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Machining Performance and Optimization of Process Parameters of Monel alloy 400 Using ECM Process

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Abstract

Monel alloy 400, a mixture of copper and nickel is widely renowned for its resistance to chemical and physical strength. This alloy is most likely among the toughest as well as least corrosive metal recognized in the industry and research fields. These qualities have increased its uses in a variety of domains such as aerospace, marine, and automotive. Because work hardens fast on its surface, Monel alloys are very difficult to cut using typical machine equipment or other procedures.The current study examines the effect of ECM method parameters like applied voltage source (V), electrolyte conc. (EC) as well as inter electrode gap (IEG) upon material removal rate (MRR), tool wear rate (TWR), including surface roughness (Ra). The basic electrolytes utilized in machining of Monel Alloy 400 are a mixture of aqueous sodium nitrate ($NaNO_3$) & sodium chloride (NaCl). As an experimental strategy, the Box-Behnken Design (BBD) generated from response surface methodology (RSM) is utilized and effects of variables and their relationships are investigated, and process variables are adjusted.

***Keywords**:* ECM; Super alloy; MRR; Surface roughness; TWR.

1. Introduction

ECM is a novel machining technique based on electrochemistry. ECM is commonly employed in sectors where different components that are hard to cut and where complicated contours are required. A direct current (DC) (5-30 volt) voltage is provided throughout the IEG across the pre-shaped electrode tool and the job material. Electrolyte moves quickly across the IEG and typical density of current is about 20 - 200 A/cm^2. Electrochemical characteristics of metal, electrolyticproperties, and electric voltage/current provided all influence the anode dissolution that is determined by the Faraday's equations of electrolysis. ECM produces nearly similar imprint of the tool electrode upon that work item. [1-3]

ECM clearly outperforms other traditional machining methods in terms of application irrespective of work hardness, greater MRR, reduced tool wear, plane and brilliant surface, and manufacturing of parts with complicated structures having crack-free &stress-free surfaces. [4-5]High residual stresses are created during conventional machining with Monel 400 alloys, resulting in a quick hardening which slows down the operation and causes tool electrode failure. As a result, machining these metals using ordinary machine tools is extremely challenging. On the other hand, could machine almost every alloy regardless of hardness or tensile strength. As a result, it may be a profitable option to machine Monel alloys, and its importance may grow in future.The goal here is to create comprehensive computational equations for relating interactive as well as higher-order effects of different process variables like applied voltage (V), electrolyte conc., (EC) as well as inter electrode gap (IEG), on the machining work, namely material removal rate (MRR), Tool wear rate (TWR) as wellas surface roughness (Ra), to effectively utilise optimum potential of ECM [5-7].To organise and analyse the studies, response surface methodology (RSM) is used. The goal of employing the response surface methodology(RSM) is to study the response across whole factor space, and also to identify the area of concern in which response achieves the optimal or close to optimum value. [8-10]

2. Current status of research

Haisch et al. [11] Anodic metal dissoluteness for Steel-100Cr6 was considered in aqueous $NaNO_3$as well as NaCl solutions. Flow of passage investigations was conducted with a large density of current up to 70 A/cm^2. Unsolvable carbide particles enhanced apparent current efficiency for NaCl by more than 100% and in $NaNO_3$ by more than 67%. **Munda and Bhattacharyya [12]** The paper aims to obtain an overall mathematical prototype using for relating the collective & high-order factors of various machining parameters such as applied voltage pulse off/on ratio, electrolyte conc., frequency of voltage, as well as frequency of tool vibration upon most significant machining standards, namely the MRR as well as overcut. **Santhi et al. [13]** His objective was to develop a revolutionary method for optimising titanium alloy process parameters (Ti6Al4V). Design, strategy, and method - A desire function study, the fuzzy set concept, & Order preference method through similarity to Ideal Solution methods were used in order to construct ECM processing parameters for titanium alloys. **Bahre et al. [14]** The feasibility of PECM for lamellar cast iron machining is investigated in terms of machinability with $NaNo_3$ as the electrolyte & stainless steel as the tool material. The accuracy of created geometries, as well as the possibility of producing certain surface properties, is investigated in this study. **Muthu kumar et al. [15]** The core composite design technique was used in his experiment. After analysing 30 tests, a mathematical model was created to connect the machining factors with the ROC. The relevant coefficients were calculated using ANOVA with a 5% significance level.**Kalaimathi et al. [16]**, different process parameters affect machining outcomes in terms of MRR& SR for Monel 400 alloy. MRR and SR were improved by using an electrolyte conc., of 15gm/lt and also an IEG of 0.4mm. ANOVA is used to evaluate the results. **Tiwari et al. [17]** attempted to build a mathematical prototype for characteristics like MRR& SR for ECM over EN 19 steel using regression analysis. The Analysis of variance was utilized to evaluate the sufficiency of developed prototypes.**Krishnamurthy et al. [18]**MRR has been discovered as being very important in ECM, and employing the best ECM process parameters may typically save operating, tool, & maintenance costs while generating higher-accuracy products. The paper explored the affect and direct development of several process factors for Titanium ECM. **Li et al. [19]** Using a 10% sodium nitrate slurry, via ECM was used to make number of holes in Titanium alloy sheet. To recognize the electric characteristics of Titanium alloy (Ti6Al4V) inside a 10 per centof $NaNO_3$ electrolyte, current efficiency graph including polarisation graph of the alloy was investigated. **Chen et al. [20]** In this study, orthogonal experiments were performed to test Ti60 ECM in order to regulate the impacts of different electrochemical method factors on SR and the most relevant characteristic was found to be the frequency of a voltage source. It has been observed that using correctly adjusted ECM settings may greatly reduce a work item's surface roughness. **Rao et al. [21]** on the basis of combination of the ECM process with a high MRR and a standard honing process that generates a controlled smooth surface finish, electrochemical honing was investigated as the maximum precise machining technology discovered for machining gears and cylinders. **Jeykrishnan et al. [22]** His study focuses on the application of three critical factors in the vehicle industry: current, voltage, & electrolyte concentration. As a result, updated methods must be implemented to achieve the best results. **Soundrapandian et al. [23]** The microscopic system was used in his research to measure overcut & conicity for drilled hole,& the profilometer was utilized to analyse the SR of the machined region to discover the optimal machine variable. ANOVA was used to evaluate the impact of each variable on MRR, overcut and drilled hole circularity. **Geethapriyan et al. [24]**In his work, he used the Taguchi-grey relational analysis technique to discover the relevance of various process factors and to examine the variables for machining of titanium. **Sharma et al. [25]** the outcomes of process variables like applied voltage, IEG, electrolyte conc., & electrolyte flow uponMRR& radial over cut were examined. A Taguchi (Orthogonal Array)-based approach was used to optimise several input parameters and final responses in ECM. **Kumar [26]** ECM is a novel machining technique that employs Faraday's law to eliminate metal from a work piece. Titanium alloys are employed in the manufacture of jet engines as well as other aerospace components. In this review study, the process properties of ECM, like the MRR, surface finish, and overcut, were examined when Titanium alloy was deposited in different electrolytes. **Khan et al. [27]** sought to improve ECM method variables using a combination comprising SS 316 (work piece) & Copper as a tool (tool material). Total 27 tests were performed to assess the effect of ECM variables like electrolyte conc., applied voltage, current, as well as feed rate of tool upon the work's MRR& SR. **Khan et al. [28]** Other than the mechanical qualities of metal, it was discovered that thermal properties play a more important role; the forces created in this technique are modest, and thus burrs are not obtained. **Khan et al. [29]** explored the possibility of utilizing jatropha oil as a source of dielectric medium in replacement with kerosene oil, which is environmentally benign. Other dielectric fluids, such as hydrocarbons, have a negative effect on environment. **Khan et al. [30]** Micro-machining was investigated, and the combining of micro-EDM & laser produced a decrease in machining time. He also discovered that a mixture of ultrasonic machining and the EDM Process is commonly employed. **Yadav et al. [31]** Researchers examined multi-objective optimisation of process variables using principal component examination & grey relational examination to improve metal removal and to minimise roughness of Ti 6Al 4V. **Daniel et al. [32]** In his study, he used a variety of SiC combinations based on its weight percentage and particle size. In addition, a preset weight proportion of molybdenum disulphide has been used. The aluminium composite was created by stir casting. Aluminium was fused using silicon carbide elements sized 10, 20, and 40 m that are 5, 10, & 15 per cent by wt., accordingly, and 2% Molybdenum disulphide. Taguchi L27 array is utilizedto achieve desired target levels & investigate the influence of ECM parameters on MRR& SR. **Debta et al. [33]** investigated the most intriguing magnesium alloys, AZ91D (90 per cent Magnesium), because of its remarkable toughness, high strength-weight ratio, exceptional resistance to environmental rust. It can also be cast well, enabling it to be employed in the automobile and aerospace sectors. **Kumar et al. [34]** examined the behaviour of Incoloy during EDM machining, with response variables based on input power, pulse on/off duration, and voltage applied. They also demonstrated that variable optimization in EDM may be accomplished by combining dielectric fluid with powder. **Sahu et al. [35]** studied and discovered variable optimization in the EDM process. Because ANOVA was applied, optimum findings were achieved. Suitable optimization was also used to optimise machining.**Thakur et al. [36]** considered the use of graphite tool electrodes in suitable dielectric media for machining of titanium alloy. Machining performance is designed using appropriate methodologies for performance evaluation. Following adequate testing in the EDM process, optimal variables were determined. **Sharma et al. [37]** examined Electrochemical machining of Titanium alloy using various electrolytes using a Cu tool in his experimental study. As electrolytes, KCl, $NaNO_3$, & NaCl were used. **Gobikrishnan et al. [38]**One of the most important aspects of removing the MRR was determining electrolyte content. As input variables, voltage, current, & electrolyte concentration were used. The output parameters were obtained using MRR. In their study, the value of the trial was based on the orthogonal array of

Taguchi's technique. **Ramana et al. [39]** His study focused on the ability to machine the Nickel A286 utilising PVD coated materials over a lengthy period of time. The machining performance of Nickel A286 has been evaluated utilising experimental tests that adjusted the speed of cutting and depth of cut, as well as tool electrode feed rate with taking chip shape, flank wear rate, and surface roughness into mind. **Jerin et al. [40]** Special materials, like Steel 12X18H10T, could withstand extreme temperatures while retaining their inherent properties. In order to widen its usefulness, this study will evaluate at its machining capabilities in the ECM technique for surface finishing. **Thangamani et al. [41]** His research looks at how three different NaCl-based electrolytes affect the cutting of alloy Ti 6Al 4V and the taguchi model of experimentation is used to find features on the basis of ECMM constraints such as voltage, electrolyte conc., frequency of voltage,& duty cycle. **Khan et al. [42]** examined how vegetable oil contributes to sustain EDM machining and so prevents environmental harm, although no such adjustment is necessary to support other types of biodegradable lubricants. **Wasif et al. [43]** Al 5454 alloys, that are widely used in the industrial works to create tool dies, moulds, blocks for engine, aviation parts, and a range of other components, were studied. **Nagarajan et al. [44]** In his work, he discovered that by altering the voltage (11-15 Volts), flow rate for electrolyte (1-3.0 liter/minute),& electrolyte conc. of (120-190 gm/lt), algorithms (i.e. MFO, GWO, PSO) was employed to figure out desired variables like MRR& Nickel presence in the sludge. **Vengatajalapathi et al. [45]** In his work, nickel hydroxide was eco-friendly cleaned from sludge during Monel 400 ECM. Filter materials included powdered coconut shell & wood dust. RSM's CCD was used for experiments. **Singh et al. [46]** In his work, a higher MRR was obtained with a electrolyte conc., of 200g/liter and feed rate of about 18micron/min. To obtain increased MRR with regulated input settings, a little expenditure of tool life was incurred.

3. Experimental Methodology

The pilot experiments conducted utilising the OFAT technique aided in providing appropriate ranges of input variables for the ECM machine. Before starting the machining, a certain layer of input variables are chosen and associated range is established, accompanied by a systematic layout of the experimentation performance. Accurate evaluation of variables for input, as shown in Table 1, and proper setting of their ranges are essential for obtaining appropriate results. It enables the reduction of the optimal number of tests of performance to be employed when machining.This basic experiment served as a platform for future investigation. As a result, the OFAT approach determines the input parameters to be employed as well as the optimal range of primary experiments. The multiple pieces of Monel alloy 400 with dimensions of 25mm*25mm*5mm depicted in figure 1 below are used for pilot & experimental operations. The notable ranges observed are as follows.

Table 1:Rangesfixedformainexperimentbasedonpilotexperiment

S.No.	**Parameter**	**level(-1)**	**level(0)**	**level(+1)**
1.	Voltage	15	17	19
2.	Electrolyte conc.	40	50	60
3.	IEG	0.15	0.2	0.25

To develop the Design of Experiment, the model is created utilising the three stages of experiment design based on BBD approach. As the electrode, the most appropriate instrument is copper. The electrode has a length of 60 mm and a diameter of 3mm, as illustrated in figure 2.Asurface roughness tester is utilized to assess the integrity of surface. MRR as well as TWR are computed by the weight change between them (initial wt.-final wt.).

3.1 Results obtained and discussions

This study was carried out with the usage of copper tool and the RSM-based BBD method approach. Three levels of each input variable were chosen for testing performance by running every run for 10 minutes, and the outcomes are displayed in table 2. The weight difference between the MRR and TWR was calculated after each experimental run. Each experimental run includes three levels of parameter values for analysis and optimization.

Table 2: Experimental Outcomes

		Parameter 1	Parameter 2	Parameter 3	Response 1	Response 2	Response 3
Std	Run	Applied voltage	Electrolyte conc.	IEG	MRR	TWR	SR
		volts	gm/l	mm	mm^3/minute	mm^3/minute	Micro meter
8	1	19	50	0.25	6.8613	0.1858	1.51
14	2	17	50	0.2	3.56	0.0669	3.44
9	3	17	40	0.15	2.4545	0.0732	3.85
4	4	19	60	0.2	4.242	0.0389	4.06
17	5	17	50	0.2	2.6386	0.0468	3.42
10	6	17	60	0.15	3.01	0.0145	4.28
6	7	19	50	0.15	3.61	0.029	3.2
16	8	17	50	0.2	3.5534	0.01	3.4
12	9	17	60	0.25	5.3034	0.1101	3.229
7	10	15	50	0.25	5.79	0.0569	2.03
1	11	15	40	0.2	4.7545	0.0111	3.35
3	12	15	60	0.2	2.52	0.0256	4.28
15	13	17	50	0.2	4.1727	0.0044	3.05
2	14	19	40	0.2	3.54	0.0234	4.006
11	15	17	40	0.25	6.51	0.0322	2.529
13	16	17	50	0.2	3.2295	0.0145	3.41
5	17	15	50	0.15	2.625	0.114	2.896

Figure1: Machined Work piece

Figure2: Copper Tool

3.2 Analysis and optimization for MRR, TWR and SR.

In table 3, the F value of 13.71 shows model to be significant. Large F values occur due to the noise which is just 0.12 percent of time. P values which are less than 0.0500 are significant terms. In this situation C, AB and C^{2}are critical model variables. Model terms are insignificant when values are greater than 0.1000. Model having greater insignificant values; it can be improved by model reduction. F value of 0.42 indicating Lack of fit is not significant when compared to pure error. Noise has approximately 74.66 percent chance of causing significant Lack of Fit value. When we want model to be fit, a small lack of fit is OK.

Table 3: ANOVA for TWR

Source	**Sum of Squares**	**df**	**Mean Square value**	**F-value**	**p-value**	
Model type	29.05	9	3.23	13.71	0.0012	significant
A- Applied voltage	0.8216	1	0.8216	3.49	0.1039	
B-Electrolyte conc.	0.5960	1	0.5960	2.53	0.1556	
C-IEG	20.37	1	20.37	86.53	< 0.0001	
AB	2.16	1	2.16	9.16	0.0192	
AC	0.0019	1	0.0019	0.0079	0.9316	
BC	0.7762	1	0.7762	3.30	0.1122	
A^2	0.5693	1	0.5693	2.42	0.1639	
B^2	0.0050	1	0.0050	0.0212	0.8884	
C^2	3.59	1	3.59	15.24	0.0059	
Residuals	1.65	7	0.2354			
Lack of Fit	0.3975	3	0.1325	0.4239	0.7466	not significant
Errors	1.25	4	0.3126			
Total Cor	30.69	16				

Table 4: ANOVA FOR MRR

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model type	0.0337	9	0.0037	8.09	0.0058	significant
A- Applied voltage	0.0006	1	0.0006	1.30	0.2909	
B-Electrolyte conc.	0.0003	1	0.0003	0.6539	0.4453	
C-IEG	0.0030	1	0.0030	6.43	0.0389	
AB	2.500E-07	1	2.500E-07	0.0005	0.9821	
AC	0.0114	1	0.0114	24.72	0.0016	
BC	0.0047	1	0.0047	10.08	0.0156	
A^2	0.0013	1	0.0013	2.81	0.1375	
B^2	0.0019	1	0.0019	4.15	0.0812	
C^2	0.0107	1	0.0107	23.05	0.0020	
Residuals	0.0032	7	0.0005			
Lack of Fit	0.0003	3	0.0001	0.1415	0.9300	not significant
Errors	0.0029	4	0.0007			
Total Cor	0.0369	16				

In table 4, the F value of 8.09 shows model to be significant. Large F values occur due to the noise which is just 0.58 percent of time. P values which are less than 0.0500 are significant terms. In this situation C, AC, BC and $C^2$are critical model variables. Model terms are insignificant when values are greater than 0.1000. Model having greater insignificant values; it can be improved by model reduction. F value of 0.14 indicating Lack of fit is not significant when compared to pure error. Noise has approximately 93.00 percent chance of causing significant Lack of Fit value. When we want model to be fit, a small lack of fit is OK.

In table 5, the F value of 40.69 shows model to be significant. Large F values occur due to the noise which is just 0.01 percent of time. P values which are less than 0.0500 are significant terms. In this situation B, C, AB, AC, A^2, B^2 and $C^2$are critical model variables. Model terms are insignificant when values are greater than 0.1000. Model having greater insignificant values; it can be improved by model reduction. F value of 0.73 indicating Lack of fit is not significant when compared to pure error. Noise has approximately 58.34 percent chance of causing significant Lack of Fit value. When we want model to be fit, a small lack of fit is OK.

3.3 Mathematical modelling and regression analysis

MRR=59.2866 + -4.84361 * voltage + -0.440684 * electrolyte conc. + -75.3891 * IEG + 0.0367062 *voltage*electrolyte conc. + 0.21575 * voltage*IEG + -0.88105 * electrolyte conc.*IEG + 0.0919231 * voltage^2 + -0.000344075 * electrolyte conc^2 + 369.217 * IEG^2

The real equation is derived after doing the experiment; therefore the metal removal rate is significantly dependent on the main voltage.

TWR=3.90008 + -0.25264 * voltage + 0.00809 * electrolyte conc. + -20.1724 * IEG + 1.2505 * voltage*electrolyte conc. + 0.53475 * voltage*IEG+ 0.0683 * electrolyte conc.*IEG + 0.00439437 * voltage^2 + -0.000213475 * electrolyte conc.^{2} + 20.131 * IEG^2

Because the tool wear rate is significantly dependent on the voltage, the following real equation was generated while completing the experiment.

SR$=-18.7154 + 3.026 * \text{voltage} + -0.635925 * \text{electrolyte conc.} + 126.91 * \text{IEG} + -0.01095 * \text{voltage}*\text{electrolyte conc.} + -2.06 * \text{AC} + 0.135 * \text{electrolyte conc.}*\text{IEG} + -0.060375 * \text{voltage}^2 + 0.008215 * \text{electrolyte conc.}^2 + -277.4 * \text{IEG}^2$

The real equation is derived after doing the experiment, so the Surface Roughness is significantly dependant on the voltage.

Table 5: ANOVA for SR

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	8.84	9	0.9822	40.69	< 0.0001	significant
A- Applied voltage	0.0061	1	0.0061	0.2507	0.6320	
B-Electrolyte concentration	0.5586	1	0.5586	23.14	0.0019	
C-IEG	3.04	1	3.04	125.77	< 0.0001	
AB	0.1918	1	0.1918	7.95	0.0258	
AC	0.1697	1	0.1697	7.03	0.0328	
BC	0.0182	1	0.0182	0.7551	0.4137	
A^2	0.2456	1	0.2456	10.17	0.0153	
B^2	2.84	1	2.84	117.73	< 0.0001	
C^2	2.03	1	2.03	83.90	< 0.0001	
Residuals	0.1690	7	0.0241			
Lack of Fit	0.0600	3	0.0200	0.7349	0.5834	not significant
Errors	0.1089	4	0.0272			
Total Cor	9.01	16				

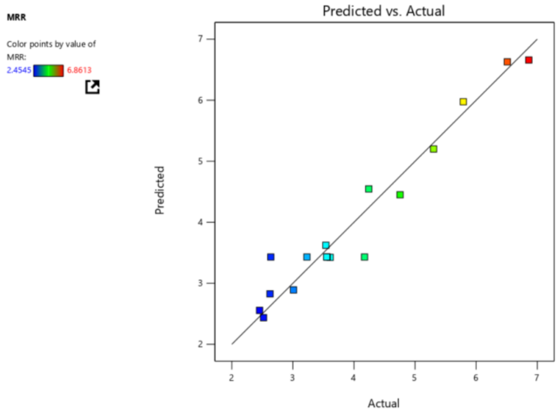

Fig 3 Predictedvs.Actual valuesofMRR

Figure 3 depicts the projected vs. real value of Material Removal Rate (MRR) where graph evidently illustrates that real model of MRR established differs from theoretical values predicted during the experimental performance, which can be easily checked by examining the spread of the true values to the predict line.

Figure 4 depicts the expected vs the real value of the outcome parameter, which is the amount of tool wear rate. The graph clearly illustrates that the real model of tool wear rate created is next to and near to the expected theoretical values obtained during the experimental performance, which can be easily checked by examining the spread of the true values to the expected actual line.

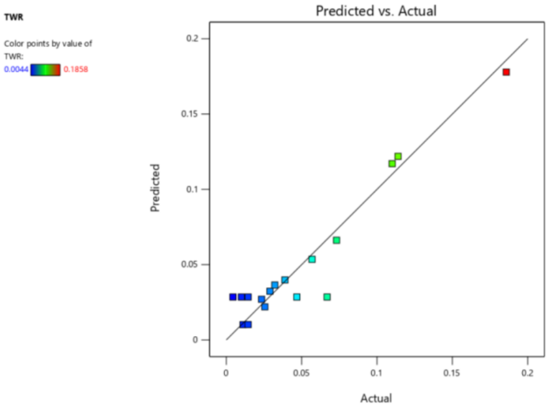

Figure 4: Predicted vs Actual value of tool wear Rate

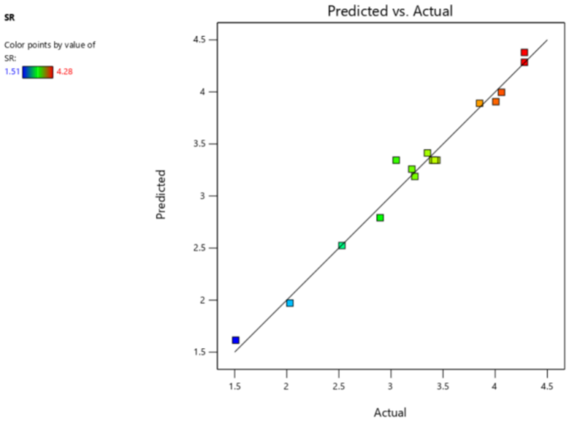

Figure 5: Predicted vs. Actual value of the Surface Roughness

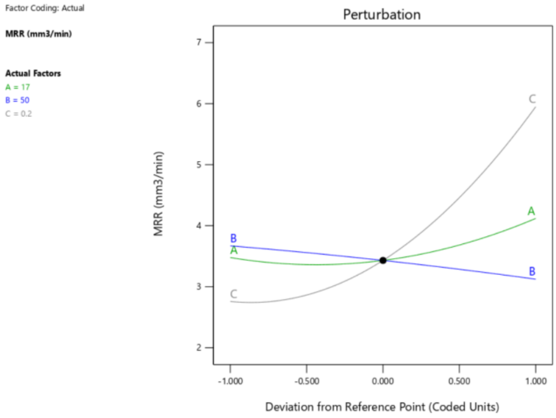

Figure 6: Perturbation graph for the Material Removal Rate (MRR)

Figure 5 depicts the expected vs. experimental result of Surface integrity. This graph clearly illustrates that the real model of Surface Roughness established is very near to the expected theoretical values obtained during the experimental performance, which can be readily checked by looking at the dispersion of the real values to the estimated actual line.

Figure 6 displays a perturbation graph for MRR, which may be used to compare the effect on various variables in an appropriate point position in the design area. The output is distinguished by the variation of each element within its assigned holdings. A strong inclination in the characteristic curve indicates that the reaction is sensitive to the output parameter factor MRR. Closeness to the flat line indicates insensitivity to change upon that particular element.

Perturbation plot for Rate of tool wear shown in Figure 7 below will aid in comparing the effect on various factors in an appropriate point position in the design region. Variation of each element within its assigned holdings and other static factors characterizes the result. A strong inclination in the slope indicates that the reaction is sensitive to the specified output variable Electrode wear Rate. Closeness to the flat line indicates insensitivity to change upon that particular element.

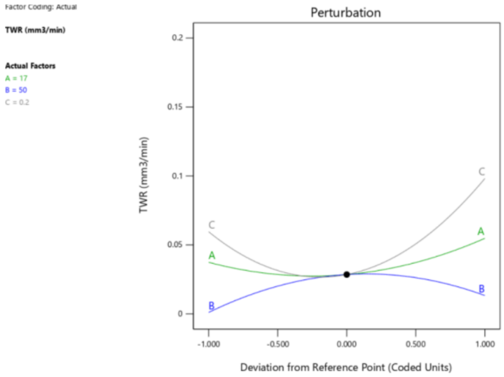

Figure7: Perturbation graph of Tool wear Rate

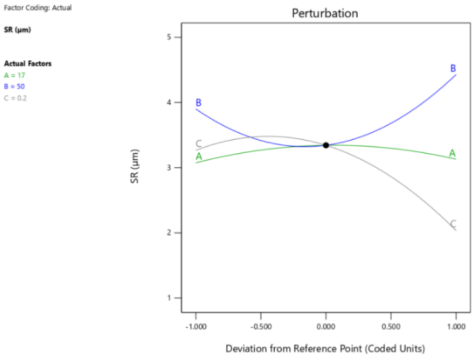

Figure8: Perturbation graph for the Surface Roughness

Figure 8 depicts a perturbation plot for Roughness of Surface, which will aid in assessing the effect on various factors in a suitable point position in the design area. The outcome is defined by altering each element within its specified limitations. A strong inclination in the characteristic curve indicates that the reaction is sensitive to the output variable factor Surface Roughness. Closeness to the flat line indicates insensitivity to change upon that particular element.

3.4 Multi response optimization

Design Expert 13 Software does Multiple Response Optimization. The suggested model has three response variables and three input parameters, which are listed in table 6 below. The instance illustrates how to optimise all output variables by evaluating each outcome and optimising the variables. The optimisation produced from the numeric report comprises tables, the first of which presents a description of the constraints utilised to construct the next table of optimum process solutions.

Table 6: Optimization of parameters

Name	Aim	lower limit	upper limit	lower weight	upper weight	Significance
Applied voltage	in range	15	19	1	1	3
Electrolyte conc.	in range	40	60	1	1	3
IEG	in range	0.15	0.25	1	1	3
Material removal rate	To maximize	2.4545	6.8613	1	1	3
Tool wear rate	To decrease	0.0044	0.1858	1	1	3
Surface roughness	To decrease	1.51	4.28	1	1	3

Table 7: Optimized Results

S.No.	Voltage (V)	Electrolyte conc.(gm/l)	IEG	MRR(mm^3/minute)	TWR(mm^3/minute)	SR(µm)	Desirability
1.	15	41.54	0.25	7.175	0.004	2.093	0.924

The optimal value of the different parameters achieved during the electrochemical machining of Monel 400 alloy for output parameters were voltage=15 volts, electrolyte concentration=41.54 gm/l, and IEG=0.25 by machining it with a copper tool.

4. Conclusions

Box-Behnken Design (BBD) is utilized at three levels in order to build mathematical models for calculating the Surface integrity factor of Monel alloy 400. The results were synthesised using a variety of multiple objective optimization techniques. The conclusions drawn are to be achieved:

- Influential factors for output results are as follows: applied voltage, electrolyte concentration, and IEG.
- Surface roughness was more noticeable at substantially higher voltages. The anticipated optimal value for surface roughness is 2.093µm.
- It was discovered that a voltage of 15 volts, an electrolyte concentration of 41.54 gm/l, and an IEG of 0.25 mm worked well for machining. Surface roughness of 2.093m, material removal rate (MRR) of 7.175 mm^3/minute, and tool wear rate (TWR) of 0.004 mm^3/minute were measured as reaction metrics.

- On the Monel alloy 400, the copper tool produced the best reaction results.

Terminology

ANOVA	Analysis of variance
BBD	Box-Behnken Design
CCD	Central composite design
ECM	Electrochemical Machining
ECH	Electro chemical honing
EDX	Energy-dispersive X ray spectroscopy
EMM	Electro micro machining
GWO	Grey wolf optimizer
IEG	Inter electrode gap
MFO	Moth-flame optimization
MRR	Material removal rate
RSM	Response surface methodology
SR	Surface roughness
PECM	Precision electrochemical machining
TWR	Tool wear rate

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