow 2NaOH$

$2NaOH + Fe\ (NO_3)_2 \rightarrow 2NaNO_3 + Fe\ (OH)_2$

EXPERIMENTAL SETUP

The copper tool is the cathode in ECM, whereas the workpiece is the anode. The copper tool transfers electrolytes to the workpiece. Between the tool and the workpiece, there is little space. This gap is called the inter-electrode gap. The electrolyte is pumped by a water pump and controlled by a flow regulating valve.

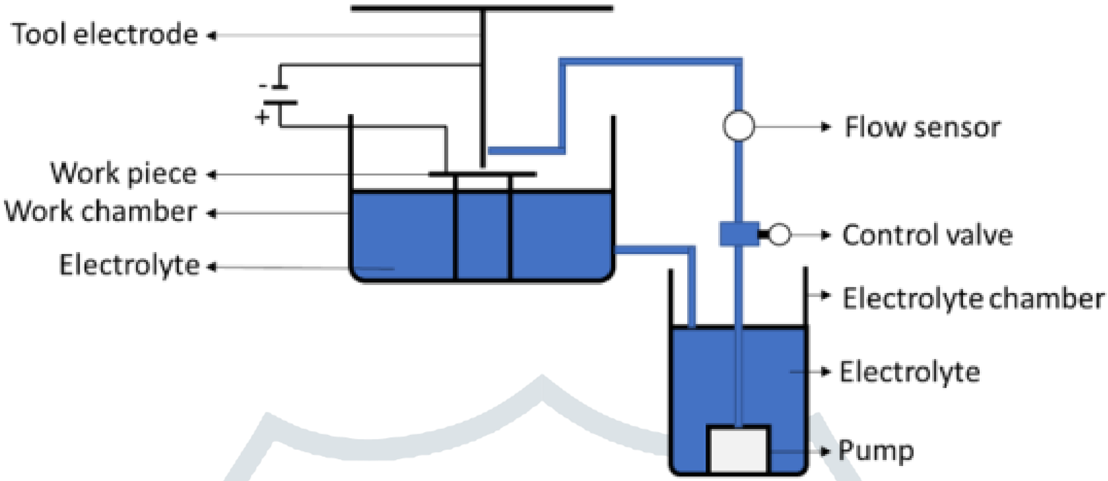


Fig.1 Experimental setup

A flow sensor is connected at the end of the flow regulating valve to measure the electrolyte flow. This flow sensor is connected to an Arduino, and this Arduino is connected to a computer, discharge of flow is directly seen in the computer. During the experiment, precipitate occurs on work material and is flushed out by the electrolyte flow.

Table.1 lists all the working conditions, and Fig.1 depicts the experimental setup.

Table 1 Working condition

S.No.	Parameters	Working Range
1	Voltage	20-30 V
2	Concentration	80-140 g/l
3	Inter electrode gap	0.5-1.5 mm
4	Flow rate	0.54-0.95 L/min

MODEL FORMYLATION FOR COPPER WORKPIECE

The statistical design of the experiment is an effective technique for arranging better outcomes, analyses, and conclusions. The process parameter is the input parameter, and the response from the statistical design is the output parameter.

1. Design of experiments

It is essential to make a plan with high accuracy to complete the whole process without any loss. This planning helps during the experiment without drawbacks or any failure, and it also saves time and material and reduces the overall cost of the product. Before the experiment, we have several input parameters, but we cannot take all these parameters during the experiment. So some parameters are taken as constant to complete the experiment. As we have four input parameters with four numbers of levels to design the experiment Taguchi L_9 orthogonal array approach was used.

Table 2 Experimental outcome for various sets of process parameter

S.no	Voltage (V)	Concentration (gram/lit)	IEG (mm)	Flow Rate (lit/hour)	MRR (gram/min)	Taper Angle (in degree)
1	20	80	0.5	0.54	0.037867	0.3512
2	20	110	1	0.81	0.014602	0.59448
3	20	140	1.5	0.95	0.009692	0.06992
4	25	80	1	0.95	0.025374	0.53863
5	25	110	1.5	0.54	0.024458	1.14318
6	25	140	0.5	0.81	0.018944	1.12982
7	30	80	1.5	0.81	0.027075	1.22634
8	30	110	0.5	0.95	0.037216	0.91732
9	30	140	1	0.54	0.0336	0.9382

2. ANOVA and Regression analysis

After collecting the input data such as voltage, electrolyte, IEG, and flow rate to calculate the material removal rate, we have to perform the next step. The next step is to use MINITAB 17 software to do ANOVA and regression analysis on the acquired data. This procedure aids in determining the most critical factors used as input parameters.

Table 3 Analysis of variance for MRR

Source	DF	Adj SS	Adj MS	F- value	P- value
Regression	6	0.000769	0.000128	5274.70	0.000
Voltage	1	0.000014	0.000014	591.88	0.002
Concentration	1	0.000001	0.000001	41.27	0.023
IEG	1	0.000120	0.000120	4958.71	0.000
Flow Rate	1	0.000044	0.000044	1810.84	0.001
Voltage*concentration	1	0.000004	0.000004	171.25	0.006
Concentration*IEG	1	0.000103	0.000103	4274.55	0.000
Error	2	0.000000	0.000000		
Total	8	0.000769			

The P-value in Table 3 indicates whether or not a factor is significant. The input factor with the highest F-value with predictor term is the most remarkable, while the input factor with the lowest F- value with predictor word is the least remarkable. As a result, we may infer that IEG has the essential input factor, with an F- the value of 4958.71, while predictor term concentration has the least exceptional input factor, with an F- the value of 41.27.

Table 4 Model summary

S	R- sq.	R-sq. (adj)	R- sq. (pred)
0.0001558	99.99%	99.97%	99.68%

Table 4 demonstrates that the developed model for MRR can predict the reaction of fresh observations with a 99.68 percent accuracy by fitting 99.99 percent of data points with an average distance of 0.0001558 percent from the fitted line.

Table 5 Analysis of variance for Taper Angle

Source	DF	Adj SS	Adj MS	F- value	P- value
Regression	7	1.27670	0.182386	2654.20	0.015
Voltage	1	0.07628	0.076282	1110.11	0.019
Concentration	1	0.10224	0.102244	1487.93	0.017

IEG	1	0.15961	0.159614	2322.82	0.013
Flow Rate	1	0.17255	0.172551	2511.09	0.013
Voltage*concentration	1	0.02944	0.029440	428.43	0.031
Voltage*IEG	1	0.07883	0.078831	1147.20	0.019
Concentration*IEG	1	0.29928	0.299276	4355.28	0.010
Error	1	0.00007	0.000069		
Total	8	1.27677			

Table 5 shows that "concentration*IEG" has the most outstanding F- the value of 4355.28, and the predictor term "voltage*concentration" has the lowest F- value of 428.43, indicating that the most notable input factor is "concentration*IEG." The P-value of factor “voltage*concentration” is significant, meaning it could not affect the response factor higher than other factors.

Table 6 Model summary for Taper Angle

S	R- sq.	R- sq. (adj)	R- sq. (pred)
0.0082895	99.99%	99.96%	97.27%

Table 6 demonstrates that the developed taper angle model fits about 99.99 percent of data points with an average distance of 0.0082895 from the fitted line and can predict the response of fresh observations with a 97.27 percent accuracy.

The regression equation for MRR and Taper Angle is:-

MRR=0.03298+0.003921*voltage-0.000206*concentration-0.068634*IEG 0.025807*flowrate-0.000018*voltage*concentration+0.000500*concentration*IEG (1)

Taper Angle = -8.726+0.32774*Voltage+0.06795*Concentration+7.035*IEG-2.1529*flow rate-0.001565*Voltage*concentration-0.13848*voltage*IEG-0.034488*concentration*IEG (2)

With the aid of MS EXCEL 2007, the following equation was utilised to plot the graph between material removal rate and input parameter.

RESULT AND DISCUSSION

1. Effect of applied voltage on MRR and Taper angle

The graph in figure 2 shows that as the machining voltage increases, the rate of material removal rises. The reason for this is that according to the rules of faraday, the amount of material removed from the workpiece is proportional to the machining current. As the voltage of the ECM rises, the current density rises, and the material removal rate rises.

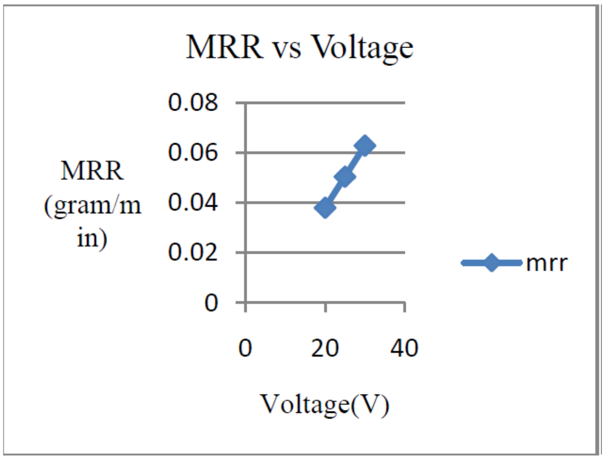


Fig.2 Graph of MRR v/s Voltage

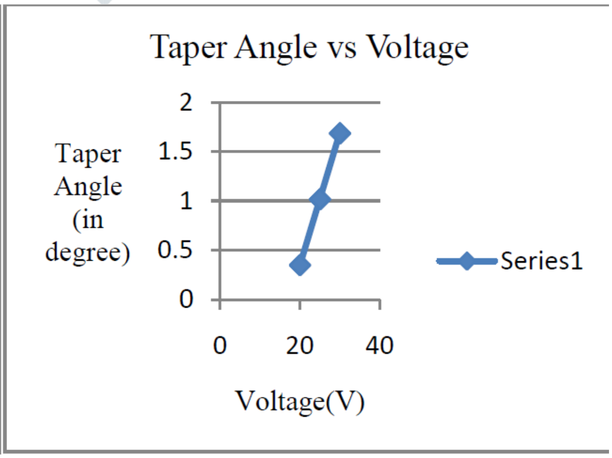
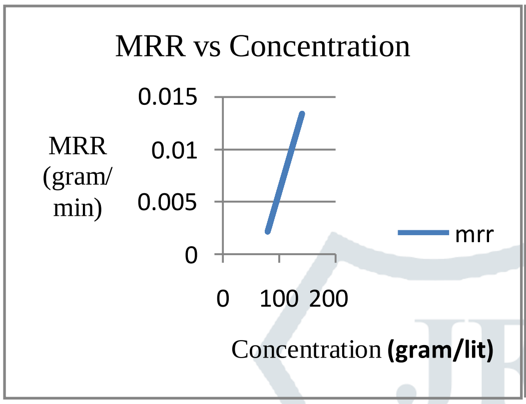


Fig.3 Graph of Taper angle v/s Voltage

Figure 3 depicts the taper vs. voltage curve. The average change in a taper is linear with increasing voltage, and the taper angle shifts from divergent to convergent. Low voltage results in a lower-intensity electric field, reducing the stray current impact and overcut. If the applied voltage increases to higher levels, the current increases proportionately, resulting in a more significant heating effect at a deeper depth. As a result of the increased overcut occurrence, the taper angle rises.

2. Effect on Concentration in MRR and Taper Angle

The graph in figure 4 shows that as the electrolysis concentration increases, the atoms in the workpiece react fast to the electrolysis, forming a precipitate on the workpiece that is swiftly flushed off by the electrolysis flow. The rate of material removal increases as the electrolysis concentration rises.



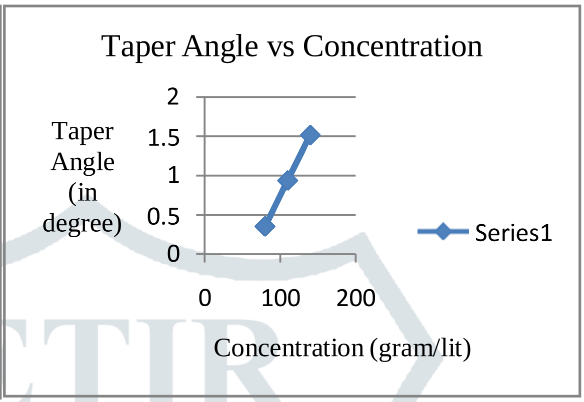
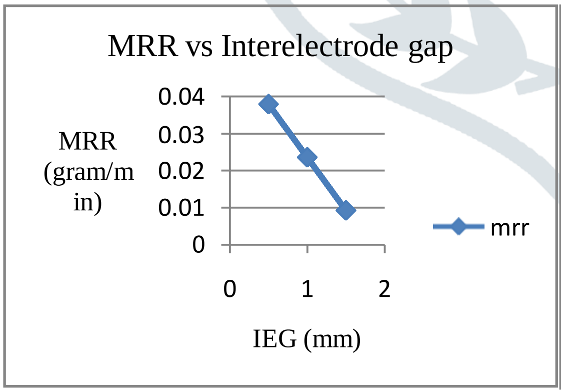


Fig.4 Graph of MRR v/s Concentration Fig.5 Graph of Taper angle v/s Concentration

Figure 5 shows a graph of taper vs. electrolyte concentration; with a slight rise in electrolyte content, the taper increases. In addition, the taper's nature shifts from divergent to convergent. This is because raising the metal ion concentration improves hole taper.

3. Effect of Inter electrode gap (IEG) on MRR and Taper angle

Figure 6 shows that the material removal rate decreases when the space between the tool and the workpiece widens. The rise is because the inter-electrode gap charge cannot be easily transported on the surface of the workpiece, preventing the charge from reacting with the surface and precipitation from forming on the workpiece. As IEG lowers, more precipitate forms on the workpiece surface, which is then eliminated by electrolysis flow.



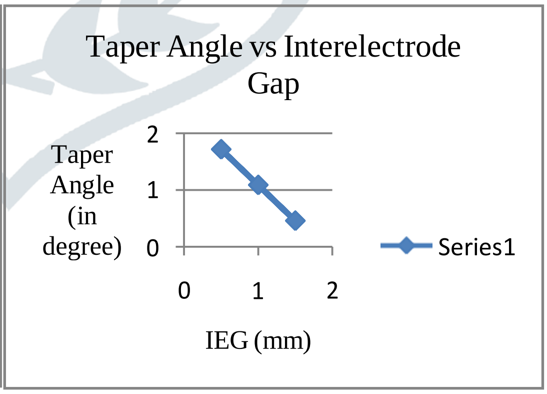


Fig.6 Graph of MRR v/s Inter electrode gap Fig.7Taper angle v/s Inter electrode gap

Figure 7 shows a plot of the taper vs. inter-electrode gap. With increasing IEG, the taper angle lowers. When the inter-electrode gap widens, the region at the top of the hole dissolves more slowly, resulting in an overcut at the top. Higher IEG causes more hydrogen bubbles to develop between the machining gaps, increasing local electric resistance. As a result, the current flows mainly to the tool's bottom, where resistance is low and the exit diameter grows.

4. Effect of Flow rate on MRR and Taper angle

Figure 8 illustrates the MRR vs. flow rate graph, which indicates that as the electrolyte flow rises, more material is taken from the workpiece faster because it flushes the cavity on the workpiece surface during machining.

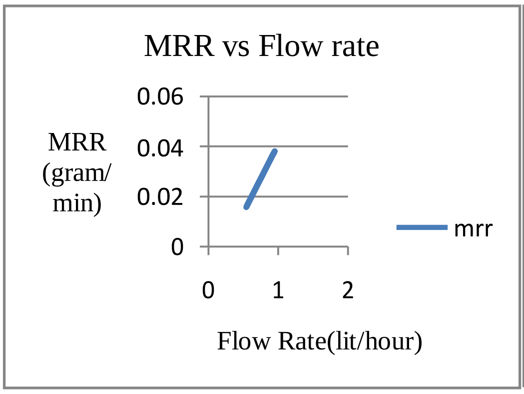


Fig.8 Graph of MRR v/s Flow Rate

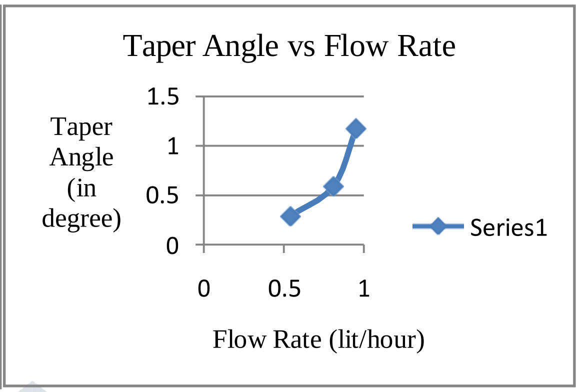


Fig.9 Graph of Taper angle v/s Flow Rate

The machining hole by ECM process material is dissolved from the hole's side wall and bottom surface simultaneously, as demonstrated in the plot taper angle v/s flow rate in figure 9. Taper formation is achieved by cutting the sidewall, and hole depth is increased by machining the bottom surface. As a result, as the flow rate rises, the taper angle rises.

OPTIMIZATION OF MRR AND TAPER ANGLE

These empirical equations were produced using MINITAB 17 and the Regression Fit Model. MRR and Taper Angle both have R-square values of 99.99 percent.

To optimize response and decision variables, we used the multi-objective Matlab2015 environment. The following are the Pareto fronts determined for response: -

Where:-

Objective1 = MRR

Objective 2 = Taper Angle

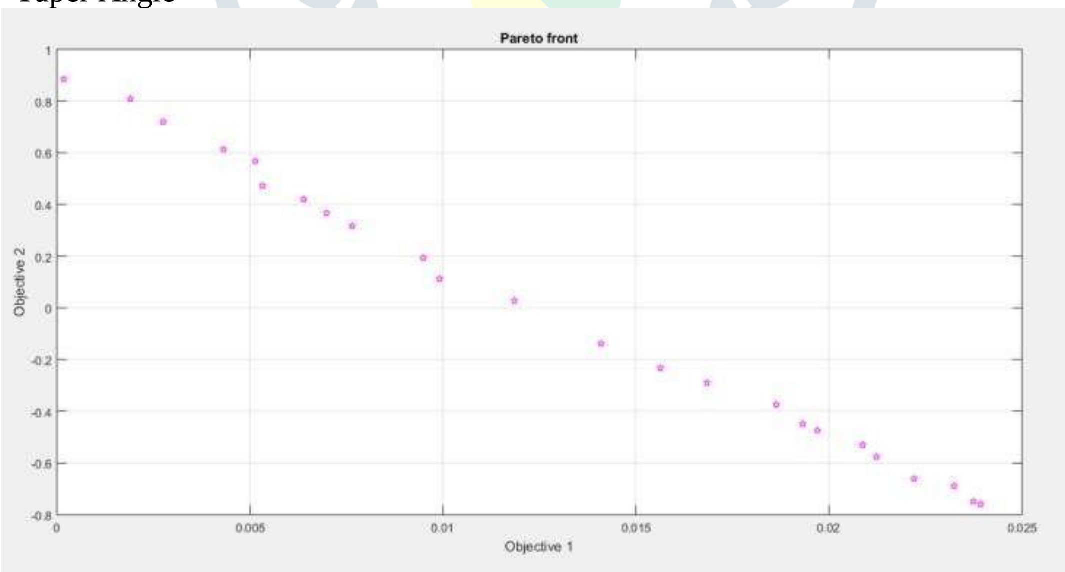


Fig.10Pareto Front of Response (MRR & Taper Angle)

CONCLUSION

Using a copper tool electrode, this experiment revealed that:-

a. With increasing voltage, concentration, and flow rate, the characteristic curve between MRR/taper grows.
b. The characteristic curve shows that the MRR/taper drops as the inter-electrode gap increases.
c. The best solution from the Pareto front for response and decision variable is found using Non-Sorted Genetic Algorithm-II in (between voltage = 20-30volt, concentration = 80-140 gram/lit, IEG = 0.5-1.5mm, and flow rate = 0.54-0.95) as follows:-

Table 7 Optimized set for optimum response

S. No	MRR	Taper Angle	Voltage	Concentration	IEG	Flow Rate
1	0.024	-0.76	29.917	137.191	1.48	0.937
2	0.003	0.718	20.108	95.343	1.46	0.943
3	0.005	0.569	20.518	104.906	1.459	0.943
4	0.005	0.471	20.128	113.905	1.498	0.943
5	0	0.884	20.006	86.896	1.498	0.943
6	0.008	0.319	20.392	122.85	1.468	0.942
7	0.024	-0.76	29.917	137.191	1.48	0.937
8	0.023	-0.687	29.478	135.506	1.488	0.938
9	0.009	0.194	21.175	126.995	1.484	0.942
10	0.021	-0.576	28.134	136.055	1.483	0.939
11	0.007	0.365	20.399	119.625	1.483	0.943
12	0.014	-0.137	23.281	136.228	1.479	0.939
13	0.021	-0.529	27.87	135.4	1.482	0.937
14	0.022	-0.661	28.775	137.146	1.481	0.939
15	0.017	-0.29	25.123	135.797	1.481	0.937
16	0.01	0.113	20.558	135.31	1.496	0.94
17	0.006	0.419	20.444	116.18	1.494	0.941
18	0.012	0.027	22.045	133.264	1.472	0.941
19	0.016	-0.235	24.36	136.066	1.48	0.941
20	0.004	0.613	20.451	130.105	1.483	0.943
21	0.002	0.809	20.379	91.488	1.498	0.941
22	0.019	-0.374	26.446	134.549	1.471	0.941
23	0.019	-0.449	26.871	135.485	1.482	0.94
24	0.024	-0.749	29.792	137.191	1.48	0.937
25	0.02	-0.475	27.121	135.61	1.482	0.94

Pictures of all machined micro hole on the Copper workpiece is given below

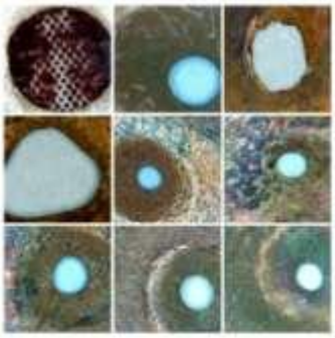
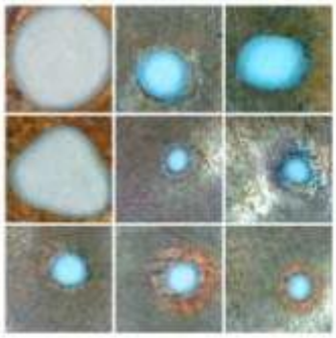



Fig.11 Front Side Fig.12Back Side

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